Human Health Risk Assessment for Iron and Steel Slag

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List of Abbreviations

<75 um	particles less than 75 µm
<300 um	particles less than 300 µm
A	ATSDR (Agency for Toxic Substances and Disease Registry) Table 4.1
AADT	annual average daily traffic
ADAF	age-dependent adjustment factor
Ag	silver
Al	aluminum
As	arsenic
AT	averaging time
Ba	barium
BF	blast furnace
BOF	basic oxygen furnace
B_{oral}	oral bioaccessibility factor
BW	body weight
C	California Environmental Protection Agency (Table 4.1)
c	carcinogenic effects
Ca	calcium
CAS	Chemical Abstracts Service
Cd	cadmium
Cr	chromium
Cr(VI)	hexavalent chromium
COI	constituent of interest
conc	concentration
CSF	oral cancer slope factor
CSFi	inhalation cancer slope factor
Csoil	chemical concentration in soil
d	day
d/yr	day per year
DRA	deterministic risk assessment
EAF	electric arc furnace
ED	exposure duration
ET	exposure time
Fe	iron
ft	feet or foot
G mean	geometric mean
g/m^2-sec	gram per square meter per second
GGBFS	ground granulated blast furnace slag
GI	gastrointestinal
GSD	geometric standard deviation
Hg	mercury
HHRA	human health risk assessment
HQ	hazard quotient
I	USEPA Integrated Risk Information System (IRIS), Table 4.1

List of Abbreviations (Continued)

IRIS	USEPA Integrated Risk Information System
IFSMo	age-adjusted soil ingestion rate
in	inch
ing	ingestion pathway
Inh	inhalation pathway or inhalation rate
IR	ingestion rate
IRIS	Integrated Risk Information System
ISC	Industrial Source Complex
J	Joule or New Jersey Department of Environmental Protection
K_d	water-solid partitioning coefficient
kg	kilogram
kg/mg	kilogram per milligram
K-S test	Kolmogorov-Smirnov goodness-of-fit test
lb/ft^3	pound per cubic foot
L/kg	liter per kilogram (L/kg)
m^3/kg	cubic meter per kilogram
max	maximum concentration
M_{doz}	mass emitted during dozing
MCA	Monte-Carlo analysis
MDT	Montana Department of Transportation
M_{dump}	mass emitted during dumping
MFi	multiplying factor for inhalation exposure
MFo	multiplying factor for oral exposure
Mg	magnesium
mg/d	milligram per day
mg/kg	milligram per kilogram
mg/kg-d	milligram per kilogram per day
mg/kg-day	milligram per kilogram per day
(mg/kg-d)$^{-1}$	per milligram per kilogram per day
Mg/L	milligram per liter
mg/m^3	milligram per cubic meter
mg-yr/kg-d	milligram year per kilogram per day
M_{grad}	mass emitted during grading
min	minimum concentration
MLE	most likely exposure
mm	millimeter
Mn	manganese
MOA	mode of action
MOE	margin of error
m/s	meter per second
MW	molecular weight
N	number of samples
NA	not applicable
nc	noncarcinogenic effects

List of Abbreviations (Continued)

ND	not detected
nonres	nonresidential
NSA	National Slag Association
NYDOT	New York Department of Transportation
P	phosphorus
P	USEPA Provisional Peer Reviewed Toxicity Value (Table 4.2)
PCOI	constituent of interest for probabilistic analysis
PEF	particulate emission factor
PRA	probabilistic risk assessment
p-RBC	probabilistic-risk-based concentration
PS	processed slag
RBC	risk-based concentration
res	residential
RfC	inhalation reference concentration
RfD	oral reference dose
RME	reasonable maximum exposure
RSL	US Environmental Protection Agency Regional Screening Level
SD	standard deviation
SFS	spent foundry sand
Si	silicon
sig	significantly
SSC	Steel Slag Coalition
TCEQ	Texas Commission on Environmental Quality
TCLP	Toxicity Characteristic Leaching Procedure
THQ	target hazard quotient
Tl	thallium
tot	total (oral + inhalation pathways)
TRL	target risk level
URF	inhalation unit risk factor
USDOT	US Department of Transportation
USEPA	US Environmental Protection Agency
USGS	US Geological Survey
UCL	upper confidence limit
μg/kg	microgram per kilogram
$(ug/m^3)^{-1}$	per microgram per cubic meter
μg/mg	microgram per milligram
μm	micrometer
V	vanadium
V_20_5	vanadium pentoxide
VDOT	Virginia Department of Transportation
VKT	total distance traveled along road (kilometers)
VPD	vehicles per day
yr	year

Human Health Risk Assessment for Iron and Steel Slag

Executive Summary

This human health risk assessment (HHRA) was conducted to evaluate the potential for adverse human health risks associated with the use of iron and steel slags. Iron and steel slags are generated as co-products of iron and steel production and are classified according to the type of furnace in which the slag was generated. Blast Furnace (BF) slag is produced from the melting of iron ore and limestone or dolomite during iron production, and steelmaking slags are produced during steel production by processing iron and metal scrap with lime in basic oxygen furnaces (BOF) and electric arc furnaces (EAF) to produce BOF and EAF slags, respectively. Iron and steel slags have a wide range of applications, but are used primarily as construction aggregates.

A previous health risk assessment of the environmental applications of steel-making slags produced in the United States (US) concluded that commercial uses do not pose significant risks to human health (Proctor et al. 2002). This HHRA updates, and supersedes, previous assessments. It is based on new slag characterization data and the most current risk assessment guidance, including the new exposure models and toxicity information. As described herein, the current HHRA confirmed the previous assessment finding that commercial and construction uses of steel industry slags do not pose a health risk.

New Slag Characterization Program

For the purpose of this HHRA, a slag characterization project was conducted in 2008 and 2009 by the National Slag Association. This project was designed to generate data specifically for use in a human health risk assessment by quantifying the concentrations of metals in processed slag, which is sold for use in construction projects. In addition, the metal concentrations in smaller particle sizes of slag were also characterized. The smaller particles have greater relevance for human exposure because they may adhere to skin or clothing and be incidentally ingested, or suspended to ambient air during construction, traffic or by wind and be inhaled.

Specifically, the metal content of slag was characterized for three size fractions: 1) processed slag (PS, 0-1 inch), which is a primary commercial construction product, 2) processed slag samples screened to less than 300 μm (#50 Mesh), and 3) processed slag samples screened to less than 75 μm (#200 Mesh). A total of 41 slag samples were collected for this risk assessment—22 EAF slag samples, 11 BOF slag samples, and 8 BF slag samples, with metal concentrations measured in each of the three slag sizes, for a data set of 123 samples. In addition, measures of the bioaccessible fraction of metals in slag were collected. The bioaccessible faction is the fraction of metals in slag that may be extracted from the solid matrix in gastrointestinal conditions. These new data substantially expand on the data available for health risk assessment of iron- and steel-making slag. Concentrations of metals in steel slag, by type and particle size are summarized in Table 2.2.

Interestingly, the 2008/2009 slag characterization study demonstrated that the concentrations of iron, manganese, chromium and vanadium are higher in the larger particle sizes of processed EAF and BOF slag. In contrast, concentrations of calcium and magnesium increase with decreasing particle size for all three slag types. This is of interest because the toxicologically-significant metals that are thought to pose the greatest potential health hazard (Proctor et al., 2002) occur at lower concentrations in the smaller size fractions to which people are more likely to be exposed. In addition, the characterization project demonstrated that metals are tightly bound to the physical matrix of slag and that only a fraction of metals in slag would be bioaccessible (or available for absorption) if incidentally ingested.

Risk Assessment Methodology

This HHRA was conducted in three tiers. In the first tier—also called the hazard identification—constituent concentrations in slag were compared to USEPA Regional Screening Levels (RSLs) and to concentrations that occur naturally in US soil. In the second tier, constituents measured above RSLs and background concentrations in soil, termed constituents of interest (COIs), were evaluated in a deterministic risk assessment (DRA). In the DRA, Tier II Risk-Based Concentrations (RBCs), or acceptable concentrations of COIs in slag by exposure scenario were calculated and compared to the mean and 95% upper confidence limit (UCL) of concentrations of these constituents in slag. COIs measured at concentrations above the Tier II RBCs were evaluated in the third tier, which was a probabilistic risk assessment (PRA). In the PRA, distributions of RBCs were calculated and compared to the concentrations of COIs in slag by particle size. Tier III RBC are the 50th and 90th percentiles of the RBC distributions, representative of the central tendency and upper-bound of possible exposures, respectively.

In an effort to ensure that the conclusions of this HHRA have broad application for uses of iron and steel slag, conservative toxicity factors and exposure parameters were selected to overestimate, rather than underestimate, potential human exposures and health risks. As in the previous assessments, USEPA toxicity criteria were used to characterize the potential for adverse effects resulting from exposure to COIs in slag.

Tier I Hazard Identification Methods and Results

Constituents measured at concentrations higher than naturally occurring background and EPA screening criteria were identified as COIs in Tier I. COIs for both residential and non-residential scenarios for EAF and BOF slag were hexavalent chromium, iron, manganese and vanadium. For BF slag, the only residential COI was manganese, and there were no COIs for non-residential applications of BF slag. The results of the Tier I Hazard Identification screening are presented in Table ES.1 with the RSLs for those constituents which were measured in slag at concentrations higher than background concentrations in soil.

Tier II Deterministic Risk Assessment (DRA) Methods and Results

In the Tier II Deterministic Risk Assessment (DRA), generally accepted, conservative default exposure parameters, and representative data for potential exposures associated with the environmental applications of steel slag were used to develop Tier II Risk-Based Concentrations (Tier II RBCs). Tier II RBCs were calculated using exposure scenarios that are specific for environmental slag applications. Specifically, for carcinogens, Tier II RBCs were developed to achieve a theoretical excess cancer risk of one-in-a-million (1×10^{-6}), and for non-carcinogens the Tier II RBCs were developed to be consistent with EPA's reference doses (RfDs) and inhalation reference concentrations (RfCs). RfDs and RfCs were developed by EPA and are estimates (with uncertainty spanning perhaps an order of magnitude) of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime (USEPA 2010a). The exposure scenarios evaluated in the DRA were:

- Residential exposure associated with the use of slag for driveway cover (Residential driveway scenario)
- Residential exposure for a residence adjacent to a road with slag used for road cover (Roadside residential scenario)
- Construction scenario where the construction workers are using slag as for road base
- Industrial or maintenance worker at a site where slag is used as fill material.

The 95% UCL concentrations of hexavalent chromium, manganese and vanadium in EAF slag and hexavalent chromium, manganese and vanadium in BOF slag exceed the Tier II RBCs for the residential scenarios, and thus these constituents were COIs for the PRA. All constituents in BF slag were below the Tier II RBCs, and thus, BF slag was not evaluated in the PRA. Tier II RBCs are presented in Table ES.2.

Tier III Probabilistic Risk Assessment (PRA) Methods and Results

Probabilistic Risk Assessment (PRA) allows for the characterization of variability and uncertainty in exposure and risk estimates, or in the case of this HHRA, in the determination of RBCs. In the DRA, upper bound estimates of exposure parameters are multiplied together, and as a result the Tier II RBCs are based on compounded conservative assumptions. As a result, the Tier II RBCs are protective of an extreme upper-bound of possible exposures. As compared with the DRA, in the PRA, distributions of exposure parameters are multiplied together in a probabilistic model to generate a probability distribution of results. Thus, PRAs avoid the overestimation that results from multiplying upper-bound estimates together, and the upper percentiles of the resulting RBC distribution are more representative of the true upper-bound of potential exposure. Thus, the PRA approach generates probabilistically-based RBCs, hereafter referred to as Tier III RBCs, and values at the 50th and 90th percentiles of the risk or hazard distribution were chosen to represent typical and upper-bound exposure conditions.

For the PRA, a target risk level (TRL) of 10-in-a-million (10^{-5}) was used because 10^{-5} is the mid-point in EPA's acceptable risk range of 10^{-4} to 10^{-6} (USEPA 1989). In addition, 10^{-5} was used by the USEPA in its PRA of the environmental applications of Spent Foundry Sand (SFS) (USEPA 2009b).

The 95%UCL concentrations of hexavalent chromium and vanadium in EAF and BOF slags were less than the Tier III RBCs at the 90th percentile, for all exposure scenarios, indicating that these slag constituents do not pose a significant cancer risk or health hazard. In addition, it should be noted that the 90th percentile Tier III RBCs for hexavalent chromium in EAF and BOF slags (50 and 153 mg/kg, respectively) were approximately 10-times and 60-times higher than the 95th UCL concentrations of hexavalent chromium in EAF slag (5.1 mg/kg) and BOF slag (2.5 mg/kg), respectively. Thus, the 95%UCLs of hexavalent chromium in EAF and BOF slags are approximately equal to and 6-times higher than Tier III RBC calculated using a 10^{-6} target risk level. Hexavalent chromium was the only carcinogenic COI.

Similarly, for the roadside residential scenario, the 95%UCL concentration of manganese did not exceed the 90th percentile Tier III RBCs, indicating that manganese in BOF and EAF slags, used as cover for unpaved roads, does not pose a significant hazard.

For the residential driveway scenario, the 95% UCL concentrations of manganese in processed slag (PS) samples of BOF and EAF slags (34,469 and 25,252 mg/kg, respectively) exceed the 90th percentile Tier III RBCs (24,588 and 23,171, respectively). However, inhalation and ingestion exposures to metals in PS, which is less than 1 inch in diameter, is not realistic due to the large particle size. Manganese concentrations in slag are concentrated in the larger particle sizes of PS. The 95% UCL concentrations of manganese in the smaller size fractions (<300 μm size fraction and <75 μm size fraction) of both EAF and BOF slags, which were all < 24,000 mg/kg, see Table 2.2) were lower than the Tier III RBCs. The <300 μm size fraction is most representative of particles that could adhere to skin and be incidentally ingested, and therefore, comparison of the <300 μm size fraction with the Tier III RBCs is more appropriate for assessing the potential health hazards. As the 95%UCL concentrations of manganese in the <300 μm size fractions of EAF and BOF slag (23,272 and 24,000 mg/kg) are less than the Tier III RBCs, manganese in EAF and BOF slags do not pose a hazard for residential exposure scenarios. Tier III RBCs are presented in Table ES.3.

In conclusion, measured concentrations of constituents in BF, BOF and EAF slags do not pose a hazard to human health from direct contact exposures associated with environmental applications of steel slag.

Table ES.1
Tier I Screening - Comparisons to Background and USEPA RSLs

Constituent	EAF Comparison to Background	BOF Comparison to Background	BF Comparison to Background	Tier I RBC (EPA Residential Soil RSL) (mg/kg)	Tier I RBC (EPA Industrial Soil RSL) (mg/kg)
Aluminum	Below	Below	Below	--	--
Antimony	Above	Above	Above	31	410
Arsenic	Below	Below	Below	--	--
Barium	Above	Above	Above	15,000	190,000
Beryllium	Above	Below	Above	160	2,000
Cadmium	Below	Below	Below	--	--
Calcium[a]	Above	Above	Above	No EPA RSL	No EPA RSL
Chromium (Total)	Above	Above	Below	125,000	1,500,000
Chromium (VI)	No background data	No background data	No background data	0.29	5.60
Cobalt	Above	Below	Below	23	300
Copper	Above	Above	Below	3,100	41,000
Iron	Above	Above	Below	55,000	720,000
Lead	Above	Above	Below	400	800
Magnesium[a]	Above	Above	Above	No EPA RSL	No EPA RSL
Manganese	Above	Above	Above	1,800	23,000
Mercury	Below	Below	Below	--	--
Molybdenum	Above	Above	Below	5.6	5,100
Nickel	Above	Below	Below	390	20,000
Phosphorus[b]	Above	Above	Above	1,500	20
Selenium	Above	Above	Above	1.6	5,100
Silicon	Below	Below	Below	--	--
Silver	Below	Below	Below	--	--
Thallium	No background data	No background data	No background data	5.2	67
Tin	Above	Above	Below	47,000	610,000
Vanadium	Above	Above	Below	5.5	72

Notes

[a] Calcium and magnesium exist in slag at concentrations exceeding background concentrations in US soil (Dragun and Chekiri, 2005), and there are no USEPA RSLs available for these constituents. Consistent with the approach used by the Texas Commission on Environmental Quality (TCEQ) for essential nutrients in soil (TCEQ 2001), calcium and magnesium are not considered COIs because ingestion of pure calcium at the child and adult soil ingestion rates results in a dose that is lower than the Recommended Daily Allowance (RDA) for calcium as a nutrient. Also, in accordance with TCEQ (2001), magnesium in slag is not considered a COI because the concentrations of magnesium in slag are lower than concentrations associated with the RDA for children and adults for a soil ingestion exposure scenario. Hence, the dose of magnesium one could receive from incidental ingestion of slag is lower than the RDA.

[b] Phosphorus exists in slag at concentrations that exceed USEPA RSLs (USEPA 2010b) and concentrations of phosphorus in background US soil. However, the USEPA RSLs for phosphorus are based on phosphoric acid, which is not consistent with the form of phosphorus in slag (phosphorus oxide). Consistent with the approach used by the TCEQ (2001) for essential nutrients in soil, phosphorus is not considered a COI because ingestion of pure phosphorus at the child and adult soil ingestion rates would result in a dose that is lower than the RDA for phosphorus as a nutrient. Hence, the dose of phosphorus one could receive from incidental ingestion of slag is lower than the RDA.

Definitions

-- = Below background concentrations for all three slag types, so RSL comparisons were not performed, BF = blast furnace, BOF = basic oxygen furnace, chromium (VI) = hexavalent chromium, EAF = electric arc furnace, EPA = US Environmental Protection Agency, mg/kg = milligram per kilogram, RBC = risk-based concentration, RSL = Regional Screening Level

Table ES.2
Tier II RBCs[a]

Constituent[b]	Residential Driveway Scenario			Residential Roadside Scenario[c]		
	EAF	BOF	BF	EAF	BOF	BF
Chromium (VI)	1.0	1.7	--	23.8	19.3	--
Iron	212,209	251,147	--	NC	NC	--
Manganese	9,604	7,668	3,690	17,951	14,575	16,389
Vanadium	589	594	--	35,901	29,150	--

Constituent[b]	Industrial and Maintenance Worker Scenario		Construction Worker Scenario	
	EAF	BOF	EAF	BOF
Chromium (VI)	21.4	--	20.4	--
Iron	--	--	--	--
Manganese	108,785	90,876	37,186	29,490
Vanadium	8,480	8,543	2,581	2,597

Notes

[a] Tier II RBCs are calculated using a deterministic risk assessment approach. The Tier II RBCs presented in this table are based on a reasonable maximum exposure scenario.

[b] RBC values are presented only for slag types and scenarios remaining as constituents of interest after Tier I screening.

[c] For each scenario, except the residential roadside scenario, exposures via incidental ingestion and inhalation were quantified. For the resident living adjacent to unpaved roads with slag cover (residential roadside scenario), exposure by inhalation was evaluated, because it was assumed that incidental ingestion would not occur for this scenario. Residential exposure to slag by ingestion is assessed for the residential driveway scenario.

Definitions

-- = Not a Constituent of Interest. NC = Not Calculated because iron does not have an inhalation toxicity criteria, BF = blast furnace, BOF = basic oxygen furnace, chromium (VI) = hexavalent chromium, EAF = electric arc furnace, mg/kg = milligram per kilogram, RBC = risk-based concentration

Table ES.3
Tier III RBCs (mg/kg)[a]

Constituent[b]	Residential Driveway Scenario		Residential Roadside Scenario	
	EAF	BOF	EAF	BOF
Chromium (VI)	50	153	--	--
Manganese	24,588	23,171	38,725	31,056
Vanadium	5,642	5,137	--	--

Notes

[a] Tier III RBCs are calculated using a probabilistic risk assessment approach. Values presented here are the 90th percentile of the RBC distribution, protective of 90% of exposures. The 95% UCL concentrations of COIs by particle size are presented in Table 2.2.

[b] RBC values are presented only for slag types and scenarios remaining as constituents of interest after Tier II screening

Definitions

BOF = basic oxygen furnace, chromium (VI) = hexavalent chromium, EAF = electric arc furnace, mg/kg = milligram per kilogram, RBC = risk-based concentration

1.0 Introduction

Iron and steel slags are generated as co-products of iron and steel production and are classified according to the type of furnace in which the slag was generated. Blast Furnace (BF) slag is produced from the melting of iron ore and limestone or dolomite during iron production, and steelmaking slags are produced during steel production by processing iron and metal scrap with lime in basic oxygen furnaces (BOF) and electric arc furnaces (EAF) to produce BOF and EAF slags, respectively.

Slag is produced in BFs, BOFs and EAFs during the separation of molten steel from impurities in the furnace. In slag production, materials, including iron, iron ore, scrap metal and lime, are charged into the furnace and heated beyond their melting points. In each furnace, two or more liquids are formed. The liquid with the lowest specific gravity forms a layer on the surface of the melt and is called slag. This slag collects impurities from the liquid metal and is removed from the liquid metal layer by pouring or skimming. Slag formation during the process is an important step in the process of producing and maintaining liquid steel chemistry and steel quality. Chemically, steelmaking slag is a matrix structure which consists primarily of oxides of aluminum, calcium, iron, magnesium, manganese and silicon in complexes of calcium silicates, aluminosilicates and aluminoferite, which are similar to those found in the natural environment. The furnaces operate at about 2,700º F, which eliminates the potential for organic compounds in slag.

Slag aggregate is produced in various sizes and densities based on the processing and end user applications. The slag aggregate is screened for size, inspected for quality and sold for various commercial uses.

1.2 Uses of Iron and Steel Slag

The major uses of steel- and iron-making slag are as aggregates for asphaltic paving, construction fill, road bases, concrete, and as feed for cement kilns. Applications for slag are diverse and continue to be developed for these and other markets, including thermal insulation, agricultural soil conditioner and drainage buffering agents (US Environmental Protection Agency [USEPA] 2006; Drizo et al. 2006). Also, there has been considerable research and interest associated with the use of steel-making slag for neutralizing acid mine drainage (Simmons and Ziemkiewic 2003). A typical use of steel-making slag for a roadway shoulder is depicted in Figure 1.1.

The consumption of iron- and steel-making slag has generally risen over time. Production in the US in 2008 is estimated to have ranged from 17 to 23 million tons, with approximately 15 million tons of iron and steel slag, valued at $380 million, sold in 2008 (US Geological Survey [USGS] 2009). Approximately 60% of the tonnage sold consisted of BF slag, largely in the granulated form (USGS 2009). Ground granulated blast furnace slag (GGBFS) is used as an additive in blended cements and concrete.

Iron and steel making slag competes with crushed stone, sand, and gravel as aggregates in the construction sector. In addition, BF slags may be used as a cement substitute and steel making slags are used as a partial substitute for virgin raw materials in cement kilns. The use of slag in cement manufacturing significantly decreases carbon dioxide emissions, and reduces the energy needed to calcine limestone. Also, use of slag as aggregate reduces the need for virgin materials, as well as energy use and emissions produced during the mining, processing and transportation of those materials.

The versatility of slag is based on its chemical and physical properties. Although steel-industry slags generated by different furnace types and grades of steel vary in their chemical compositions and specific physical properties, all steel-industry slags are alkaline, consisting primarily of oxides of calcium, iron, silicon, aluminum, magnesium and manganese, in complexes of calcium silicates, aluminosilicates and aluminoferrite (primarily with BOF and EAF slag). These complexes are similar to those found in natural aggregates. Metals in slag are fused together and tightly bound, and thus not readily liberated or leached into the environment.

Generally, slag is vesicular, angular, and cementitious in quality, with a high bulk specific gravity, high bearing strength, and high heat and moderate water absorption capacity (US Department of Transportation [USDOT] 2004). Such physical properties facilitate its mechanical binding to other materials, such as asphalt and concrete, making slag a cost-effective and often superior substitute to many quarried raw aggregates (USGS 2004; National Slag Association [NSA] 2006).

Most metals in iron- and steel-industry slag occur at concentrations that are higher than those typically found in US soils; however, the mobility of metals in slag is limited because the metals are tightly bound to the slag matrix, which is relatively alkaline. Water leachate data have been used to calculate the water-solid partitioning coefficient (K_d) for metals in slag (Proctor et al. 2000). K_d values exceed 1,000 liters per kilogram (L/kg) for all metals in slag that occur at concentrations exceeding background levels of metals in soil, indicating low potential for leaching (Proctor et al. 2000). The USEPA (1996a) calculated K_d values for metals in soil at acid, neutral, and alkaline pH. For most metals, K_d values increase with pH; thus, it is not surprising that metals in highly alkaline slag are not readily solubilized. Consistently, under the strongly acidic conditions of the USEPA's Toxicity Characteristic Leaching Procedure (TCLP; USEPA 1991b), metals are not leached from iron and steel slag at levels that exceed TCLP standards (Proctor et al. 2000).

1.3 Previous Health Risk Assessments for Iron and Steel Slag

In previous risk assessments, the potential human health risks associated with environmental exposures to iron- and steel-making slag were assessed, and it was concluded that the environmental uses of iron and steel slag do not pose significant risks to human health (ChemRisk 1998; Proctor et al. 2002; Exponent 2007). These earlier risk assessments also evaluated the potential for ecological risks associated with steel-making slag and concluded that most applications do not pose a hazard, but that site-specific assessment might be required for slag applications near small stagnant water bodies, where the alkaline nature of steel slag could elevate the pH of surface water to a level that might be harmful to aquatic life. Also, with EAF slag, in surface water bodies with limited dilution, there is a potential for aluminum or barium to leach at levels that exceed ambient water quality standards. In general, iron and steel slag may be applied safely in aquatic environments such as rivers, lakes and streams without impacting water quality or aquatic life. Care should be taken when applying slag in smaller aquatic bodies where low water flow conditions exist, such as wetlands or shallow ditches. The ecological risk assessment for steel slags from Exponent (2007) is included in Appendix E.

Figure 1.1 Photograph of Steel Slag Used to Construct a Roadway Shoulder

2.0 2008-2009 Slag Characterization Project

To update the human health risk assessment of iron- and steel-making slag, a characterization project was initiated in 2008. This characterization project was designed to generate data specifically for use in a human health risk assessment by characterizing the metal content of slags as used in the environment. In addition, the levels of inorganic constituents (metals) that exist in the smaller particle sizes of slag, which have greater relevance for human exposure, were characterized for this assessment. Smaller particles are more likely to adhere to hands or other surfaces and be incidentally ingested, or be suspended in ambient air, increasing the potential for inhalation exposure. Larger particles are less likely to be inhaled or incidentally ingested. Similar to the previous slag characterization project, analysis of metals in slag was performed separately for BF, EAF and BOF slags (Proctor et al. 2000).

2.1 Sample Size for the 2008-2009 Slag Characterization Project

The number of slag samples needed per slag type for this characterization project was estimated using the coefficients of variation for manganese in EAF and BOF slag. Manganese was the primary constituent of interest (COI) in the previous risk assessment (Proctor et al. 2002). The number of slag samples needed for the new project was calculated using two different approaches for BOF and EAF slags, as described below. Because the levels of manganese in BF slag are not at a level of potential concern, a sample size of eight BF slag samples was deemed sufficient as this is the minimum number of samples, with detectable concentrations, recommended for use in USEPA's Pro95UCL guidance (USEPA 2008b).

First, using the manganese concentrations from the 1990s slag characterization data, the number of samples needed to characterize the concentrations of COIs by slag type for an updated risk assessment was calculated using USEPA guidance *Soil Sampling Quality Assurance Guidance (Second Edition)* (USEPA 1989a) with the goal of achieving a high degree of statistical power and confidence, with a margin of error (MOE) of less than 25% in the resulting dataset. For this calculation, it was assumed that the variability in the sample dataset from the 1990s characterization would be consistent with that in the new dataset. Based on the 1990s data, the following numbers of samples were calculated by slag type to achieve MOEs (or minimally detectable relative differences) of ≤ 25%, with 90% power and confidence:

- 11 samples of BOF slag to obtain an MOE of 25%
- 17 samples of EAF slag to obtain an MOE of 10%

Second, to assess if greater variability exists in manganese concentrations among the smaller particles of slag, which would result in the need for a larger sample size to reliably characterize concentrations, data from five samples each of BOF and EAF slag were collected and analyzed in 2008. Samples of slag particles less than 75 micrometer (μm, #200 Mesh size samples) were used in sample size calculations, and the results used to calculate the numbers of samples needed to achieve a statistically robust data set for risk assessment.

Using the 2008 data for BOF slag, it was determined that only six samples would be needed to achieve an MOE of 10% because variability of manganese levels in the small size fraction of BOF slag was lower than in the 1990s characterization. Using the 2008 small particle-sized data for EAF slag, it was determined that 21 samples of EAF slag were needed to achieve an MOE of 20%.

Combining the results of the two methods used to calculate sample size, the number of samples needed for the 2008-2009 slag characterization project was determined as summarized in Table 2.1. (See end of section 2 for all section 2 tables.)

2.2 Sample Preparation and Analysis

In the 1990s slag characterization project, samples of slag from all sizes produced by each mill were collected, crushed to less than 75 microns, and homogenized to generate a representative sample per mill. For integrated mills that operate multiple furnace types, one slag sample per furnace type was collected. Because the chemistry of certain metals might vary by particle size, for the 2008-2009 slag characterization project, metal content of slag was characterized for three size fractions: 1) processed slag (PS, 0-1 inch), which is the primary commercial product used in environmental applications, 2) processed slag samples screened to less than 300 μm (screened by #50 Mesh), which is representative of particles that could be incidentally ingested, and 3) processed slag samples screened to less than 75 μm (screened by #200 Mesh), which was the smallest particle size fraction of this material that could be separated with a sieve without crushing the samples. Because the samples were not crushed during the separation process, the smaller size fraction samples are thought to be representative of the smaller slag particle sizes that are present in the environment in association with slag applications.

As a result of the size separation process, inorganic constituents were characterized in three particle sizes of each of the 41 samples of steel-industry slag collected for this characterization, for a total of 123 samples used in this evaluation. Total chromium (Cr) was characterized in all particle size fractions, and hexavalent chromium [Cr(VI)] was analyzed for in the PS samples. Total Cr concentrations were highest in the PS samples, as compared to the smaller particle sizes, and Cr(VI) concentrations were relatively low in EAF and BOF PS samples (≤14.2 and < 2.5 mg/kg, respectively) as compared to total Cr concentrations (5,250 mg/kg for EAF and 3,800 mg/kg). Cr(VI) was not detected in BF slag samples.

The PS samples used in this characterization were collected from 31 mills using ASTM D-75 *Standard Practice for Sampling Aggregates* in order that samples were representative of PS from each source. The PS samples had a maximum particle size of 1 inch (25.0 millimeters [mm]).

Samples of PS were split into two portions following ASTM C-702 *Practice for Reducing Samples of Aggregates to Testing Size*. The PS portion was prepared for constituent analysis by crushing to ¼ inch (4.75 mm) using a jaw crusher and then again reduced to a <75 μm size utilizing a shatterbox (Spex Model #8500-115). The second PS sample split was again reduced into two samples using ASTM C-702 particle size separation. These samples were then screened to obtain two distinct samples representing naturally occurring size fractions of slag which were <300 μm and <75 μm. The screening was accomplished utilizing ASTM C-136 *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregate*. Following particle size separation into <300 and <75 μm size fraction samples, these samples were also reduced to <75 μm, homogenized and frozen prior to shipment to Brighton Analytical Laboratory (Brighton, MI) for analysis. Cr(VI) analyses were conducted at Lancaster Laboratories in Lancaster, PA.

Slag samples were analyzed for aluminum, antimony, arsenic, barium, beryllium, calcium, cadmium, chromium, cobalt, copper, iron, lead, magnesium, manganese, molybdenum, nickel, selenium, silver, thallium, vanadium and zinc using USEPA method 6020—Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Analysis for phosphorous, silicone and tin were performed by USEPA method 6010—Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES). Cr(VI) was analyzed by USEPA method 7199—Ion chromatography (IC), and mercury was analyzed by USEPA method 7470A/7471A—Cold Vapor Atomic Absorption (AA). All samples collected in 2009 were analyzed in duplicate, and duplicate values were averaged.

2.3 Results of the Slag Characterization Project

Table 2.2 provides summary data for the slag characterization project results by slag type, and the individual sample data are provided in Appendix A. For calculation of summary statistics, one-half the limit of detection was substituted for all non-detectable concentrations. Mean and maximum concentrations for each chemical for each slag type and particle combination were calculated using Systat 12. With non-detected values considered, 95% UCLs were calculated using ProUCL 4.0.

The primary constituents of BOF and EAF slag are calcium and iron along with magnesium, manganese and aluminum. The primary constituents of BF slag are similar to those in BOF and EAF slag, with notably lower concentrations of iron and manganese and higher concentrations of aluminum. Concentrations of the other metals in BF slag are also notably lower than those in BOF and EAF slag.

2.4 Concentrations of metals by particle size

Analysis of slag constituents by particle size demonstrated variability of metal concentrations by particle size, and by slag type, for certain metals. Concentrations by particle size for the primary constituents of slag, including the COIs for this risk assessment, are presented in Figure 2.1. Of note, the concentrations of iron, manganese, chromium and vanadium are higher in the larger particle sizes of processed EAF and BOF slag, but demonstrate little variability in BF slag. By comparison, concentrations of calcium and magnesium are lowest in the larger PS samples of all three types.

2.5 Oral Bioaccessibility Analysis

Measures of oral bioaccessibility, or the fraction of metals that could be extracted from the slag matrix in the acidic conditions of the stomach, were characterized for all metals in all <300 μm sized samples collected in 2009. The <300 μm sized samples were used per USEPA guidance because particles in this size range are more likely to adhere to the skin and be incidentally ingested (USEPA 2007). To calculate the bioaccessible fraction of metals in by slag type, slag samples were extracted in pH 1.5 hydrochloric acid for 1 hour, with glycine, at 37 ^{o}C to simulate the gastric environment. The fraction of metals solubilized from the solid matrix of the slag in this extraction is the bioaccessible fraction because only metals in solution can be systemically absorbed by the gastrointestinal tract. As discussed in section 4, the bioaccessible fraction of metals in slag was included in the calculation of dose by the oral route of exposure. Because metals in slag are tightly fused to the slag matrix, the bioaccessibility assessment demonstrated that only a fraction of the metal content could be released from slag and available for systemic absorption. Results of the bioaccessibility analysis are presented in Appendix A Table A.4.

2.6 Scope of this Human Health Risk Assessment

This human health risk assessment of iron- and steel- slag provides several technical improvements and updates relative to the approaches used in previous assessments. First, as noted above, the risk assessment uses new slag characterization data from three size fractions—PS (the primary commercial construction product), and two smaller particle sizes that have greater relevance for assessing human exposures. Also, the new characterization data are more representative of environmental exposures, as compared to the data used in previous assessments, because the new samples were not crushed or homogenized with large slag products prior to analysis.

Second, the current assessment includes recent refinements to health risk assessment procedures developed by the USEPA since the previous assessments. The USEPA preferred AERMOD air dispersion model was used for the residential inhalation exposure pathway, replacing the older Industrial Source Complex (ISC) model, and new parameters from USEPA's 2009 Exposure Factors Handbook (USEPA 2009a) were incorporated. Toxicity criteria were taken from current information in the USEPA Integrated Risk Information System (IRIS) database, with the exception of that for hexavalent chromium [Cr(VI)]. As discussed in more detail in Section 4, a more conservative approach described in USEPA's draft *Toxicological Review of Hexavalent Chromium* (2010c) was used for Cr(VI) to ensure that the risk assessment is based on the most conservative information available.

In the previous risk assessments for iron and steel slag, possible exposures to slag by residents, construction and industrial workers, and farmers were quantitatively estimated, and from these exposure estimates, the potential health risks were characterized. In contrast, this risk assessment follows the approaches used recently by USEPA in the Spent Foundry Sand (SFS) Risk Assessment (USEPA 2009b), wherein the risk assessment was conducted in tiers, and rather than calculating dose and theoretical health risk, safe levels for the constituents of slag were calculated and compared to the measured levels of constituents in slag.

The first tier of the new assessment is the hazard identification in which constituent concentrations in slag are compared to USEPA Regional Screening Levels (RSLs) (USEPA 2010b) and concentrations in background US soil (Dragun and Chekiri 2005). In the second tier, constituents measured above RSLs and background concentrations in soil, termed COIs, are evaluated in a deterministic risk assessment (DRA). In the DRA, Risk-Based Concentrations (RBCs), or acceptable concentrations of constituents in slag by exposure scenario, were calculated and compared to the mean and 95% upper confidence limit (UCL) of concentrations of these constituents in slag. COIs measured at concentrations above the DRA RBCs were evaluated in the third tier, which is a probabilistic risk assessment (PRA). As discussed in Section 6, the PRA calculates probabilistic-RBC (PRA/RBC) distributions and compares the PRA/RBC distribution to the concentrations of COIs in slag by particle size. This tiered risk assessment process is depicted in Figure 2.2.

Modeling analysis of the leaching and migration of metals from slag leachate to groundwater, as well as an evaluation of the potential ecological risks associated with land applications were not updated in this risk assessment because no new data are available to evaluate slag constituent leaching in the environment. The previous assessments found that leaching of metals from slag did not exceed USEPA TCLP criteria, and thus, applications of steel slag are not expected to impact groundwater. Most USEPA models for evaluating leachate, including the model used by USEPA in the SFS risk assessment, are not capable of assessing the potential for leaching of alkaline constituents, and thus would not be helpful for evaluation of the potential impacts due to elevated pH from slag. For these reasons, the current risk assessment focuses on the potential human health risk associated with current environmental applications of iron- and steel-making slag using the recent federal risk assessment guidance, but does not update the ecological risk assessment or evaluation of potential impacts to groundwater. The screening-level ecological risk assessment conducted in 2007 is included in Appendix E.

Finally, consistent with approaches used by USEPA, and the previous risk assessments for iron- and steel-making slag, this assessment uses very conservative approaches to evaluate the potential exposures and health hazards associated with constituents in slag. For example, the assessment assumes that slag is not diluted or mixed prior to application and, although it is not expected to be necessary as discussed in Section 4.1.1, the additional three-fold modifying factor for manganese, which is suggested for non-dietary exposures in the USEPA manganese IRIS file, was used for all scenarios in this assessment. These measures, as well as adherence to conservative risk assessment assumptions and methods, were incorporated to ensure that the assessment of potential hazards is not under-estimated and broad acceptance of the risk assessment findings by state and federal regulators.

Table 2.1
Results of Sample Size Calculations For Each Slag Type

Slag Type	Sample Size	Basis Considering Mn Levels in Slag
BF	8	Minimum number of samples per USEPA Pro95UCL guidance
BOF	11	90% Power and Confidence with 25% MOE based on the 1990s dataset, also achieves 10% MOE based on 2008 data
EAF	22	90% Power and Confidence with 10% MOE based on the 1990s dataset, and achieves a 20% MOE based on 2008 data
Total number of slag samples	41	Total number of slag samples in new characterization dataset

Definitions
BF = blast furnace, BOF = basic oxygen furnace, EAF = electric arc furnace, Mn = manganese, MOE = margin of error

Table 2.2

Constituent Concentrations by Particle Size in Electric Arc Furnace, Basic Oxygen Furnace and Blast Furnace Slag from the 2008-2009 Iron and Steel Slag Characterization Project

Electric Arc Furnace Slag

	Processed Slag (mg/kg)				<300 μm Particle Size (mg/kg)				<75 μm Particle Size (mg/kg)			
	Mean	**Min**	**Max**	**95% UCL**	**Mean**	**Min**	**Max**	**95% UCL**	**Mean**	**Min**	**Max**	**95% UCL**
Aluminum	27,561	15,000	50,000	31,694	31,739	7,600	82,000	54,285	30,624	7,400	73,000	39,358
Antimony	1	0	3	2	2	0	4	2	2	0	7	3
Arsenic	5	2	9	5.4	5	2	10	6	7	2	13	8
Barium	478	87	960	577	356	64	710	434	338	76	710	412
Beryllium	1.08	0.10	3.60	1.38	0.77	0.10	1.80	0.93	0.83	0.20	1.80	0.98
Cadmium	0.97	0.12	5.40	1.39	2.31	0.27	12	3.58	2.44	0.29	13.00	4.91
Calcium	203,258	160,000	280,000	215,000	233,788	140,000	390,000	256,600	233,788	140,000	360,000	255,100
Chromium (Cr)	3,136	1,350	5,250	3,521	1,810	530	4,800	2,280	1,528	410	4,300	1,980
Hexavalent Cr	1.9	0.5	14.2	5.1	--	--	--	--	--	--	--	--
Cobalt	11	4	18	12	9	1	23	11	7	1	16	8
Copper	134	39	365	166	149	47	480	188	155	44	540	197
Iron	192,780	104,500	290,000	210,500	119,470	12,000	290,000	154,100	98,508	30,000	240,000	125,400
Lead	13	0	90	22	65	3	280	101	75	4	370	118
Magnesium	52,871	37,500	70,000	56,292	68,288	28,000	140,000	77,208	67,364	27,000	170,000	78,270
Manganese	31,182	14,000	45,500	34,460	18,402	4,800	41,000	23,272	15,624	3,800	38,000	20,018
Mercury	0.01	0.01	0.07	NC	0.02	0.01	0.09	0.02	0.02	0.01	0.13	0.03
Molybdenum	41	6	270	58	29	5	66	38	29	6	69	39
Nickel	49	9	230	66	61	10	230	82	50	7	150	66
Phosphorus	2,195	1,250	4,100	2,463	1,297	520	3,900	1,537	1,284	440	3,800	1,596
Selenium	1	0	5	2	2	0	12	3	2	0	8	3
Silicon	1,742	790	4,650	2,041	2,930	1,267	6,300	3,391	4,405	1,117	18,000	8,886
Silver	1	0	12	4	3	0	25	4	3	0	23	5
Thallium	0.21	0.01	0.36	0.22	0.07	0.01	0.25	0.04	0.07	0.01	0.25	NC
Tin	4	1	15	6	6	1	19	8	7	1	23	12
Vanadium	601	240	1,300	686	336	59	1,100	435	289	50	1,100	384
Zinc	209	31	1,200	309	592	46	4,000	964	686	61	4,000	1,115

Definitions mg/kg = milligram per kilogram, μm = micrometer, "--" = not analyzed, max = maximum, min= minimum, NC = not calculated due to low number of detected samples, UCL = upper confidence limit

Note that the mean concentration of thallium in < 300 μm slag exceeds the 95%UCL due the large number of non-detected concentrations.

Table 2.2
Constituent Concentrations by Particle Size in Electric Arc Furnace, Basic Oxygen Furnace and Blast Furnace Slag from the 2008-2009 Characterization Project
(Continued)

Basic Oxygen Furnace Slag

	Processed Slag (mg/kg)				<300 μm Particle Size (mg/kg)				<75 μm Particle Size (mg/kg)			
	Mean	**Min**	**Max**	**95% UCL**	**Mean**	**Min**	**Max**	**95% UCL**	**Mean**	**Min**	**Max**	**95% UCL**
Aluminum	22,550	9,550	39,500	28,355	21,391	6,500	47,000	28,251	21,209	7,200	45,000	29,759
Antimony	0.43	0.15	1.25	0.64	0.63	0.03	3.60	1.33	1.12	0.15	6.70	2.44
Arsenic	4	2	8	5	5	1	23	9	7	1	30	14
Barium	173	55	605	449	182	45	960	549	196	55	1,100	609
Beryllium	0.63	0.25	1.75	0.96	0.54	0.10	1.40	0.77	0.66	0.10	2.40	1.52
Cadmium	0.42	0.09	1.13	0.6	0.70	0.13	2.70	1.25	0.82	0.11	4.10	2.3
Calcium	235,909	175,000	290,000	252,400	245,000	200,000	290,000	260,000	264,545	190,000	310,000	287,800
Chromium (Cr)	1,800	1,000	3,800	2,228	1,564	750	2,500	1,848	1,481	600	2,100	1,748
Hexavalent Cr	0.83	0.50	2.50	NC	--	--	--	--	--	--	--	--
Cobalt	7	3	13	9	5	1	11	7	3	1	10	5
Copper	44	20	150	93	74	30	320	186	70	5	350	196
Iron	181,545	112,000	225,000	199,300	158,364	70,000	190,000	181,100	134,909	61,000	170,000	155,900
Lead	11	1	46	30	43	2	140	86	48	3	170	104
Magnesium	48,091	42,000	55,000	50,618	64,000	49,000	78,000	68,669	62,545	45,000	84,000	68,351
Manganese	22,545	14,000	33,000	25,252	19,182	7,500	24,000	21,882	17,673	6,400	23,000	20,520
Mercury	0.01	0.01	0.03	NC	0.02	0.01	0.03	0.02	0.02	0.01	0.03	0.02
Molybdenum	28	6	91	67	28	6	76	47	26	8	75	60
Nickel	19	7	38	24	26	4	77	38	23	5	82	39
Phosphorus	3,218	2,050	4,500	3,696	2,644	980	3,900	3,131	2,504	940	3,800	3,042
Selenium	1	0	2	1.2	1	0	3	2	1	0	4	2
Silicon	3,072	890	12,500	7,235	1,995	1,500	2,450	2,137	3,945	1,600	11,000	6,210
Silver	0	0	1	0.6	1	0	2	1.6	1	0	3	2
Thallium	0.27	0.01	0.36	0.34	0.12	0.01	0.25	N	0.14	0.01	0.25	0.12
Tin	2	1	5	4.4	2	1	8	NC	2	1	8	4
Vanadium	762	445	1,100	865	657	200	990	788	704	180	1,200	859
Zinc	138	14	510	248	439	26	2,300	949	556	28	3,500	1,281

Definitions mg/kg = milligram per kilogram, μm = micrometer, "--" = not analyzed, max = maximum, min= minimum, NC = not calculated due to low number of detected samples, UCL = upper confidence limit

Note that the mean concentration of thallium in <75 μm slag exceeds the 95%UCL due the large number of non-detected concentration

Table 2.2
Constituent Concentrations by Particle Size in Electric Arc Furnace, Basic Oxygen Furnace and Blast Furnace Slag from the 2008-2009 Characterization Project
(Continued)

Blast Furnace Slag

	Processed Slag (mg/kg)				<300 μm Particle Size (mg/kg)				<75 μm Particle Size (mg/kg)			
	Mean	**Min**	**Max**	**95% UCL**	**Mean**	**Min**	**Max**	**95% UCL**	**Mean**	**Min**	**Max**	**95% UCL**
Aluminum	36,500	34,000	42,000	38,198	38,125	36,000	41,000	39,577	37,375	32,000	41,000	39,334
Antimony	0.03	0.03	0.03	NC	0.03	0.03	0.03	NC	0.04	0.03	0.09	0.07
Arsenic	2.14	1.30	3.85	2.71	1.09	1.00	1.20	1.14	3.89	1.70	4.80	4.72
Barium	510	320	720	607	505	400	750	584	633	390	1,100	799
Beryllium	10	8	12	11	7	6	9	8	11	8	13	12
Cadmium	0.32	0.16	0.46	0.39	0.29	0.17	0.56	0.37	0.27	0.17	0.45	0.23
Calcium	211,250	190,000	230,000	220,200	240,000	210,000	260,000	251,300	223,750	200,000	280,000	243,000
Chromium (Cr)	38	17	75	51	42	21	55	51	42	16	66	53
Hexavalent Cr	0.5	0.5	0.5	NC	--	--	--	--	--	--	--	--
Cobalt	8	5	15	10	9	4	27	21	4	3	6	5.9
Copper	2	1	3	2.5	31	14	100	54	41	14	170	83
Iron	4,600	1,450	8,750	6,239	4,950	2,900	7,000	5,981	5,375	2,800	7,800	6,455
Lead	0.21	0.01	0.68	0.38	3.35	1.30	6	4.41	3.91	1.80	7.80	5.36
Magnesium	45,625	38,000	55,000	48,801	58,375	54,000	67,000	61,215	50,750	41,000	60,000	55,747
Manganese	2,881	1,950	4,000	3,273	3,350	2,500	4,500	3,731	3,338	2,600	3,900	3,624
Mercury	0.01	0.01	0.01	NC	0.01	0.01	0.01	NC	0.01	0.01	0.02	NC
Molybdenum	0.59	0.03	3.25	3.02	0.67	0.31	1.20	0.88	0.84	0.29	2.60	1.5
Nickel	4	2	5	4.3	3	1	6	4	6	3	12	8
Phosphorus	434	400	495	456	401	360	460	423	399	320	480	430
Selenium	4	3	5	4.2	6	5	7	6.2	7	5	9	8
Silicon	1,725	1,350	2,100	1,882	1,725	1,400	2,300	1,962	2,100	1,700	2,800	2,358
Silver	0.52	0.25	0.91	0.68	0.61	0.37	1.20	0.81	0.54	0.37	0.85	0.65
Thallium	0.35	0.31	0.40	0.37	0.03	0.01	0.10	0.07	0.05	0.01	0.19	0.10
Tin	2	1	3	NC	2	1	3	NC	2	1	3	NC
Vanadium	27	16	33	31	26	14	37	31	28	17	44	33
Zinc	6	2	12	8	20	8	37	26	29	17	50	37

Definitions mg/kg = milligram per kilogram, μm = micrometer, "--" = not analyzed, max = maximum, min= minimum, NC = not calculated due to low number of detected samples, UCL = upper confidence limit

Figure 2.1 Variability of Key Slag Constituents by Slag Type and Particle Size

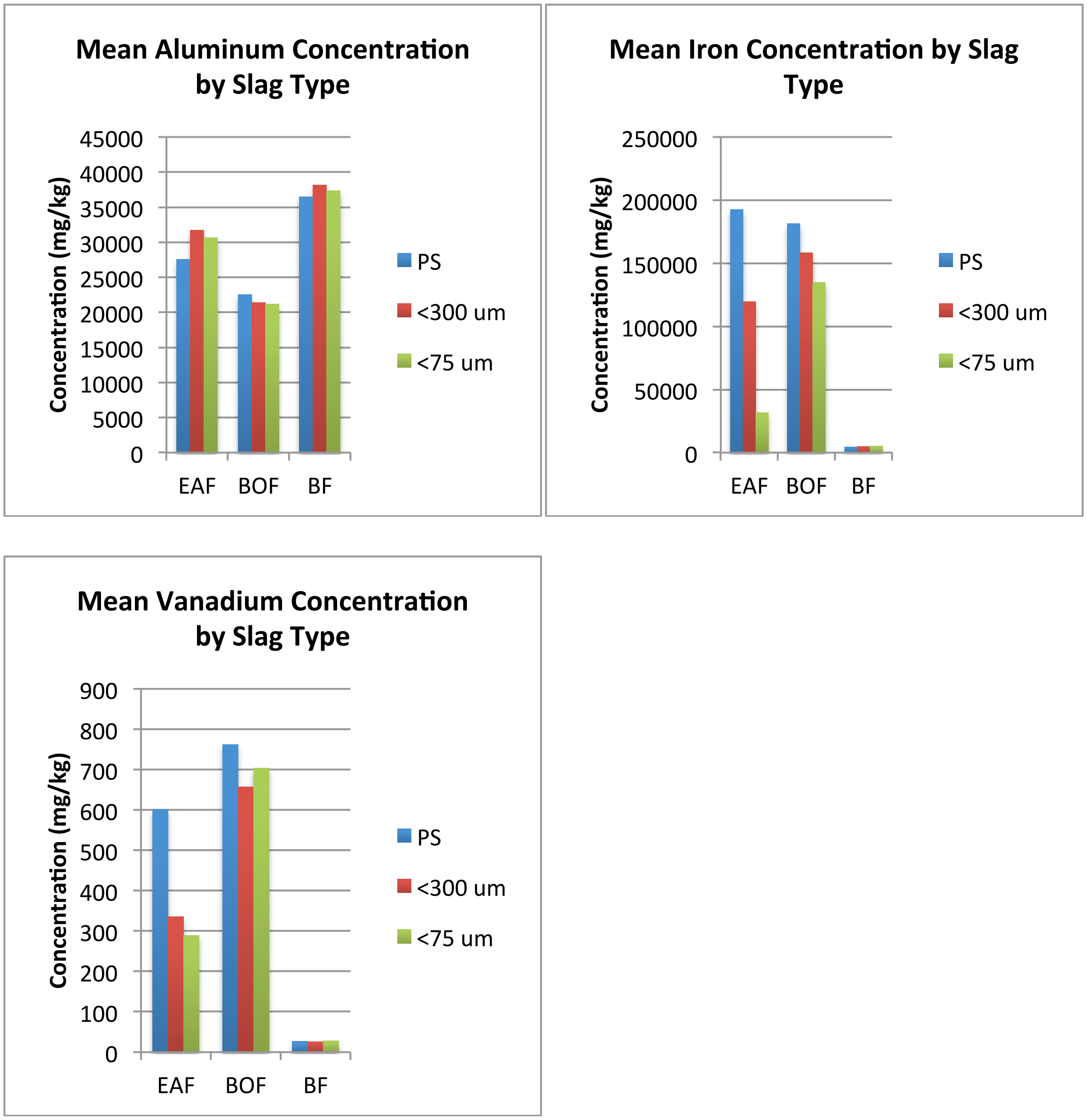
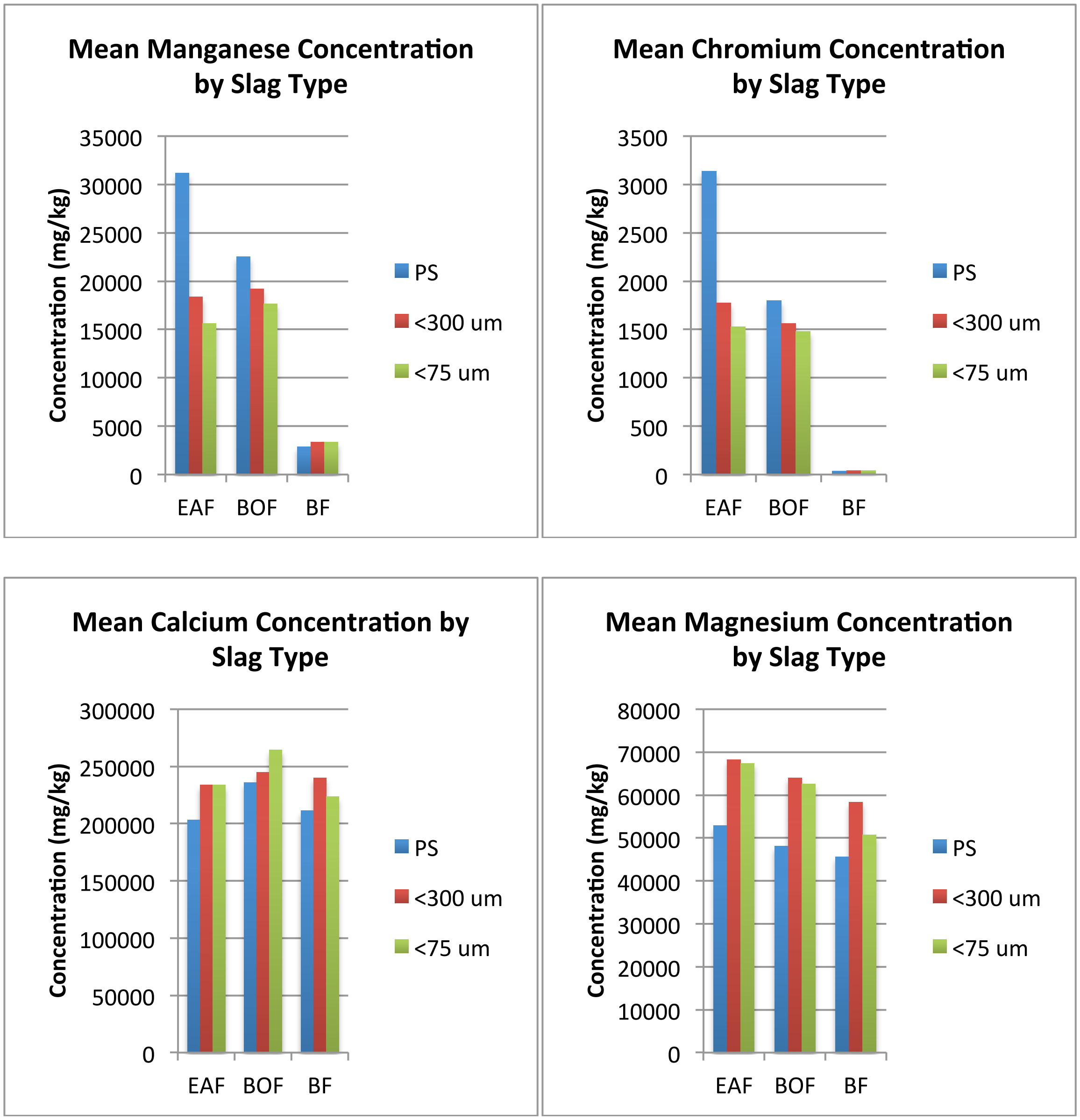


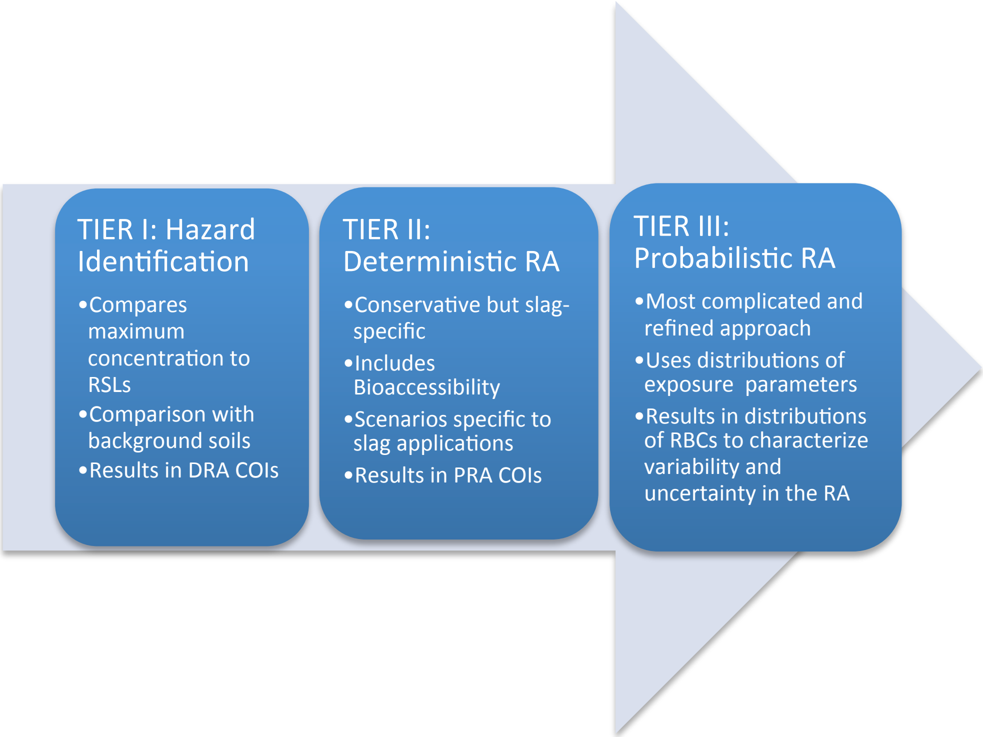
Figure 2.1 Variability of Key Slag Constituents by Slag Type and Particle Size (Continued)



Definitions

BF = blast furnace, BOF = basic oxygen furnace, EAF = electric arc furnace, PS = processed slag; <300 um = particles less than 300 µm; <75 um = particles less than 75 µm

Figure 2.2 Tier Risk Assessment Approach



TIER I: Hazard Identification

- Compares maximum concentration to RSLs
- Comparison with background soils
- Results in DRA COIs

TIER II: Deterministic RA

- Conservative but slag-specific
- Includes Bioaccessibility
- Scenarios specific to slag applications
- Results in PRA COIs

TIER III: Probabilistic RA

- Most complicated and refined approach
- Uses distributions of exposure parameters
- Results in distributions of RBCs to characterize variability and uncertainty in the RA

Definitions: RSLs = USEPA Regional Screening Levels; RA = Risk Assessment; PRA = Probabilistic Risk Assessment; COIs = Constituents of Interest; RBCs = Risk Based Concentrations

3.0 Tier I - Hazard Identification

3.1 Description of Approach

To identify COIs in slag for the DRA, two approaches were used. Concentrations of constituents in slag, by slag type in PS slag, were first compared to the background concentrations of each in US soil (Dragun and Chekiri 2005) using Kolmogorov-Smirnov goodness-of-fit tests (K-S test). These statistical tests were used to determine if the distributions of measured concentrations in slag were greater than the distribution of metals in background soil. Second, metal concentrations were compared against the USEPA Regional Screening Levels (RSLs) (USEPA 20010b). Comparisons with the RSLs were based on the maximum concentrations of constituents in all slag sizes. If the maximum concentration of any constituent in each type of slag exceeded the selected screening level, the constituent was considered a COI for the DRA.

3.2 K-S Tests

To determine if constituent concentrations in the slag occur at concentrations that are greater than concentrations in US soil, K-S tests were performed using the background soils data presented in *Elements in North American Soils* (Dragun and Chekiri, 2005). Dragun and Chekiri (2005) reported the number of samples for each constituent, the minimum and maximum values and a combination of geometric mean and geometric standard deviation, or arithmetic mean and arithmetic standard deviation (Table 3.1). According to Dragun and Chekiri (2005), if only the geometric mean and standard deviation were reported, the distribution of the element in soil was assumed to be log-normal. If arithmetic statistics were reported instead of geometric, the distribution of the element in soils was assumed to be normal. For silver, only a range was provided, so the distribution was assigned a uniform distribution. No background data for Cr(VI) are provided in Dragun and Chekiri (2005), and Cr(VI) is typically not measurable in background soils. Thallium was not tested because background data for the conterminous US was not available. Thallium levels in slag are low with a maximum detected concentration in all types and sizes of 0.4 mg/kg, which is lower than all state-specific maximum values reported in Dragun and Chekiri (2005) (2.8 mg/kg for Illinois, 10 mg/kg for Michigan, 0.46 mg/kg for New Jersey, and 0.59 for Ohio).

The null hypothesis of the K-S test was that the distribution of the slag concentration data is not significantly greater than the distribution of concentrations in US soils. A significance level of 0.05 was assigned for the K-S test. A value lower would reject the null hypothesis and suggest that the distribution of the constituent was significantly greater than background. Table 3.2 provides the results of the K-S tests, as well as the distribution for each constituent tested.

As noted above, concentrations of Cr(VI) and thallium in iron- and steel-making slag could not be compared to background because suitable background data were not available. Of the testable constituents, aluminum, arsenic, cadmium, lead, mercury, silicon, and silver were not found to be significantly greater than background, for all slag types. In contrast, the distributions of concentrations for all slag types for barium, calcium, magnesium, manganese, phosphorus, and selenium were determined to be significantly greater than background.

3.3 Comparisons of Maximum Concentrations with USEPA Regional Screening Levels

To identify COIs for the DRA, the maximum constituent concentrations, across all size fractions, for each slag type were compared to the respective USEPA Regional Screening Levels (RSL) for soil (USEPA 2010b). The USEPA RSLs are chemical-specific health-based concentrations that may be used for screening purposes. Exceedance of an RSL may warrant further investigation or site cleanup, but RSLs are not cleanup standards (USEPA 2010b). USEPA RSLs for soil are not available for calcium, magnesium or silicon.

COIs for the residential exposure scenarios (driveway and roadside scenarios in the exposure assessment, see Section 5) were developed using comparisons to the residential USEPA RSLs. COIs for non-residential exposure scenarios (industrial and maintenance worker, construction worker) were developed using comparisons to the industrial RSLs. Results of comparisons of maximum slag concentrations for all 26 constituents, across fraction sizes, for the three slag types are presented in Table 3.3.

3.4 Resulting COIs by Slag Type and Scenario

For the Tier I Hazard Identification, results of the slag type-specific comparisons of constituent concentrations in slag to US background in soil and the USEPA RSLs were combined to identify COIs for each slag type and scenario (Table 3.4). Constituents exceeding both background soil concentrations and RSLs were included in COIs for the DRA. The DRA COIs are summarized in Table 3.5.

Table 3.1
Concentration Statistics of Constituents in Soils of the Conterminous United States (Developed from Dragun and Chekiri, 2005)

Constituent	Mean (mg/kg)	SD (mg/kg)	G Mean (mg/kg)	GSD (mg/kg)	N	Min (mg/kg)	Max (mg/kg)
Aluminum	72,000		47,000	2.48	1,247	700	100,000
Antimony	0.67		0.48	2.27	354	1	8.8
Arsenic	7.2		5.2	2.23	1,257	0.1	97
Barium	580		44	2.14	1,319	10	5,000
Beryllium	0.92		0.63	2.38	1,303	1	15
Cadmium					1,319	ND	11
Calcium	24,000		9,000	4.00	1,291	100	320,000
Chromium (Total)	0.054		0.037	0.00	1,319	0.001	2
Cobalt	9.1		6.7	2.19	1,311	3	70
Copper	25		17	2.44	1,311	1	700
Iron	26,000		18,000	2.38	1,317	100	100,000
Lead	19		16	1.86	1,319	10	700
Magnesium	9,000		4,400	3.28	1,306	50	100,000
Manganese	550		330	2.77	1,317	2	7,000
Mercury	0.089		0.058	2.52	1,267	0.01	4.6
Molybdenum	0.97		0.59	2.72	1,298	3	15
Nickel	19		13	2.31	1,318	5	700
Phosphorus	430		260	2.67	906	20	6,800
Selenium	0.39		0.26	2.46	1,267	0.1	4.3
Silicon	310,000	64,800			406	16,000	450,000
Silver					1,319	ND	5
Thallium[1]	0.57				191	0.02	2.8
Tin	1.3		0.89	2.36	355	0.1	10
Vanadium	80		58	2.25	1,319	7	500
Zinc	60		48	1.95	1,248	5	2,900

[1] Statewide values for Illinois provided here as nation-wide data were not available.

Definitions
G mean = geometric mean, GSD = geometric standard deviation, max = maximum concentration, min = minimum concentration, mg/kg = milligram per kilogram, N = number of samples, ND = not detected, SD = standard deviation

Table 3.2
K-S Test Results For Comparison of Concentration of Constituents in PS Slag to Concentrations in Background Soil[a]

Constituent	Distribution Tested	EAF	BOF	BF
Aluminum	Lognormal	Not	Not	Not
Antimony	Lognormal	Sig greater	Not	Not
Arsenic	Lognormal	Not	Not	Not
Barium	Lognormal	Sig greater	Sig greater	Sig greater
Beryllium	Lognormal	Sig greater	Not	Sig greater
Cadmium	Uniform	Not	Not	Not
Calcium	Lognormal	Sig greater	Sig greater	Sig greater
Chromium	Lognormal	Sig greater	Sig greater	Not
Cobalt	Lognormal	Sig greater	Not	Not
Copper	Lognormal	Sig greater	Sig greater	Not
Iron	Lognormal	Sig greater	Sig greater	Not
Lead	Lognormal	Not	Not	Not
Magnesium	Lognormal	Sig greater	Sig greater	Sig greater
Manganese	Lognormal	Sig greater	Sig greater	Sig greater
Mercury	Lognormal	Not	Not	Not
Molybdenum	Lognormal	Sig greater	Sig greater	Not
Nickel	Lognormal	Sig greater	Not	Not
Phosphorus	Lognormal	Sig greater	Sig greater	Sig greater
Selenium	Lognormal	Sig greater	Sig greater	Sig greater
Silicon	Normal	Not	Not	Not
Silver	Uniform	Not	Not	Not
Thallium	NA	NA	NA	NA
Tin	Lognormal	Sig greater	Sig greater	Not
Vanadium	Lognormal	Sig greater	Sig greater	Not
Zinc	Lognormal	Sig greater	Sig greater	Not

Note

a Shaded cells identify which slag constituents significantly exceed background concentrations of constituents in soil of the conterminous US [Dragun and Chekiri (2005)] are shaded.

Definitions

BF = blast furnace, BOF = basic oxygen furnace, EAF = electric arc furnace, NA = not tested due to a lack of background data for the conterminous US, not = does not exceed background, sig = significantly

Table 3.3
Comparisons of Maximum Concentrations of Constituents in Slag to USEPA RSLs[a,b]

Chemical	USEPA	USEPA	EAF		BOF		BF	
	Residential Soil RSL	Industrial Soil RSL	Residential Soil RSL	Industrial Soil RSL	Residential Soil RSL	Industrial Soil RSL	Residential Soil RSL	Industrial Soil RSL
Aluminum	7.7E+04	9.9E+05	Exceeds	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Antimony	3.1E+01	4.1E+02	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Arsenic	3.9E-01	1.6E+00	Exceeds	Exceeds	Exceeds	Exceeds	Exceeds	Exceeds
Barium	1.5E+04	1.9E+05	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Beryllium	1.6E+02	2.0E+03	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Cadmium	7.0E+01	8.0E+02	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Calcium	--	--	No RSL	No RSL	No RSL	No RSL	No RSL	No RSL
Total Chromium	1.3E+05	1.5E+06	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Chromium (VI)	2.9E-01	5.6E+00	Exceeds	Exceeds	Exceeds	Does not exceed	Exceeds	Does not exceed
Cobalt	2.3E+01	3.0E+02	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Exceeds	Does not exceed
Copper	3.1E+03	4.1E+04	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Iron	5.5E+04	7.2E+05	Exceeds	Does not exceed	Exceeds	Does not exceed	Does not exceed	Does not exceed
Lead	4.0E+02	8.0E+02	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Magnesium	--	--	No RSL	No RSL	No RSL	No RSL	No RSL	No RSL
Manganese	1.8E+03	2.3E+04	Exceeds	Exceeds	Exceeds	Exceeds	Exceeds	Does not exceed
Mercury	5.6E+00	3.4E+01	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Molybdenum	3.9E+02	5.1E+03	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Nickel	1.5E+03	2.0E+04	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Phosphorus	1.6E+00	2.0E+01	Exceeds	Exceeds	Exceeds	Exceeds	Exceeds	Exceeds
Selenium	3.9E+02	5.1E+03	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Silicon	--	--	No RSL	No RSL	No RSL	No RSL	No RSL	No RSL
Silver	3.9E+02	5.1E+03	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Thallium	5.2E+00	6.7E+01	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Tin	4.7E+04	6.1E+05	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed
Vanadium	5.5E+00	7.2E+01	Exceeds	Exceeds	Exceeds	Exceeds	Exceeds	Does not exceed

	USEPA	USEPA	EAF		BOF		BF	
Chemical	**Residential Soil RSL**	**Industrial Soil RSL**	**Residential Soil RSL**	**Industrial Soil RSL**	**Residential Soil RSL**	**Industrial Soil RSL**	**Residential Soil RSL**	**Industrial Soil RSL**
Zinc	2.3E+04	3.1E+05	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed	Does not exceed

Notes

a USEPA RSLs are listed in units of milligram per kilogram (mg/kg). USEPA RSLs for soil are not available for Ca, Mg, or Si.

b Maximum Values by slag type are presented in Table 2.2 and Appendix A.

Definitions

BF = blast furnace, BOF = basic oxygen furnace, chromium (VI) = hexavalent chromium, EAF = electric arc furnace, RSL = US Environmental Protection Agency Regional Screening Level

Table 3.4
COI Screening Based on Comparisons to Background and USEPA RSLs[a]

Chemical	EAF		BOF		BF	
	Comparison to Background	**Comparison to EPA RSL**	**Comparison to Background**	**Comparison to EPA RSL**	**Comparison to Background**	**Comparison to EPA RSL**
Aluminum	Below	EXCEED	Below	Below	Below	Below
Antimony	EXCEED	Below	EXCEED	Below	EXCEED	Below
Arsenic	Below	EXCEED	Below	EXCEED	Below	EXCEED
Barium	EXCEED	Below	EXCEED	Below	EXCEED	Below
Beryllium	EXCEED	Below	Below	Below	EXCEED	Below
Cadmium	Below	Below	Below	Below	Below	Below
Calcium[b]	EXCEED	No RSL	EXCEED	No RSL	EXCEED	No RSL
Chromium (Total)	EXCEED	Below	EXCEED	Below	Below	Below
Chromium (VI)	No background data	EXCEED	No background data	EXCEED	No background data	Not Detected in BF Slag
Cobalt	EXCEED	Below	Below	Below	Below	EXCEED
Copper	EXCEED	Below	EXCEED	Below	Below	Below
Iron	EXCEED	EXCEED	EXCEED	EXCEED	Below	Below
Lead	EXCEED	Below	EXCEED	Below	Below	Below
Magnesium[b]	EXCEED	No RSL	EXCEED	No RSL	EXCEED	No RSL
Manganese	EXCEED	EXCEED	EXCEED	EXCEED	EXCEED	EXCEED
Mercury	Below	Below	Below	Below	Below	Below
Molybdenum	EXCEED	Below	EXCEED	Below	Below	Below
Nickel	EXCEED	Below	Below	Below	Below	Below
Phosphorus[c]	EXCEED	EXCEED	EXCEED	EXCEED	EXCEED	EXCEED
Selenium	EXCEED	Below	EXCEED	Below	EXCEED	Below

Chemical	**EAF**		**BOF**		**BF**	
	Comparison to Background	**Comparison to EPA RSL**	**Comparison to Background**	**Comparison to EPA RSL**	**Comparison to Background**	**Comparison to EPA RSL**
Silicon	Below	No RSL	Below	No RSL	Below	No RSL
Silver	Below	Below	Below	Below	Below	Below
Thallium	No background data	Below	No background data	Below	No background data	Below
Tin	EXCEED	Below	EXCEED	Below	Below	Below
Vanadium	EXCEED	EXCEED	EXCEED	EXCEED	Below	EXCEED
Zinc	EXCEED	Below	EXCEED	Below	Below	Below

Notes

a Shaded cells indicate that slag concentrations exceed both background and EPA RSLs. Background screening was performed using the K-S test. RSL screening was conducted using maximum concentrations for each slag type, which represent maximum concentrations across all slag size fractions by slag type. For simplicity, exceedances of either residential or industrial RSLs are indicated in this table but COIs were developed separately for residential and non-residential scenarios.

b Calcium and magnesium exist in slag at concentrations exceeding background concentrations in US soil (Dragun and Chekiri, 2005), and there are no USEPA RSLs available for these constituents. Consistent with the approach used by the Texas Commission on Environmental Quality (TCEQ) for essential nutrients in soil (TCEQ 2001), calcium and magnesium are not considered COIs. Calcium is excluded because ingestion of pure calcium at the child and adult soil ingestion rates would result in a dose that is lower than the Recommended Daily Allowance (RDA) for calcium as a nutrient. Similarly, magnesium is not considered a COI because the magnesium RDA is higher than the dose associated with ingestion of magnesium at the soil ingestion rates for children and adults.

c Phosphorus exists in slag at concentrations that exceed USEPA RSLs (USEPA 2010b) and concentrations of phosphorus in background US soil. However, the USEPA RSLs for phosphorus are based on phosphoric acid, which is not consistent with the form of phosphorus in slag (phosphorus oxide). Consistent with the approach used by the TCEQ (2001) for essential nutrients in soil, phosphorus is not considered a COI because ingestion of pure phosphorus at the child and adult soil ingestion rates results in a dose that is lower than the RDA for phosphorus as a nutrient.

Definitions
BF = blast furnace, BOF = basic oxygen furnace, chromium (VI) = hexavalent chromium, COI = constituent of interest, EAF = electric arc furnace, RSL = US Environmental Protection Agency Regional Screening Level

Table 3.5
Constituents of Interest[a]

EAF		BOF		BF	
Residential	**Non-Residential**	**Residential**	**Non-Residential**	**Residential**	**Non-Residential**
Chromium (VI)	Chromium (VI)	Chromium (VI)	Manganese	Manganese	None
Iron	Manganese	Iron	Vanadium		
Manganese	Vanadium	Manganese			
Vanadium		Vanadium			

Notes

a Constituents of interest (COI) are constituents that were measured in slag at a concentration that exceeded the residential or non-residential RSLs, and at concentrations that exceed background levels in US soils (Dragun and Chekiri, 2005).

Definitions

BF = blast furnace, BOF = basic oxygen furnace, chromium (VI) = hexavalent chromium, COI = constituent of interest, EAF = electric arc furnace

4.0 Toxicity Assessment

4.1 Slope Factors, Unit Risks, Reference Doses and Reference Concentrations for COIs

USEPA-developed toxicity criteria were used to characterize the potential for adverse effects resulting from exposure to COIs in slag. With the few exceptions discussed below and footnoted in Table 4.1, toxicity factors used in this HHRA are consistent with those provided in the USEPA IRIS data base (2010a), per USEPA guidance (USEPA 1989b). For constituents and pathways that currently do not have IRIS toxicity criteria, values from the USEPA Regional Screening Level (RSL) table were used (2010b). Toxicity criteria used in this HHRA, as well as the sources for these values, are shown in Table 4.1.

Quantitative evaluation of dose-response for a given chemical is consistent with the nature of the type of health effect. Risks associated with low levels of carcinogenic exposure are predicted using low-dose extrapolation models, which estimate cancer risk potential at low exposure levels based on tumors observed in high-dose animal or epidemiological studies. The potential for exposure to a COI to result in a theoretical excess cancer risks was characterized for Cr(VI) using a draft USEPA oral cancer slope factor (CSF) and the final USEPA inhalation unit risk factor (URF). Of the COIs, only Cr(VI) is considered carcinogenic and has an oral CSF and inhalation URF.

For noncarcinogenic effects, potential adverse effects are evaluated by applying oral reference doses (RfD) and inhalation reference concentrations (RfC). RfDs and RfCs are derived by applying uncertainty and modifying factors to a no-observed adverse effect level (NOAEL) or lowest-observed adverse effect level (LOAEL) to estimate an acceptable dose for sensitive human subpopulations (USEPA 1989b). Oral RfDs were applied for all four COIs; inhalation RfCs were identified for all COIs except iron because an RfC for iron is not currently available from either source.

Additional discussion of the toxicity criteria used in this assessment for Cr(VI) and manganese are provided below.

4.1.1 Manganese Oral Reference Dose (RfD)

The USEPA RfD for manganese is 0.14 milligram per kilogram per day (mg/kg-day, USEPA 2010a). EPA recommends applying an additional modifying factor of three (RfD divided by 3) when assessing the potential hazard from exposure to manganese in soil or groundwater. A modifying factor is similar to an uncertainty factor and is used when data are inadequate to address a particular concern. There are four reasons given in IRIS as to why the additional modifying factor may be needed: 1) there is increased uptake of manganese from drinking water among individuals who are fasting, 2) a study by Kondakis et al. (1989) “raises some concerns” for possible adverse effects associated with lifetime exposure to Mn in drinking water at a concentration of 2 milligram per liter (mg/L) (0.06 mg/kg-day), 3) there is concern that infant formula contains more manganese than human breast milk, and 4) there is some evidence that neonates may be more susceptible to manganese toxicity, due to increased absorption and a less effective blood-brain barrier. It is believed that the additional modifying factor is not necessary for risk assessment of manganese in iron and steel-making slag, because exposure does not occur via drinking water, and neonates (infants of less than 1 month) are not expected to be exposed to slag. Unlike older children, neonates do not play in soil. Further, absorption and elimination of manganese from oral uptake is homeostatically controlled in the body. Thus, the body burden of manganese is maintained within a relatively narrow range, in spite of fluctuations in the amount of manganese ingested. Given that manganese uptake and elimination are under homeostatic control, the total amount in the diet, rather than the physical form in which manganese is ingested, determines whether or not it is absorbed following ingestion (Kies 1987).

Nonetheless, to unsure that this risk assessment is adequately conservative, the 3-fold modifying factor recommended in IRIS for non-dietary exposures was included for manganese in the slag risk assessment.

4.1.2 Discussion of Chromium (VI) Oral Cancer Slope Factor (CSF)

USEPA does not include an oral CSF in the IRIS file for Cr(VI). However, a preliminary draft Toxicological Review for Cr(VI) was released September 30, 2010, which includes a draft oral CSF and the designation of Cr(VI) as a mutagen (USEPA 2010c). The findings of USEPA’s preliminary draft review do not currently represent agency policy, and there are several significant data gaps in the information necessary to assess the carcinogenic mode of action (MOA) (Thompson et al. 2010) and oral cancer risk assessment for Cr(VI). However, to ensure the risk assessment for ingestion of Cr(VI) is sufficiently conservative, the oral CSF presented in USEPA (2010c) is used in this risk assessment for iron- and steel-making slag. Also, risk assessment methods consistent with the application of age-dependent adjustment factors (ADAFs) for mutagenic MOA have been included in the development of Risk Based Concentrations (RBCs) in Sections 5 and 6.

4.1.3 Discussion of Chromium (VI) Inhalation Unit Risk Factors (URF)

The inhalation unit risk factor (URF) for Cr(VI) used in this HHRA is 0.012 $(\mu g/m^3)^{-1}$, which was obtained directly from USEPA’s Integrated Risk Information System (IRIS, USEPA 2010a). The inhalation URF for Cr(VI) listed in the USEPA Regional Screening Level (RSL) tables (USEPA 2010b) is 0.084 $(\mu g/m^3)^{-1}$. Although the RSL table references IRIS, the RSL User’s Guide (USEPA 2010b) states that the IRIS URF was multiplied by a factor of 7, because the ratio of hexavalent to total chromium used to derive the IRIS URF is unknown, and a ratio of 1:6 for hexavalent:total chromium was conservatively assumed. However, the RSL User’s Guide does not provide an accurate interpretation of the Cr(VI) IRIS file, and the fraction of hexavalent to total chromium was characterized as part of the original risk assessment used to set the URF (USEPA 1984). USEPA IRIS has not deviated from the original approach in any of the updates of the IRIS file since it was first derived in 1984, and the risk assessments of others are supportive of the USEPA URF provided in IRIS (Crump et al. 2003; Park et al. 2004; OSHA 2006; Proctor et al. 2003). As such, this HHRA uses the IRIS URF, as published in the current IRIS file for Cr(VI).

Table 4.1
Toxicity Factors for COIs

Toxicity Values[a,b]									
		CSF		URF		RfD		RfC	
COI	CAS	(mg/kg-d) [1]	Key	(ug/m^3)$^{-1}$	Key	(mg/kg-d)	Key	(mg/m^3)	Key
Cr(VI)[c]	16065-83-1	5.0E-01	J	1.2E-02	I	3.0E-03	I	1.0E-04	I
Fe	7439-89-6	--	--	--	--	7.0E-01	P	--	--
Mn	7439-96-5	--	--	--	--	4.7E-02	I	5.0E-05	I
V	7440-62-2	--	--	--	--	5.0E-03	S	1.0E-04	A

Notes

a With the exception of the Cr(VI) URF and Mn RfD, which were acquired directly from IRIS, toxicity factors were obtained from the USEPA RSL tables (USEPA 2010b). Designations in the Key columns reflect the toxicity factor sources as listed in the USEPA RSL tables (USEPA 2010b).

b The oral RfD for vanadium is derived from the IRIS oral RfD for vanadium pentoxide by factoring out the molecular weight (MW) of the oxide ion. Vanadium pentoxide (V_20_5) has a molecular weight of 181.88. The two atoms of vanadium contribute 56% of the MW. Vanadium pentoxide's oral RfD of 9E-03 multiplied by 56% gives a vanadium oral RfD of 5.04E-03 (USEPA 2010b). The vanadium RfC is based on metallic vanadium.

c Cr(VI) is the only COI considered to be mutagenic.

Definitions

A = ATSDR (Agency for Toxic Substances and Disease Registry), CAS = Chemical Abstracts Service, COI = constituent of interest, Cr(VI) = hexavalent chromium, CSF = oral cancer slope factor, Fe = iron, I = IRIS (USEPA Integrated Risk Information System), J = New Jersey Department of Environmental Protection, mg/kg-d = milligram per kilogram per day, (mg/kg-d)$^{-1}$ = per milligram per kilogram per day, mg/m^3 = milligram per cubic meter, Mn = manganese, P = PPRTV (USEPA Provisional Peer Reviewed Toxicity Value), RfC = inhalation reference concentration, RfD = oral reference dose, S = see USEPA RSL User's Guide Section 5b, USEPA = US Environmental Protection Agency, URF = inhalation unit risk factor, (ug/m^3)$^{-1}$ = per microgram per cubic meter, V = vanadium, -- = no value available

5.0 Tier II - Deterministic Risk Assessment (DRA)

In the DRA, generally accepted, conservative exposure parameters, and representative data for slag-specific exposure scenarios were used to develop Tier II Risk-Based Concentrations (RBCs). RBCs, which are health-protective concentrations of COIs in iron and steel-making slag, were developed for slag-specific exposure scenarios and compared to average and 95% UCL concentrations of COIs in slag. Approaches, exposure scenarios, pathways and results of the DRA are discussed below.

Several approaches for the toxicity and exposure portions of the DRA differed from those used for the previous assessment. These differences include:

- The current assessment focuses on inhalation and oral exposure routes; exposures by dermal contact were not quantitatively evaluated because the dose due to dermal contact with slag was deemed insignificant in both of the previous risk assessments. For example, in the previous risk assessment by Exponent (2007), hazard indices for dermal exposure to all COIs combined ranged from 0.00000006 to 0.002 for all scenarios. These hazard indices were at least 500-fold lower than the target hazard index of 1, indicating that dermal exposure to COIs in slag is not significant.
- Only one construction worker scenario was evaluated in the current assessment. The most highly exposed construction worker scenario from the previous assessment, which was the scenario for construction of road base, was evaluated in the current assessment.
- Exposure to farmers was not evaluated in this HHRA because exposures for the farmer scenario were not significant in either of the previous risk assessments (Proctor et al. 2002; Exponent 2007). Exposures to industrial/maintenance and construction workers should be similar to that for farmers, and thus exposures to farmers may be evaluated using the industrial/maintenance worker scenarios. Moreover, data regarding slag constituent uptake of metals into crops are currently inadequate for quantitative risk assessment, and the application rates for slag on agricultural fields, as a liming agent, are relatively low—with a typical application rate of 2,000 pounds per acre. For these reasons, it was not deemed necessary to estimate RBCs for the farmer scenario or for exposure by crop uptake in this risk assessment.
- RBCs were calculated rather than the potential health risks and hazards associated with environmental exposures to slag.
- The risk assessment used the most current risk assessment guidance, including:
  - Current toxicity criteria
  - Age-Dependent Adjustment Factors (ADAFs) were applied for assessing the carcinogenic risk associated with exposures to Cr(VI) to account for potential increased sensitivity associated with early-life exposures. This approach is consistent with the USEPA draft Toxicological Review for Cr(VI) (USEPA 2010c).
  - Air dispersion modeling with AERMOD was used rather than ISC for the residential roadway scenario.

5.1 Approach for Calculating Risk Based Concentrations (RBCs)

The RBC calculation combines the results of the exposure and toxicity assessments to derive acceptable health-based concentrations of COIs in slag. RBCs for non-cancer health effects are characterized using the USEPA toxicity factors, and assuming a hazard index (HI) of 1.0, e.g., exposures to slag at the RBC results in a dose that is equal to the RfD. Cr(VI) is the only carcinogenic COI in slag. The RBCs for Cr(VI) was developed to achieve a theoretical excess cancer risk of one-in-a-million (1×10^{-6}). Pathway-specific RBCs were combined to reflect a total combined-exposure RBC protective of exposures from both oral and inhalation pathways. USEPA has established that a hazard index (HI) greater than one suggests that a hazard may exist and that further evaluation is warranted. USEPA considers cumulative cancer risks in the range of 1×10^{-6} to one-in-ten-thousand (1×10^{-4}) to be negligible (USEPA 1990).

The RBC equations were structured after those used by USEPA to develop its RSLs (USEPA 2010b). Equations used to develop the RBCs for this HHRA are provided in Appendix B.

5.2 Exposure Scenarios

The exposure scenarios evaluated in this HHRA for both the DRA and PRA are:

- Residential exposure (including children and adults) to slag cover for an unpaved driveway at a residential property (residential driveway scenario)
- Residential exposure (including children and adults) to dust generated by vehicle traffic on an unpaved roadway with slag cover adjacent to the residence (residential roadside scenario)
- Industrial and maintenance worker exposures to slag at an industrial or commercial site
- Construction worker exposures to slag during construction of road base.

For each scenario, except the residential roadside scenario, exposures via incidental ingestion and inhalation were quantified. For the resident living adjacent to unpaved roads with slag cover (residential roadside scenario), only exposure by inhalation was evaluated because it was assumed that incidental ingestion would not occur for this scenario. Residential exposure to slag by ingestion is assessed for the residential driveway scenario. The exposure assessment was refined using application-specific slag use information and slag characterization data provided by the National Slag Association.

5.3 Exposure Factors

In accordance with USEPA guidelines, both reasonable maximum exposure (RME) and most likely exposure (MLE) scenarios were evaluated. For consistency with common USEPA risk assessment practice, upper-bound values (e.g., 95th percentile) were used to describe the RME scenarios, and average or 50th percentile values were used to describe the MLE scenarios. Exposure parameters were primarily obtained from EPA guidance documents, mainly the Soil Screening Levels Guidance (USEPA 2002a) and Exposure Factors Handbook (USEPA 2009a). All exposure factors employed in the DRA are provided in Table 5.1.

5.4 Particulate Emission Factors

Exposure scenario-specific particulate emission factors (PEFs) were developed for use in assessing inhalation exposures. The PEF is an estimate reflecting the relationship between the concentration of a constituent in slag and the concentrations in air, as a result of particle suspension due to vehicle traffic and wind erosion. Slag-specific information including particle size, silt and moisture content, and slag uses was considered in modeling PEF values for the residential roadside and construction worker scenarios. PEFs obtained from USEPA's Soil Screening Guidance (USEPA 2002a) were used for the residential driveway and industrial and maintenance worker scenarios. PEFs used for the various exposure scenarios are discussed below. For all scenarios, it was conservatively assumed that 100% of particulates suspended in ambient air consisted of slag.

Because manganese is one of the primary COIs in slag, and the manganese RfC is specific to particles of 5 µm or smaller, PM_{10} concentrations derived by modeling were converted in the emission equations to PM_5 concentrations using a multiplier for PM_5 particle size. The particle size multiplier for converting PM_{10} concentrations to PM_5 (0.67) assumes that 67% of PM_{10} is PM_5 and was derived from modeling approaches described in AP-42 (USEPA, 1995).

5.4.1 Residential Driveway Scenario

The standard USEPA residential PEF, developed by USEPA in its Soil Screening Guidance (USEPA 2002a), was used in the inhalation evaluation of the residential driveway scenario. The residential driveway PEF value is 1.32×10^9 cubic meters per kilogram (m^3/kg) (USEPA 2002a).

5.4.2 Residential Roadside Scenario

PEFs for the residential roadside scenario were calculated using the USEPA American Meteorological Society and USEPA Regulatory Model (AERMOD) dispersion model, with meteorological data for six representative cities across the US, and traffic frequency information were obtained from across the US.

For this HHRA, Sullivan Environmental Consulting, Inc. (Sullivan) used AERMOD to calculate the annual average suspended particulate concentrations, for unit emission rates, due to vehicular traffic on hypothetical road segments. For this model, meteorological data sets from six cities with varying meteorological conditions: 1) Austin, Texas 2) Bridgeport, Connecticut 3) Charleston, South Carolina 4) Des Moines, Iowa 5) Detroit, Michigan and 6) Fresno, California were used (Sullivan 2010). Average and maximum airborne particulate concentrations, across the six cities, were determined for distances of 10, 20, 30, 40, 50, 100, 200, and 400 meters on either side of the road. Modeling was performed for four road orientations for each of the six cities (north-south, east-west, northeast-southwest, northwest-southeast) (Sullivan 2010). For the DRA PEF determination, the distance from the road to a residence was assumed to be 50 meters. It is important to note that it was conservatively assumed that 100% of the particulates generated by traffic on slag-covered roads are comprised of slag. The air dispersion modeling report prepared by Sullivan is included in Appendix C.

Emission rates for particulates from unpaved roads were determined for each slag type based on methods from USEPA (2002a). Emission rates require estimates of the daily vehicular traffic. In the previous risk assessment, the daily traffic count for unpaved roads (25 vehicles per day) was taken from a draft New Jersey Department of Environmental Protection Agency guidance for assessing particulate emissions at non-residential sites. As part of this HHRA, a thorough literature review was conducted to determine the most representative values for traffic counts on unpaved roads. Unfortunately, published data to derive vehicle traffic counts on unpaved roads is sparse, thus individual state Department's of Transportation (DOT) were contacted to obtain these data. Although state DOTs from across the US were contacted, very few had data regarding this parameter, with the most robust data sets coming from the states of New York, Virginia and Montana. To estimate the daily vehicle traffic count (vehicles per day or VPD) for the MLE scenario in this HHRA, the median value of vehicles traveling on unpaved roads in New York and Virginia of 60/day was used (New York Department of Transportation [NYDOT] 2010; Virginia Department of Transportation [VDOT] 2010). For the RME scenario, the median number of vehicles traveling unpaved roads in Montana of 162/day was used (Montana Department of Transportation [MDT] 2010). These data were incorporated into the emission rate calculations as described below.

The total distance traveled along the road in kilometers (VKT) is calculated as:

$$VKT = n \times L / 1{,}000$$

where:

n	number VPD
L	length of modeled road (1,045 meters)

The calculated mass of PM_{10} emitted from the road for each slag type, during a given time period (M_{road}) is:

$$M_{road}(g) = [\frac{2.6 x (s/_{12})^{0.8} x (W/_{3})^{0.4}}{(M_{dry}/_{0.2})^{0.3}}] x [\frac{(365-p)}{365}] x VKT x S$$

where:

s	percent silt for each slag type (3.9% for EAF, 5.06 % for BOF, 4.37% for BF)
W	mean vehicle weight (estimated at 2 tons for rural roads)
M_{dry}	slag-type specific percent moisture content
p	number of days with <0.001-in precipitation in each city. Estimated from Exhibit E-4 of USEPA 2002a
VKT	total distance traveled along the road (kilometers)
S	Fraction of particulate emissions assumed to be slag (100%)

The road was assumed to be 6 meters wide, based on a typical rural road. The calculated precipitation adjusted emission flux (J), which is the total particle mass emitted from the road area per day is:

$$J(g/_{m^3-sec}) = \frac{M_{road}}{(A x T)}$$

Modeled data from Sullivan (2010) were converted to a per unit emission rate based on a normalized emission rate of 0.0030303 gram/second per square meter (g/s-m^2). PM_{10} emissions for each slag type and each city were calculated. These emissions were then converted to PM_5 emission rates using the PM_5-to-PM_{10} particle size multiplier (0.67). We calculated the PM_{10} concentration as follows:

$$C(mg/_{m^3}) = \frac{Unit\ Concentration(ug/_{m^2}\ per\ g/_{m^2-sec}) x J(g/_{m^2-sec}) x 0.001(mg/ug)}{(PM_{10}/_{PM_5})}$$

Slag type-specific PEFs were determined using the equation below:

$$PEF(m^3/_{kg}) = \frac{1,000,000}{C(mg/_{m^3})}$$

The calculated slag type-specific PEFs, for both RME and MLE roadside resident scenarios, are provided in Table 5.1.

5.4.3 Industrial and Maintenance Worker Scenario

The standard USEPA commercial/industrial PEF, developed by USEPA in its Soil Screening Guidance (USEPA 2002a), was used in the inhalation evaluation of the industrial and maintenance worker scenario. The industrial and commercial worker PEF value is 1.36 x 10^9 m^3/kg (USEPA 2002a).

5.4.4 Construction Worker Scenario

For construction workers involved in building roads using slag as road base, road base-specific PEF values were developed. For this PEF, it was assumed that slag is dumped out of a truck in one motion, spread out twice with a bulldozer, and graded twice with a grader. This exposure scenario for road base construction was determined based on consultation with the National Slag Association (NSA). It was conservatively assumed that construction workers would inhale slag particulates from a location adjacent and downwind of where the slag is applied and dust is generated. Based on typical slag road base projects, it was assumed that two thousand tons of slag would be applied each day to construct road base in 8-foot (ft) widths, 12 inches (in) thick. It was assumed that the bulk density of slag is 125 pounds per cubic ft (lb/ft^3) and that no dust suppression, such as wetting agents, would be employed. Moisture content was assumed to be 6.5%. This value is the measured moisture content of <¾-inch aggregate slag from the Tube City IMS Ellwood steel slag-processing site in New Castle, Pennsylvania, and slag-type-specific silt content values from the original assessment were used (EAF = 8.03% BOF = 2.9%, BF = 4.6% from Proctor et al. [2002]). Mean wind speed is assumed to be 4.69 meters per second (m/s), and wind direction is assumed to be perpendicular to the road (USEPA 2002a).

In estimating daily emissions from road construction work sites, wind speed, dimensions of the slag application area, as well as mass emitted during dumping (M_{dump}), dozing (M_{doz}), and grading (M_{grad}) were evaluated. Total mass emitted is the sum resulting from each construction activity (dumping, dozing, grading), and includes silt and moisture and contents of the slag type, as well as distance traveled by the equipment and speed. Emission area is calculated from the mass of slag applied daily (2,000 tons/day), slag depth (1.0 ft for road base), and slag bulk density (125 lb/ft^3).

$$Area(m^2) = \frac{2{,}000\,tons\ x\ 2{,}000\,lb\,/\,ton\ x\ 0.093\,m^2\,/\,ft^2}{125\,lb\,/\,ft^3\ x\ depth\,(ft)}$$

The daily road base area constructed is assumed to be 3,000 m^2, which equals 0.76 mile of 8-ft-wide road base applied per day. Based on professional judgment, this level of road base activity is likely an upper-bound, overestimating activities for most construction projects. Emission flux (in Joule [J] or g/m^2-sec) is the total mass emitted from the total area of road base constructed in an 8-hr day:

$$J(g/m^2 - sec) = \frac{M_{dump}(g) + M_{doz}(g) + M_{grad}(g)}{Area(m^2)\,x\,8(hr)\,x\,3{,}600(sec/hr)}$$

where:

M_{dump}	mass emitted during slag dumping from a truck
M_{doz}	mass emitted during slag spreading with a dozer
M_{grad}	mass emitted during slag spreading with a grader

A box model, frequently used by USEPA to assess exposures occurring near the emission source, was used to estimate airborne concentrations from the particulate emissions generated during construction. In the box model, particulates disperse into a hypothetical box which is located over the area where slag is placed each day. Emissions are assumed to enter from the bottom of the box and exit to the side. The PM_{10} concentration in the air leaving the box (C) is:

$$C(mg/m^3) = \frac{1{,}000(mg/g)\,x\,J(g/m^2 - sec)\,x\,width(m)}{Windspeed(m/sec)\,x\,height(m)}$$

where:
Box width is assumed to be 8 ft (2.4 m) (width of deposited slag)
Box height is assumed to be 2 m (the typically assumed breathing zone height)

This is considered a conservative approach as emissions are assumed to disperse only within the box and deposition within the box is not considered. The report prepared by Sullivan used to derive the PEFs for the roadside residential scenario is provided in Appendix C. The calculated slag type-specific PEFs, for both RME and MLE construction worker scenarios, used to calculate RBCs for the construction worker are listed in Table 5.1.

5.5 Oral Bioaccessibility Factors

An *in vitro* bioaccessibility study was conducted to evaluate the extent to which constituents in slag may be available for absorption from the gastrointestinal (GI) tract following incidental ingestion of slag. This approach is consistent with USEPA guidance for assessing relative bioavailability of metals in soil (USEPA 2008). Because extraction of slag constituents from finer particles is expected to be greater than from large particles, and particles of approximately 250 µm and smaller are expected to adhere to hands, the <300 µm size fraction of slag particles was used in *in vitro* extraction studies to assess bioaccessibility.

Experimental parameters for the bioaccessibility study followed the procedures outlined in USEPA (2008a) *Standard Operating Procedure for an In Vitro Bioaccessibility Assay for Lead in Soil.* Specifically, extractions were conducted to simulate the most acidic stomach conditions at normal body temperature of 37 °C and a pH of 1.4 (0.04 molar) hydrochloric acid for 1 hour to simulate gastric conditions. The fraction of individual constituents released from the slag matrix, defined here as the oral bioaccessibility factor (B_{oral}), was incorporated into the calculation of RBCs for all incidental slag ingestion exposure scenarios. The individual sample data from the bioaccessibility studies are provided in Appendix A, Table A.4.

For each sample, one gram of the <300 µm size fraction of slag was extracted with 100 mL solution. The extraction results were reported in µg/L, so B_{oral} was calculated on a sample by sample basis, from the equation:

$$B_{oral} = \frac{[C_{extraction\ solution}(\mu g/L) x\ 100\ ml\ x\ (1\ L/1000\ mL)]}{[C_{slag}(\mu g/kg) x\ 1\ gram\ slag\ x\ (1\ kg/1000\ g)]}$$

Thus, B_{oral} values were the mass of the constituent in the extraction solution divided by the mass of the constituent in the slag sample used in the extraction. Mean and 95% UCL of B_{oral} values were calculated from the individual samples by slag type. When the mass in the extraction fluid exceeded the mass in the slag sample, a factor of 100% was used. While the previous risk assessment only included B_{oral} values for a subset of chemicals in a smaller number of samples, the *in vitro* bioaccessibility assay for the current HHRA evaluated the full list of 25 constituents present in slag in each of the <300 µm slag samples collected in 2009. Therefore, the current HHRA includes a more robust evaluation of bioaccessibility and therefore more representative B_{oral} values for the DRA and PRA. Mean and 95% UCLs of B_{oral} values were developed and used for the MLE and RME scenarios, respectively. The B_{oral} values for each slag type are presented in Table 5.2.

5.6 Deterministic Risk Assessment (DRA) Results

Calculated RBCs for all RME and MLE scenarios, are provided in Tables 5.3 through 5.6. RBCs were compared to COI concentrations in slag for the relevant size-specific for the exposure scenario, e.g., concentrations in the smallest size fraction (<75 µm slag samples) were compared to inhalation RBCs. The <300 µm size fraction is consistent with the size fraction that might adhere to hands and other surfaces and therefore be incidentally ingested. Thus, concentrations of COIs in the <300 µm size samples were compared to the oral RBCs. Finally, the exposure-pathway-combined RBCs were compared to the COI concentrations in PS samples to determine where concentrations of COIs in slag exceed RBCs. Cr(VI) was only measured in PS sized particles by slag type, and thus comparisons by particle size are limited to PS slag for Cr(VI). The comparisons of RBCs to slag concentrations are presented in Tables 5.7 through 5.10. Results for each receptor type are discussed below. COIs that exceeded the respective RBCs in the DRA were further evaluated in the PRA (Table 5.11).

5.6.1 Residential Driveway Scenario

Constituents exceeding slag type-specific RBCs for the residential driveway scenario are discussed by slag type below.

5.6.1.1 EAF Slag

Chromium (VI)

RME

As shown in Table 5.7, the 95% UCL concentration for Cr(VI) in EAF PS samples is 5.1 mg/kg, which exceeds the RME total RBC of 1.0 mg/kg by 5-fold.

MLE

There are no exceedances of RBC for Cr(VI) in the MLE residential driveway scenario for EAF slag.

Iron

As shown in Table 5.7, there are no RBC exceedances for iron in the RME or MLE residential driveway scenarios for EAF slag.

Manganese

RME

As shown in Table 5.7, measured concentrations of manganese in <300 μm size slag samples and EAF PS samples exceed the respective RBCs for the RME residential driveway scenario. The 95% UCL concentration for manganese in <300 μm size EAF slag samples is approximately 23,000 mg/kg, which exceeds the RME oral RBC of 11,000 mg/kg by 2.1-fold. The 95% UCL concentration for manganese in EAF PS samples is approximately 34,000 mg/kg, which exceeds the RME total RBC of 9,600 mg/kg by 3.6-fold.

MLE

Measured concentrations of manganese in EAF PS samples exceed the total RBC for the MLE residential driveway scenario. The mean concentration for manganese in EAF PS samples is approximately 31,000 mg/kg, which exceeds the MLE total RBC of 22,000 mg/kg by 1.4-fold.

Vanadium

RME

As shown in Table 5.7, for the RME residential driveway scenario, measured concentrations of vanadium in EAF PS samples exceed the total RBC. The 95% UCL concentration for vanadium in EAF PS samples is 690 mg/kg, which exceeds the RME total RBC of 590 mg/kg by 1.2-fold.

MLE

There are no RBC exceedances for vanadium in the MLE residential driveway scenario for EAF slag.

5.6.1.2 BOF Slag

Chromium (VI)

RME

As shown in Table 5.7, for the RME residential driveway scenario, the 95% UCL concentration for Cr(VI) in BOF PS samples is 2.5 mg/kg, which exceeds the RME total RBC of 1.7 mg/kg by 1.4-fold.

MLE

There are no RBC exceedances for Cr(VI) in the MLE residential driveway scenario for BOF slag.

Iron

As shown in Table 5.7, there are no RBC exceedances for iron in the RME or MLE residential driveway scenarios for BOF slag.

Manganese

RME

As shown in Table 5.7, for the RME residential driveway scenario, measured concentrations of manganese in the <300 μm size BOF slag samples and BOF PS samples exceed the respective RBCs. The 95% UCL concentration for manganese in the <300 μm size BOF slag samples is approximately 22,000 mg/kg, which exceeds the RME oral RBC of 8,600 mg/kg by 2.5-fold. The 95% UCL concentration for manganese in BOF PS samples is approximately 25,000 mg/kg, which exceeds the RME total RBC of 7,700 mg/kg by 3.3-fold.

MLE

Measured concentrations of manganese in BOF PS samples exceed the RBC for the MLE residential driveway scenario. The mean concentration for manganese in BOF PS samples is approximately 23,000 mg/kg, which exceeds the MLE total RBC of 20,000 mg/kg by 1.1-fold.

Vanadium

RME

As shown in Table 5.7, for the RME residential driveway scenario, measured concentrations of vanadium in the <300 μm size BOF samples and BOF PS samples exceed the respective RBCs. The 95% UCL concentration for vanadium in the <300 μm size BOF slag samples is

790 mg/kg, which exceeds the RME oral RBC of 600 mg/kg by 1.3-fold. The 95% UCL concentration for vanadium in BOF PS samples is 860 mg/kg, which exceeds the RME total RBC of 590 mg/kg by 1.5-fold.

MLE

There are no RBC exceedances for vanadium in the MLE residential driveway scenario for BOF slag.

5.6.1.3 BF Slag

As shown in Table 5.7, there are no RBC exceedances for BF slag in the RME or MLE residential driveway scenario. Manganese was the only COI identified for BF slag.

5.6.2 Residential Roadside Scenario

Constituents exceeding slag type-specific RBCs for the residential roadside scenario are discussed below by slag type.

5.6.2.1 EAF Slag

Chromium (VI)

As shown in Table 5.8, there are no RBC exceedances for Cr(VI) in the RME or MLE residential roadside scenarios for EAF slag.

Iron

As shown in Table 5.8, there are no RBC exceedances for iron in the RME or MLE residential roadside scenarios for EAF slag.

Manganese

RME

As shown in Table 5.8, for the RME residential roadside scenario, measured concentrations of manganese in the <75 μm size EAF slag samples exceed the inhalation RBCs. The 95% UCL concentration for manganese in the <75 μm size EAF slag samples is approximately 20,000 mg/kg, which exceeds the RME inhalation RBC of 18,000 mg/kg by 1.1-fold.

MLE

There are no RBC exceedances for manganese in the MLE residential roadside scenario for EAF slag.

Vanadium

As shown in Table 5.8, there are no RBC exceedances for vanadium in the RME or MLE residential roadside scenarios for EAF slag.

5.6.2.2 BOF Slag

Chromium (VI)
As shown in Table 5.8, there are no RBC exceedances for Cr(VI) in the RME or MLE residential roadside scenarios for BOF slag.

Iron
As shown in Table 5.8, there are no RBC exceedances for iron in the RME or MLE residential roadside scenarios for BOF slag.

Manganese

RME
As shown in Table 5.8, for the RME residential roadside scenario, measured concentrations of manganese in the <75 μm size BOF slag samples exceed the inhalation RBC. The 95% UCL concentration for manganese in the <75 μm size BOF slag samples is approximately 21,000 mg/kg, which exceeds the RME inhalation RBC of 15,000 mg/kg by 1.4-fold.

MLE
There are no RBC exceedances for manganese in the MLE residential roadside scenario for BOF slag.

Vanadium
As shown in Table 5.8, there are no RBC exceedances for vanadium in the RME or MLE residential roadside scenarios for BOF slag.

5.6.2.3 BF Slag

As shown in Table 5.8, there are no RBC exceedances for BF slag, for any COI, in the residential roadside scenario. Manganese was the only COI identified for BF slag, and it was only a COI for residential exposure scenarios.

5.6.3 Industrial and Maintenance Worker Scenario

Constituents exceeding slag type-specific RBCs for the industrial and maintenance worker scenario are discussed in the sections below.

5.6.3.1 EAF Slag

As shown in Table 5.9, there are no exceedances of RBCs for measured COI levels in any size EAF or BOF slag fraction for the industrial and maintenance worker scenario, for both

RME and MLE exposures. There are no COIs identified for BF slag for non-residential exposure scenarios.

5.6.4 Construction Worker Scenario

As shown in Table 5.10, there are no exceedances of RBCs for any of the measured COI in any size EAF or BOF slag fractions for the construction worker scenario, for both RME and MLE exposures. There are no COIs identified for BF slag for non-residential exposure scenarios.

5.7.1 Summary of Deterministic Risk Assessment (DRA) Results

As described above and presented in Tables 5.7 through 5.10, Cr(VI), manganese and vanadium in BOF and EAF slag exceed the calculated RBCs for at least one of the exposure scenarios evaluated in the DRA. As shown in Table 5.11, COIs in BF slag did not exceed any calculated RBCs for any application scenario evaluated in the DRA.

COIs that exceeded RBCs in the DRA, were evaluated using a more realistic Probabilistic Risk Assessment (PRA) in Section 6. In the DRA there were several instances where the concentration of a COI in the EAF and BOF PS size samples and the <300 um samples exceeded the DRA RBCs, but the concentration in the <75 um smaller size fraction did not. Nevertheless, the determination of COIs for the PRA is not particle size specific.

Table 5.1
Default/Exposure Parameters

Name	Description	Value	Units
ATc.mle	Averaging time for carcinogenic effects, MLE	25,550	d
ATc.rme	Averaging time for carcinogenic effects, RME	25,550	d
ATnc.cw.mle	Averaging time for non-carcinogenic effects, construction worker, MLE	657	d
ATnc.cw.rme	Averaging time for non-carcinogenic effects, construction worker, RME	2,920	d
ATnc.iwmw.mle	Averaging time for non-carcinogenic effects, industrial/maintenance worker, MLE	2,008	d
ATnc.iwmw.rme	Averaging time for non-carcinogenic effects, industrial/maintenance worker, RME	9,125	d
ATnc.res.adult.mle	Averaging time for non-carcinogenic effects, resident, adult, MLE	10,950	d
ATnc.res.adult.rme	Averaging time for non-carcinogenic effects, resident, adult, RME	10,950	d
ATnc.res.child.mle	Averaging time for non-carcinogenic effects, resident, child, MLE	2,190	d
ATnc.res.child.rme	Averaging time for non-carcinogenic effects, resident, child, RME	2,190	d
BW.adult.mle	Body weight, adult, MLE	70	kg
BW.adult.rme	Body weight, adult, RME	70	kg
BW.child.mle	Body weight, child, MLE	15	kg
BW.child.rme	Body weight, child, RME	15	kg
CF.1	Conversion factor	1E-06	kg/mg
CF.2	Conversion factor	1E+03	ug/mg
ED.cw.mle	Exposure duration, construction worker, MLE	1.8	yr
ED.cw.rme	Exposure duration, construction worker, RME	8	yr
ED.iwmw.rme	Exposure duration, industrial/maintenance worker, RME	25	yr
ED.iwmw.mle	Exposure duration, industrial/maintenance worker, MLE	5.5	yr
ED.res.0_2.mle	Exposure duration, resident, 0-2 years, MLE	2	yr
ED.res.0_2.rme	Exposure duration, resident, 0-2 years, RME	2	yr
ED.res.16_30.mle	Exposure duration, resident, 16-30 years, MLE	14	yr
ED.res.16_30.rme	Exposure duration, resident, 16-30 years, RME	14	yr
ED.res.2_6.mle	Exposure duration, resident, 2-6 years, MLE	4	yr
ED.res.2_6.rme	Exposure duration, resident, 2-6 years, RME	4	yr
ED.res.6_16.mle	Exposure duration, resident, 6-16 years, MLE	10	yr
ED.res.6_16.rme	Exposure duration, resident, 6-16 years, RME	10	yr
ED.res.adult.mle	Exposure duration, resident, adult, MLE	30	yr
ED.res.adult.rme	Exposure duration, resident, adult, RME	30	yr
ED.res.child.mle	Exposure duration, resident, child, MLE	6	yr
ED.res.child.rme	Exposure duration, resident, child, RME	6	yr
EF.cw.mle	Exposure frequency, construction worker, MLE	160	d/yr
EF.cw.rme	Exposure frequency, construction worker, RME	225	d/yr
EF.iwmw.mle	Exposure frequency, industrial/maintenance worker, MLE	225	d/yr
EF.iwmw.rme	Exposure frequency, industrial/maintenance worker, RME	225	d/yr

Name	Description	Value	Units
EF.res.mle	Exposure frequency, resident, MLE	350	d/yr
EF.res.rme	Exposure frequency, resident, RME	350	d/yr
ET.cw.mle	Exposure time for inhalation, construction worker, MLE	0.33	unitless
ET.cw.rme	Exposure time for inhalation, construction worker, RME	0.33	unitless
ET.iwmw.mle	Exposure time for inhalation, industrial/maintenance worker, MLE	0.33	unitless
ET.iwmw.rme	Exposure time for inhalation, industrial/maintenance worker, RME	0.33	unitless
ET.res.mle	Exposure time for inhalation, resident, MLE	0.66	unitless
ET.res.rme	Exposure time for inhalation, resident, RME	1	unitless
IFS.adj.mle	Soil ingestion rate, resident, age-adjusted, MLE	57	mg-yr/kg-d
IFS.adj.rme	Soil ingestion rate, resident, age-adjusted, RME	114	mg-yr/kg-d
IFSM.adj.mle	Soil ingestion rate, resident, age-adjusted, mutagens, MLE	245	mg-yr/kg-d
IFSM.adj.rme	Soil ingestion rate, resident, age-adjusted, mutagens, RME	490	mg-yr/kg-d
IRsoil.cw.mle	Soil ingestion rate, construction worker, MLE	50	mg/d
IRsoil.cw.rme	Soil ingestion rate, construction worker, RME	330	mg/d
IRsoil.iwmw.mle	Soil ingestion rate, industrial/maintenance worker, MLE	50	mg/d
IRsoil.iwmw.rme	Soil ingestion rate, industrial/maintenance worker, RME	100	mg/d
IRsoil.res.adult.mle	Soil ingestion rate, resident, adult, MLE	50	mg/d
IRsoil.res.adult.rme	Soil ingestion rate, resident, adult, RME	100	mg/d
IRsoil.res.child.mle	Soil ingestion rate, resident, child, MLE	100	mg/d
IRsoil.res.child.rme	Soil ingestion rate, resident, child, RME	200	mg/d
PEF.cw.bf.mle	Particulate emission factor, construction worker, BF, MLE	5.86E+08	m^3/kg
PEF.cw.bof.mle	Particulate emission factor, construction worker, BOF, MLE	5.43E+08	m^3/kg
PEF.cw.eaf.mle	Particulate emission factor, construction worker, EAF, MLE	6.30E+08	m^3/kg
PEF.cw.bf.rme	Particulate emission factor, construction worker, BF, RME	5.86E+08	m^3/kg
PEF.cw.bof.rme	Particulate emission factor, construction worker, BOF, RME	5.43E+08	m^3/kg
PEF.cw.eaf.rme	Particulate emission factor, construction worker, EAF, RME	6.30E+08	m^3/kg
PEF.iwmw.mle	Particulate emission factor, industrial/maintenance worker, MLE	1.36E+09	m^3/kg
PEF.iwmw.rme	Particulate emission factor, industrial/maintenance worker, RME	1.36E+09	m^3/kg
PEF.res.driveway.mle	Particulate emission factor, resident, driveway, MLE	1.32E+09	m^3/kg
PEF.res.driveway.rme	Particulate emission factor, resident, driveway, RME	1.32E+09	m^3/kg
PEF.res.roadside.bf.mle	Particulate emission factor, resident, roadside,	8.49E+08	m^3/kg

Name	Description	Value	Units
	BF, MLE		
PEF.res.roadside.bof.mle	Particulate emission factor, resident, roadside, BOF, MLE	7.55E+08	m^3/kg
PEF.res.roadside.eaf.mle	Particulate emission factor, resident, roadside, EAF, MLE	9.30E+08	m^3/kg
PEF.res.roadside.bf.rme	Particulate emission factor, resident, roadside, BF, RME	3.14E+08	m^3/kg
PEF.res.roadside.bof.rme	Particulate emission factor, resident, roadside, BOF, RME	2.80E+08	m^3/kg
PEF.res.roadside.eaf.rme	Particulate emission factor, resident, roadside, EAF, RME	3.44E+08	m^3/kg
THQ	Target hazard quotient	1	unitless
TR	Target risk level	1E-06	unitless

Definitions
BF = blast furnace, BOF = basic oxygen furnace, c = carcinogenic effects, d = day, d/yr = day per year, EAF = electric arc furnace, kg = kilogram, kg/mg = kilogram per milligram, m3/kg = cubic meter per kilogram, mg-yr/kg-d = milligram year per kilogram per day, mg/d = milligram per day, MLE = most likely exposure, nc = noncarcinogenic effects, RBC = risk-based concentration, RME = reasonable maximum exposure, µg/mg = microgram per milligram, yr = year, RBC = risk-based concentration, RME = reasonable maximum exposure, µg/mg = microgram per milligram, yr = year

Table 5.2
Oral Bioaccessibility Factors for all Constituents of measured in < 300 µm Slag Samples

Chemical	B_{oral} (unitless)						B_{oral} (unitless)			B_{oral} (unitless)		
	95% UCL Measurement						Maximum Measurement			Mean Measurement		
	EAF	Method	BOF	Method	BF	Method	EAF	BOF	BF	EAF	BOF	BF
Total Aluminum	0.788	Student's-t	0.777	Student's-t	0.915	Student's-t	1.000	0.900	0.949	0.708	0.622	0.837
Total Antimony	0.721	Student's-t	0.974	Student's-t	1.000	^	1.000	1.000	1.000	0.614	0.661	1.000
Total Arsenic	0.802	Student's-t	0.984	Student's-t	1.000	^	1.000	1.000	1.000	0.723	0.742	1.000
Total Barium	0.803	Student's-t	0.870	Student's-t	0.745	Student's-t	1.000	0.909	1.000	0.793	0.759	0.615
Total Beryllium	0.811	Student's-t	0.831	Student's-t	0.923	Student's-t	1.000	0.857	1.000	0.752	0.759	0.817
Total Cadmium	0.385	Approx. Gamma	0.386	Student's-t	0.567	Student's-t	0.969	0.480	1.000	0.294	0.315	0.381
Total Calcium	0.904	Student's-t	0.880	Student's-t	0.973	Student's-t	1.000	0.897	1.000	0.877	0.825	0.857
Total Chromium	0.293	Approx. Gamma	0.168	Approx. Gamma	0.704	Approx. Gamma	1.000	0.225	1.000	0.181	0.099	0.569
Total Cobalt	0.674	Student's-t	0.746	Student's-t	0.976	Student's-t	0.929	0.844	1.000	0.606	0.645	0.919
Total Copper	0.289	Student's-t	0.570	Student's-t	0.360	*	0.491	0.677	0.360	0.229	0.370	0.054
Total Iron	0.258	Approx. Gamma	0.218	Approx. Gamma	0.633	Approx. Gamma	0.917	0.293	1.000	0.166	0.126	0.430
Total Lead	0.714	*	0.911	Student's-t	0.707	Student's-t	0.714	1.000	1.000	0.570	0.727	0.499
Total Magnesium	0.650	Student's-t	0.636	Student's-t	0.870	Approx. Gamma	0.862	0.738	1.000	0.557	0.464	0.807
Total Manganese	0.327	Student's-t	0.423	Student's-t	0.936	Student's-t	0.500	0.588	1.000	0.268	0.295	0.864
Total Mercury	1.000	*	1.000	*	1.000	^	1.000	1.000	1.000	0.990	0.985	1.000
Total Molybdenum	0.177	Student's-t	0.225	Student's-t	0.592	H	0.413	0.309	1.000	0.135	0.141	0.293
Total Nickel	0.275	Student's-t	0.327	Student's-t	0.734	Student's-t	0.358	0.349	1.000	0.239	0.272	0.559
Total Phosphorus	0.829	Student's-t	0.755	Student's-t	1.000	*	1.000	0.776	1.000	0.767	0.701	0.980
Total Selenium	1.000	*	1.000	*	0.120	Student's-t	1.000	1.000	0.143	0.533	0.531	0.098
Total Silicon	1.000	^	1.000	^	1.000	^	1.000	1.000	1.000	1.000	1.000	1.000
Total Silver	0.364	Approx. Gamma	0.259	Student's-t	0.381	Student's-t	1.000	0.304	0.514	0.266	0.196	0.306
Total Thallium	1.000	*	1.000	^	1.000	^	1.000	1.000	1.000	0.987	1.000	1.000
Total Tin	1.000	*	1.000	^	1.000	^	1.000	1.000	1.000	0.942	1.000	1.000
Total Vanadium	0.661	Student's-t	0.656	Student's-t	0.723	Student's-t	0.833	0.739	1.000	0.591	0.558	0.599
Total Zinc	0.521	Student's-t	0.542	Student's-t	0.826	Student's-t	0.731	0.667	1.000	0.451	0.454	0.741

Notes

Any samples exceeding unity were assigned a value of 1. Using 1 gram slag sample in 100 milliliter solution

* Recommended UCL exceeds the maximum observation, thus maximum observation selected

^ Only one distinct observation value resulting in '0' variance, UCL should not be calculated

Definitions

95% UCL = 95% upper confidence limit, B_{oral} = oral bioaccessibility factor, BF = blast furnace, EAF = electric arc furnace, BOF = basic oxygen furnace

Table 5.3
Residential Driveway Scenario Tier II Risk-Based Concentrations (mg/kg)

COI Res EAF	EAF - RME						EAF - MLE					
	oral RBC.c	inh RBC.c	tot RBC.c	oral RBC.nc	inh RBC.nc	tot RBC.nc	oral RBC.c	inh RBC.c	tot RBC.c	oral RBC.nc	inh RBC.nc	tot RBC.nc
Cr(VI)	1.0E+00	9.1E+01	1.0E+00	8.0E+02	1.4E+05	8.0E+02	3.3E+00	1.6E+02	3.2E+00	2.6E+03	2.1E+05	2.6E+03
Fe	--	--	--	2.1E+05	--	2.1E+05	--	--	--	6.6E+05	--	6.6E+05
Mn	--	--	--	1.1E+04	6.9E+04	9.6E+03	--	--	--	2.7E+04	1.0E+05	2.2E+04
V	--	--	--	5.9E+02	1.4E+05	5.9E+02	--	--	--	1.3E+03	2.1E+05	1.3E+03
COI Res BOF	**BOF - RME**						**BOF - MLE**					
	oral RBC.c	**inh RBC.c**	**tot RBC.c**	**oral RBC.nc**	**inh RBC.nc**	**tot RBC.nc**	**oral RBC.c**	**inh RBC.c**	**tot RBC.c**	**oral RBC.nc**	**inh RBC.nc**	**tot RBC.nc**
Cr(VI)	1.8E+00	9.1E+01	1.7E+00	1.4E+03	1.4E+05	1.4E+03	6.0E+00	1.6E+02	5.8E+00	4.8E+03	2.1E+05	4.6E+03
Fe	--	--	--	2.5E+05	--	2.5E+05	--	--	--	8.7E+05	--	8.7E+05
Mn	--	--	--	8.6E+03	6.9E+04	7.7E+03	--	--	--	2.5E+04	1.0E+05	2.0E+04
V	--	--	--	6.0E+02	1.4E+05	5.9E+02	--	--	--	1.4E+03	2.1E+05	1.4E+03
COI Res BF	**BF - RME**						**BF - MLE**					
	oral RBC.c	**inh RBC.c**	**tot RBC.c**	**oral RBC.nc**	**inh RBC.nc**	**tot RBC.nc**	**oral RBC.c**	**inh RBC.c**	**tot RBC.c**	**oral RBC.nc**	**inh RBC.nc**	**tot RBC.nc**
Mn	--	--	--	3.9E+03	6.9E+04	3.7E+03	--	--	--	8.4E+03	1.0E+05	7.8E+03

Definitions

BF = blast furnace, BOF = basic oxygen furnace, c = carcinogenic effects, COI = constituent of interest, Cr(VI) = hexavalent chromium, EAF = electric arc furnace, Fe = iron, inh = inhalation, mg/kg = milligram per kilogram, MLE = most likely exposure, Mn = manganese, nc = noncarcinogenic effects, RBC = risk-based concentration, res = residential, RME = reasonable maximum exposure, tot = total (oral + inhalation), V = vanadium

Table 5.4
Residential Roadside Scenario Tier II Risk-Based Concentrations (mg/kg)

	EAF - RME		EAF - MLE	
COI Res EAF	**inh RBC.c**	**inh RBC.nc**	**inh RBC.c**	**inh RBC.nc**
Chromium (VI)	2.4E+01	3.6E+04	1.1E+02	1.5E+05
Iron	--	--	--	--
Manganese	--	1.8E+04	--	7.3E+04
Vanadium	--	3.6E+04	--	1.5E+05
	BOF - RME		**BOF - MLE**	
COI Res BOF	**inh RBC.c**	**inh RBC.nc**	**inh RBC.c**	**inh RBC.nc**
Chromium (VI)	1.9E+01	2.9E+04	9.2E+01	1.2E+05
Iron	--	--	--	--
Manganese	--	1.5E+04	--	6.0E+04
Vanadium	--	2.9E+04	--	1.2E+05
	BF - RME		**BF - MLE**	
COI Res BF	**inh RBC.c**	**inh RBC.nc**	**inh RBC.c**	**inh RBC.nc**
Manganese	--	1.6E+04	--	6.7E+04

Definitions
BF = blast furnace, BOF = basic oxygen furnace, c = carcinogenic effects, COI = constituent of interest, EAF = electric arc furnace, inh = inhalation, mg/kg = milligram per kilogram, MLE = most likely exposure, nc = noncarcinogenic effects, RBC = risk-based concentration, res = residential, RME = reasonable maximum exposure

Table 5.5
Industrial and Maintenance Worker Scenario Tier II Risk-Based Concentrations (mg/kg)

COI Res EAF	EAF - RME						EAF - MLE					
	oral RBC.c	inh RBC.c	tot RBC.c	oral RBC.nc	inh RBC.nc	tot RBC.nc	oral RBC.c	inh RBC.c	tot RBC.c	oral RBC.nc	inh RBC.nc	tot RBC.nc
Cr(VI)	2.2E+01	1.5E+03	2.1E+01	1.2E+04	6.6E+05	1.1E+04	3.2E+02	7.0E+03	3.0E+02	3.8E+04	6.6E+05	3.6E+04
Mn	--	--	--	1.6E+05	3.3E+05	1.1E+05	--	--	--	4.0E+05	3.3E+05	1.8E+05
V	--	--	--	8.6E+03	6.6E+05	8.5E+03	--	--	--	1.9E+04	6.6E+05	1.9E+04
COI Res BOF	**BOF - RME**						**BOF - MLE**					
	oral RBC.c	**inh RBC.c**	**tot RBC.c**	**oral RBC.nc**	**inh RBC.nc**	**tot RBC.nc**	**oral RBC.c**	**inh RBC.c**	**tot RBC.c**	**oral RBC.nc**	**inh RBC.nc**	**tot RBC.nc**
V	--	--	--	8.7E+03	6.6E+05	8.5E+03	--	--	--	2.0E+04	6.6E+05	2.0E+04

Definitions
BF = blast furnace, BOF = basic oxygen furnace, c = carcinogenic effects, COI = constituent of interest, Cr(VI) = hexavalent chromium, EAF = electric arc furnace, inh = inhalation, mg/kg = milligram per kilogram, MLE = most likely exposure, Mn = manganese, nc = noncarcinogenic effects, nonres = nonresidential, RBC = risk-based concentration, RME = reasonable maximum exposure, tot = total (oral + inhalation), V = vanadium

Table 5.6
Construction Worker Scenario Tier II Risk-Based Concentrations (mg/kg)

COI Res EAF	EAF - RME						EAF - MLE					
	oral RBC.c	inh RBC.c	tot RBC.c	oral RBC.nc	inh RBC.nc	tot RBC.nc	oral RBC.c	inh RBC.c	tot RBC.c	oral RBC.nc	inh RBC.nc	tot RBC.nc
Cr(VI)	2.1E+01	2.2E+03	2.0E+01	3.5E+03	3.1E+05	3.5E+03	1.4E+03	1.4E+04	1.2E+03	5.3E+04	4.3E+05	4.7E+04
Mn	--	--	--	4.9E+04	1.5E+05	3.7E+04	--	--	--	5.6E+05	2.2E+05	1.6E+05
V	--	--	--	2.6E+03	3.1E+05	2.6E+03	--	--	--	2.7E+04	4.3E+05	2.5E+04
COI Res BOF	**BOF - RME**						**BOF - MLE**					
	oral RBC.c	**inh RBC.c**	**tot RBC.c**	**oral RBC.nc**	**inh RBC.nc**	**tot RBC.nc**	**oral RBC.c**	**inh RBC.c**	**tot RBC.c**	**oral RBC.nc**	**inh RBC.nc**	**tot RBC.nc**
Mn	--	--	--	3.8E+04	1.3E+05	2.9E+04	--	--	--	5.1E+05	1.9E+05	1.4E+05
V	--	--	--	2.6E+03	2.6E+05	2.6E+03	--	--	--	2.9E+04	3.7E+05	2.7E+04

Definitions
BF = blast furnace, BOF = basic oxygen furnace, c = carcinogenic effects, COI = constituent of interest, Cr(VI) = hexavalent chromium, EAF = electric arc furnace, inh = inhalation, mg/kg = milligram per kilogram, MLE = most likely exposure, Mn = manganese, nc = noncarcinogenic effects, nonres = nonresidential, RBC = risk-based concentration, RME = reasonable maximum exposure, tot = total (oral + inhalation), V = vanadium

Table 5.7

Comparison of Slag COI Concentrations with Risk-Based Concentrations for the Residential Driveway Scenario[a]

	EAF - RME			EAF - RME			EAF - RME		
	PS			<300 um[b]			<75 um[b]		
COI Res EAF	**95% UCL Conc (mg/kg)**	**tot RBC (mg/kg)**	**Conc > RBC?**	**95% UCL Conc (mg/kg)**	**tot RBC (mg/kg)**	**Conc > RBC?**	**95% UCL Conc (mg/kg)**	**tot RBC (mg/kg)**	**Conc > RBC?**
Chromium (VI)	5.1E+00	1.0E+00	EXCEEDS	5.1E+00	1.0E+00	EXCEEDS	5.1E+00	9.1E+01	--
Iron	2.1E+05	2.1E+05	--	1.5E+05	2.1E+05	--	1.3E+05	--	No RBC
Manganese	3.4E+04	9.6E+03	EXCEEDS	2.3E+04	1.1E+04	EXCEEDS	2.0E+04	6.9E+04	--
Vanadium	6.9E+02	5.9E+02	EXCEEDS	4.3E+02	5.9E+02	--	3.8E+02	1.4E+05	--
	EAF - MLE			**EAF - MLE**			**EAF - MLE**		
	PS			**<300 um[b]**			**<75 um[b]**		
COI Res EAF	**Mean Conc (mg/kg)**	**oral RBC (mg/kg)**	**Conc > RBC?**	**Mean Conc (mg/kg)**	**inh RBC (mg/kg)**	**Conc > RBC?**	**Mean Conc (mg/kg)**	**tot RBC (mg/kg)**	**Conc > RBC?**
Chromium (VI)	1.9E+00	3.2E+00	--	1.9E+00	3.3E+00	--	1.9E+00	1.6E+02	--
Iron	1.9E+05	6.6E+05	--	1.2E+05	6.6E+05	--	9.9E+04	--	No RBC
Manganese	3.1E+04	2.2E+04	EXCEEDS	1.8E+04	2.7E+04	--	1.6E+04	1.0E+05	--
Vanadium	6.0E+02	1.3E+03	--	3.4E+02	1.3E+03	--	2.9E+02	2.1E+05	--
	BOF - RME			**BOF - RME**			**BOF - RME**		
	PS			**<300 um[b]**			**<75 um[b]**		
COI Res BOF	**95% UCL Conc (mg/kg)**	**oral RBC (mg/kg)**	**Conc > RBC?**	**95% UCL Conc (mg/kg)**	**inh RBC (mg/kg)**	**Conc > RBC?**	**95% UCL Conc (mg/kg)**	**tot RBC (mg/kg)**	**Conc > RBC?**
Chromium (VI)	2.5E+00	1.7E+00	EXCEEDS	2.5E+00	1.8E+00	EXCEEDS	2.5E+00	9.1E+01	--
Iron	2.0E+05	2.5E+05	--	1.8E+05	2.5E+05	--	1.6E+05	--	No RBC
Manganese	2.5E+04	7.7E+03	EXCEEDS	2.2E+04	8.6E+03	EXCEEDS	2.1E+04	6.9E+04	--
Vanadium	8.6E+02	5.9E+02	EXCEEDS	7.9E+02	6.0E+02	EXCEEDS	8.6E+02	1.4E+05	--

COI Res BOF	BOF - MLE			BOF - MLE			BOF - MLE		
	PS			<300 um[b]			<75 um[b]		
	Mean Conc (mg/kg)	oral RBC (mg/kg)	Conc > RBC?	Mean Conc (mg/kg)	inh RBC (mg/kg)	Conc > RBC?	Mean Conc (mg/kg)	tot RBC (mg/kg)	Conc > RBC?
Chromium (VI)	8.3E-01	5.8E+00	--	8.3E-01	6.0E+00	--	8.3E-01	1.6E+02	--
Iron	1.8E+05	8.7E+05	--	1.6E+05	8.7E+05	--	1.3E+05	--	No RBC
Manganese	2.3E+04	2.0E+04	EXCEEDS	1.9E+04	2.5E+04	--	1.8E+04	1.0E+05	--
Vanadium	7.6E+02	1.4E+03	--	6.6E+02	1.4E+03	--	7.0E+02	2.1E+05	--

COI Res BF	BF - RME			BF - RME			BF - RME		
	PS			<300 um[b]			<75 um[b]		
	95% UCL Conc (mg/kg)	oral RBC (mg/kg)	Conc > RBC?	95% UCL Conc (mg/kg)	inh RBC (mg/kg)	Conc > RBC?	95% UCL Conc (mg/kg)	tot RBC (mg/kg)	Conc > RBC?
Manganese	3.3E+03	3.7E+03	--	3.7E+03	3.9E+03	--	3.6E+03	6.9E+04	--

COI Res BF	BF - MLE			BF - MLE			BF - MLE		
	PS			<300 um[b]			<75 um[b]		
	Mean Conc (mg/kg)	oral RBC (mg/kg)	Conc > RBC?	Mean Conc (mg/kg)	inh RBC (mg/kg)	Conc > RBC?	Mean Conc (mg/kg)	tot RBC (mg/kg)	Conc > RBC?
Manganese	2.9E+03	7.8E+03	--	3.4E+03	8.4E+03	--	3.3E+03	1.0E+05	--

Notes

a The RBCs presented here reflect the lower of the carcinogenic and noncarcinogenic RBCs for Cr(VI)

b Chromium (VI) slag data are available for only the PS fraction. Therefore, in the absence of data for other fractions, the PS data were used as surrogates for the smaller fractions for chromium (VI).

Definitions

-- = 95%UCL is less than the RBC, BF = blast furnace, BOF = basic oxygen furnace, COI = constituent of interest, conc = concentration, EAF = electric arc furnace, inh = inhalation, mg/kg = milligram per kilogram, MLE = most likely exposure, PS = processed slag, RBC = risk-based concentration, res = residential, RME = reasonable maximum exposure, tot = total (oral + inhalation combined), µm = micrometer

Table 5.8
Comparison of Slag COI Concentrations with Risk-Based Concentrations for the Residential Roadside Scenario[a]

	EAF - RME			**EAF - MLE**		
	<75 um[b]			**<75 um[b]**		
COI Res EAF	**95% UCL Conc (mg/kg)**	**inh RBC (mg/kg)**	**Conc > RBC?**	**Mean Conc (mg/kg)**	**inh RBC (mg/kg)**	**Conc > RBC?**
Chromium (VI)	5.1E+00	2.4E+01	--	1.9E+00	1.1E+02	--
Iron	1.3E+05	--	No RBC	9.9E+04	--	No RBC
Manganese	2.0E+04	1.8E+04	EXCEEDS	1.6E+04	7.3E+04	--
Vanadium	3.8E+02	3.6E+04	--	2.9E+02	1.5E+05	--

	BOF - RME			**BOF - MLE**		
	<75 um[b]			**<75 um[b]**		
COI Res BOF	**95% UCL Conc (mg/kg)**	**inh RBC (mg/kg)**	**Conc > RBC?**	**Mean Conc (mg/kg)**	**inh RBC (mg/kg)**	**Conc > RBC?**
Chromium (VI)	2.5E+00	1.9E+01	--	8.3E-01	9.2E+01	--
Iron	1.6E+05	--	No RBC	1.3E+05	--	No RBC
Manganese	2.1E+04	1.5E+04	EXCEEDS	1.8E+04	6.0E+04	--
Vanadium	8.6E+02	2.9E+04	--	7.0E+02	1.2E+05	--

	BF - RME			**BF - MLE**		
	<75 um			**<75 um**		
COI Res BF	**95% UCL Conc (mg/kg)**	**inh RBC (mg/kg)**	**Conc > RBC?**	**Mean Conc (mg/kg)**	**inh RBC (mg/kg)**	**Conc > RBC?**
Manganese	3.6E+03	1.6E+04	--	3.3E+03	6.7E+04	--

Notes

a The RBCs presented here for Cr(VI) are lower of the calculated carcinogenic and noncarcinogenic RBCs

b Chromium (VI) slag data are available for only the PS fraction. Therefore, in the absence of data for other fractions, the PS data were used as surrogates for the smaller fractions for chromium (VI).

Definitions

-- = 95%UCL is less than the RBC, BF = blast furnace, BOF = basic oxygen furnace, COI = constituent of interest, conc = concentration, EAF = electric arc furnace, inh = inhalation, mg/kg = milligram per kilogram, MLE = most likely exposure, PS = processed slag, RBC = risk-based concentration, res = residential, RME = reasonable maximum exposure, μm = micrometer

Table 5.9
Comparison of Slag COI Concentrations with Risk-Based Concentrations for the Industrial and Maintenance Worker Scenario[a]

COI Nonres EAF	EAF - RME			EAF - RME			EAF - RME		
	PS			<300 um[b]			<75 um[b]		
	95% UCL Conc (mg/kg)	oral RBC (mg/kg)	Conc > RBC?	95% UCL Conc (mg/kg)	inh RBC (mg/kg)	Conc > RBC?	95% UCL Conc (mg/kg)	tot RBC (mg/kg)	Conc > RBC?
Chromium (VI)	5.1E+00	2.1E+01	--	5.1E+00	2.2E+01	--	5.1E+00	1.5E+03	--
Manganese	3.4E+04	1.1E+05	--	2.3E+04	1.6E+05	--	2.0E+04	3.3E+05	--
Vanadium	6.9E+02	8.5E+03	--	4.3E+02	8.6E+03	--	3.8E+02	6.6E+05	--

COI Nonres EAF	EAF - MLE			EAF - MLE			EAF - MLE		
	PS			<300 um[b]			<75 um[b]		
	Mean Conc (mg/kg)	oral RBC (mg/kg)	Conc > RBC?	Mean Conc (mg/kg)	inh RBC (mg/kg)	Conc > RBC?	Mean Conc (mg/kg)	tot RBC (mg/kg)	Conc > RBC?
Chromium (VI)	1.9E+00	3.0E+02	--	1.9E+00	3.2E+02	--	1.9E+00	7.0E+03	--
Manganese	3.1E+04	1.8E+05	--	1.8E+04	4.0E+05	--	1.6E+04	3.3E+05	--
Vanadium	6.0E+02	1.9E+04	--	3.4E+02	1.9E+04	--	2.9E+02	6.6E+05	--

	BOF - RME			BOF - RME			BOF - RME		
	PS			<300 um[b]			<75 um[b]		
COI Nonres BOF	95% UCL Conc (mg/kg)	oral RBC (mg/kg)	Conc > RBC?	95% UCL Conc (mg/kg)	inh RBC (mg/kg)	Conc > RBC?	95% UCL Conc (mg/kg)	tot RBC (mg/kg)	Conc > RBC?
Manganese	2.5E+04	9.1E+04	--	2.2E+04	1.3E+05	--	2.1E+04	3.3E+05	--
Vanadium	8.6E+02	8.5E+03	--	7.9E+02	8.7E+03	--	8.6E+02	6.6E+05	--

	BOF - MLE			BOF - MLE			BOF - MLE		
	PS			<300 um[b]			<75 um[b]		
COI Nonres BOF	Mean Conc (mg/kg)	oral RBC (mg/kg)	Conc > RBC?	Mean Conc (mg/kg)	inh RBC (mg/kg)	Conc > RBC?	Mean Conc (mg/kg)	tot RBC (mg/kg)	Conc > RBC?
Manganese	2.3E+04	1.7E+05	--	1.9E+04	3.6E+05	--	1.8E+04	3.3E+05	--
Vanadium	7.6E+02	2.0E+04	--	6.6E+02	2.0E+04	--	7.0E+02	6.6E+05	--

Notes

a The RBCs presented here for Cr(VI) are the lower of the calculated carcinogenic and noncarcinogenic RBCs

b Chromium (VI) slag data are available for only the PS fraction. Therefore, in the absence of data for other fractions, the PS data were used as surrogates for the smaller fractions for chromium (VI).

Definitions

-- = 95%UCL is less than the RBC, BF = blast furnace, BOF = basic oxygen furnace, COI = constituent of interest, conc = concentration, EAF = electric arc furnace, inh = inhalation, mg/kg = milligram per kilogram, MLE = most likely exposure, nonres = nonresidential, PS = processed slag, RBC = risk-based concentration, RME = reasonable maximum exposure, tot = total (oral + inhalation combined), μm = micrometer

Table 5.10
Comparison of Slag COI Concentrations with Risk-Based Concentrations for the Construction Worker Scenario[a]

	EAF - RME			EAF - RME			EAF - RME		
	PS			<300 um[b]			<75 um[b]		
COI Nonres EAF	**95% UCL Conc (mg/kg)**	**oral RBC (mg/kg)**	**Conc > RBC?**	**95% UCL Conc (mg/kg)**	**inh RBC (mg/kg)**	**Conc > RBC?**	**95% UCL Conc (mg/kg)**	**tot RBC (mg/kg)**	**Conc > RBC?**
Chromium (VI)	5.1E+00	2.0E+01	--	5.1E+00	2.1E+01	--	5.1E+00	2.2E+03	--
Manganese	3.4E+04	3.7E+04	--	2.3E+04	4.9E+04	--	2.0E+04	1.5E+05	--
Vanadium	6.9E+02	2.6E+03	--	4.3E+02	2.6E+03	--	3.8E+02	3.1E+05	--
	EAF - MLE			**EAF - MLE**			**EAF - MLE**		
	PS			**<300 um[b]**			**<75 um[b]**		
COI Nonres EAF	**Mean Conc (mg/kg)**	**oral RBC (mg/kg)**	**Conc > RBC?**	**Mean Conc (mg/kg)**	**inh RBC (mg/kg)**	**Conc > RBC?**	**Mean Conc (mg/kg)**	**tot RBC (mg/kg)**	**Conc > RBC?**
Chromium (VI)	1.9E+00	1.2E+03	--	1.9E+00	1.4E+03	--	1.9E+00	1.4E+04	--
Manganese	3.1E+04	1.6E+05	--	1.8E+04	5.6E+05	--	1.6E+04	2.2E+05	--
Vanadium	6.0E+02	2.5E+04	--	3.4E+02	2.7E+04	--	2.9E+02	4.3E+05	--
	BOF - RME			**BOF - RME**			**BOF - RME**		
	PS			**<300 um[b]**			**<75 um[b]**		
COI Nonres BOF	**95% UCL Conc (mg/kg)**	**oral RBC (mg/kg)**	**Conc > RBC?**	**95% UCL Conc (mg/kg)**	**inh RBC (mg/kg)**	**Conc > RBC?**	**95% UCL Conc (mg/kg)**	**tot RBC (mg/kg)**	**Conc > RBC?**
Manganese	2.5E+04	2.9E+04	--	2.2E+04	3.8E+04	--	2.1E+04	1.3E+05	--
Vanadium	8.6E+02	2.6E+03	--	7.9E+02	2.6E+03	--	8.6E+02	2.6E+05	--
	BOF - MLE			**BOF - MLE**			**BOF - MLE**		
COI Nonres BOF	**PS**			**<300 um[b]**			**<75 um[b]**		

	Mean Conc (mg/kg)	oral RBC (mg/kg)	Conc > RBC?	Mean Conc (mg/kg)	inh RBC (mg/kg)	Conc > RBC?	Mean Conc (mg/kg)	tot RBC (mg/kg)	Conc > RBC?
Manganese	2.3E+04	1.4E+05	--	1.9E+04	5.1E+05	--	1.8E+04	1.9E+05	--
Vanadium	7.6E+02	2.7E+04	--	6.6E+02	2.9E+04	--	7.0E+02	3.7E+05	--

Notes

a The RBCs presented here reflect the lowest between the calculated carcinogenic and noncarcinogenic RBCs

b Chromium (VI) slag data are available for only the PS fraction. Therefore, in the absence of data for other fractions, the PS data were used as surrogates for the smaller fractions for chromium (VI).

Definitions

-- = 95%UCL is less than the RBC, BF = blast furnace, BOF = basic oxygen furnace, COI = constituent of interest, conc = concentration, EAF = electric arc furnace, inh = inhalation, mg/kg = milligram per kilogram, MLE = most likely exposure, nonres = nonresidential, PS = processed slag, RBC = risk-based concentration, RME = reasonable maximum exposure, tot = total (oral + inhalation combined), μm = micrometer

Table 5.11
Summary of COIs Exceeding Tier II RBCs That are Evaluated in the PRA

Receptor	**Residential Driveway**			**Residential Roadside**			**Industrial and Maintenance Worker**			**Construction Worker**		
Slag Type	EAF	BOF	BF	EAF	BOF	BF	EAF	BOF	BF	EAF	BOF	BF
COIs with RBC Exceedances	Cr(VI), Mn, V	Cr(VI), Mn, V	--	Mn	Mn	--	--	--	--	--	--	--

Definitions
BF = blast furnace, BOF = basic oxygen furnace, COI = constituent of interest, Cr(VI) = hexavalent chromium, EAF = electric arc furnace, Mn = manganese, RBC = risk-based concentration, V = vanadium

6.0 Tier III - Probabilistic Risk Assessment (PRA)

Probabilistic Risk Assessment (PRA) allows for the characterization of variability and uncertainty in exposure and risk estimates, or in the case of this HHRA, in the calculation of Risk Based Concentrations (RBCs). The term variability defines true heterogeneity in a parameter. For example, the body weight (BW) of an adult male shows variability in that individuals are known to vary in weight, and that variability is known and can be quantitatively described. The term uncertainty defines a lack of knowledge about a parameter. In risk assessment, it is usually necessary to include estimated values for parameters for which there is limited information upon which to base the estimate. For example, adult soil ingestion rates are based on only a very limited data set, and it is not certain that the available information reliably represents soil ingestion rates for the population being assessed. Uncertainty may be reduced by additional sampling information, whereas variability will not. Most parameters in health risk assessment are both variable and uncertain, yet for the DRA, a single point value is used to characterize the distribution. By comparison, the PRA does not rely on a single point value for parameters, but includes distributions of information for each exposure parameter, which allows for characterization of uncertainty and variability based on all available information.

In a PRA, variability and uncertainty in the risk assessment parameters and models are quantified using probability distributions. These distributions mathematically represent the range of possible values for a parameter value, and the probability associated with each value. Just as a DRA uses point values for model parameters, and results in a single estimate of risk or hazard, a PRA uses probability distributions to represent parameters of a model and generates a distribution of risk or hazard. PRAs provide the range and distribution of results (i.e., risk, hazard or RBCs), and thus provide a better measure of the most likely value or upper percentile for the upper-bound of exposure.

To conduct the PRA, distributions for exposure parameters (e.g. body weight, soil ingestion rate) and modeling parameters (e.g., PEF) were developed from slag-specific data or from the published sources. Using these distributions, we calculated constituent- and slag-specific distributions of risk and hazard. Because of complexities associated with the PRA and following USEPA guidance for conducting PRAs, the equations used for the DRA were rearranged to calculate risk or hazard rather than RBCs. Utilizing the example outlined in the Spent Foundry Sand risk assessment conducted by USEPA (2009b), the concentrations in slag, which would correspond to a specific risk/hazard estimate, were calculated from a distribution of risks/hazards. The methods used in the PRA to calculate Tier III RBCs are presented in Appendix D.

Ultimately, the PRA approach generates probabilistically-based RBCs, hereafter referred to as Tier III RBCs. The 50th and 90th percentiles of the risk or hazard distribution are used to describe the MLE and RME estimates, respectively. A target risk level (TRL) of 10 in million (10^{-5}) and target hazard quotient (THQ) of 1 were used in the PRA calculations for consistency with the target risk and hazard used in the USEPA SFS risk assessment (USEPA 2009b). Tier III RBC calculations were carried out for all COIs in each slag type that had 95% UCL concentrations greater than the Tier II RBCs. These constituents of interest for probabilistic analysis (PCOIs) are hereafter referred to as PCOIs. The PCOIs are provided in Table 5.11.

6.1 Exposure Factor Distributions

Distributions were used in the PRA to represent exposure parameters. Some were determined empirically, and others were taken from the published literature and USEPA guidance documents. Distribution assumptions are discussed below.

6.1.1 Body Weight

Normal distributions were used to represent body weights (BWs) of adults and children. For adults, the mean was 79.96 kg and the standard deviation was 20.73. For children, the mean was 17.3 kg, and the standard deviation was 5.0. These estimates were based on data in the USEPA Exposure Factors Handbook (2009a) using data from NHANES IV, Table 8-25.

6.1.2 Exposure Duration

Exposure duration describes the number of years that exposure occurs (e.g., for a residential scenario, the number of years that an individual lives in their home). Exposure duration is a parameter that is only necessary for evaluation of cancer risk, because for non-cancer risk assessment, exposure duration is set equal to averaging time, and the terms cancel. Cr(VI) is the only carcinogen assessed in the PRA. Thus, for the purposes of this assessment, we assumed exposure duration to be equivalent to residential tenure. Exposure duration was represented by a lognormal distribution, parameterized by the median (9.0 years), mean (12 years) and 95th percentile (33 years), respectively. Data used to fit this distribution were taken from the USEPA Exposure Factors Handbook, Table 16-87 (USEPA 2009a). If the exposure duration was 6 years or less, then all years were dedicated to childhood exposure. Years beyond 6 were specified as adult exposure. This is conservative since the dose received as a child is greater than that received as an adult. This is also conservative for inclusion of the Age-Dependent Adjustment Factors (ADAFs) for a mutagenic mode of action since the highest weights (multipliers) are assigned to the youngest ages.

6.1.3 Exposure Frequency

Exposure frequency describes the number of days per year that an individual is expected to participate in an activity described by that exposure scenario. For example, the exposure frequency for workers is five days per week, a standard workweek. For residential scenarios, we assumed that the slag was outside, an individual needed to be home, and weather conditions appropriate for outdoor activities (e.g., no precipitation). It was assumed that exposure frequency for a child scenario would likely be equal to or greater than that for an adult. We considered the number of days that a child would be in school (approximately 180 days in the US), the number of days of precipitation, winter months with fewer hours of sunlight, and concluded that 200 days was a reasonable central tendency estimate for exposure frequency. An exposure frequency of 200 days per year is approximately equal to 4 days of contact per week, and likely overestimates central tendency in areas with inclement weather. We used 350 days per year as the upper-end estimate—which is the standard default value used for a residential exposure scenario and was used in the DRA—and 50 days as a minimum, suggestive that exposure might occur approximately once per week. Thus for this PRA, exposure frequency was specified as a triangular distribution with minimum of 50 days, maximum of 350 days and most likely value of 200 days.

6.1.4 Exposure Time

Exposure time (ET), describes the proportion of time that an individual might contact slag while being outside and was included in the PRA. In the USEPA Exposure Factors Handbook Table 16-1, we noted the number of hours per day for a child (age 6-11) to be outside was 107 minutes (USEPA 2009a). The number of hours spent in sand and gravel was 60 minutes. The proportion of time outside playing in sand and gravel is therefore 0.56. Using these data, a distribution of ET was specified as a triangular distribution with minimum (0%), maximum (100%), and most likely values (56%).

6.1.5 Soil ingestion Rate

Soil ingestion rate is described by central tendency and RME for adults (50-100 mg/day) in the Exposure Factors Handbook, Table 5-1 (USEPA 2009a). As such, a normal distribution was specified for adult ingestion rate using a mean and 95th percentile corresponding to MLE and RME estimates of ingestion. For children, soil ingestion rate was based on Finley et al. (1994), Table IX. Finley et al. developed a distribution of soil ingestion rates from the soil ingestion rate data of Calabrese et al. 1991. The Calabrese et al. studies provide the basis for the USEPA default point estimate value of soil ingestion at the RME of 200 mg/day. A custom distribution was specified using data from this publication according to Table 6.1. The 100th percentile represents a child with soil-pica, a condition in which a child ingests unusually high amounts of soil. As is evident from Table 6.1, the USEPA RME estimate for soil ingestion (200 mg/day) falls between the 95th and 100th percentile of soil ingestion rates described by Calabrese et al. (1991).

6.1.6 Inhalation Rate

Similar to soil ingestion rate, inhalation rate (Inh) is described by mean and 95th percentiles for both children (10-14 m^3/day) and adults (16-21 m^3/day) in the Exposure Factors Handbook, Table 6-1 (USEPA 2009a). As such, normal distributions were specified for child and adult Inh using mean and 95th percentile values.

6.1.7 Particulate Emission Factor

PEFs were calculated using unit emission rates modeled for eight specified distances of a receptor (e.g., a home) from the roadway (10 m, 20 m, 30 m, 40 m, 50 m, 100 m, 200 m, and 400 m), with four orientations of receptor to roadway (as discussed in Section 5.4). Meteorological data from six cities across the US were used in this model. The dispersion model is described in Appendix C. PEFs were calculated using two vehicle counts per day (VPD) values: 60 VPD (MLE), and 162 VPD (RME). Because PEF is in the denominator of the risk calculations, lower PEF values are conservative with regard to estimating exposure and calculating risk. To construct a distribution of PEF values for the PRA, the average PEF for each city was determined for each distance modeled, and for the two vehicle traffic frequencies (60 and 162 VPD). The maximum, minimum, and average PEFs were determined from these averages, and used to construct a triangular distributions of PEFs for each slag type. Because the modeling tends to emphasize short distances (five distances modeled in the first 50 m), the average PEF is a conservative estimate over the modeling domain (400 m), i.e., over represents distances closer to the road. The PEF distribution parameters are provided below in Table 6.2.

6.1.8 Oral Bioaccessibility Factor

B_{oral} values were determined for each slag type, each constituent measured. These values were based on measurements of constituent extraction under simulated GI conditions (See Section 5.5). These data were used to determine triangular distributions of B_{oral} for each slag type from the maximum, minimum, and average B_{oral} values. These data are presented for PCOIs Cr(VI), Mn and V in Table 6.3.

6.2 Probabilistic Risk Assessment Results

The PRA was run with 10,000 iterations to generate distributions of risk and hazard for each PCOI by slag type. These distributions were queried for the 50th and 90th percentile of risk and hazard. Results of the PRA are provided in Table 6.4.

Risk and hazard estimates developed using the unit constituent concentration (1 mg/kg) were then converted to soil concentrations using as described in Appendix D Equations D.16 and D.17. The resulting PCOI concentrations are presented below in Table 6.4.

PCOI concentrations in slag were compared to the 90th percentile RBCs developed from the PRA (Tier III RBCs) to determine whether concentrations in slag pose a potential risk or hazard for the scenarios assessed. Similar to the DRA, comparisons were made to concentrations in slag that is most reflective of the exposure pathway assessed. This comparison is provided in Table 6.5.

The 95%UCL concentrations of Cr(VI) and vanadium in EAF and BOF slags for all particle sizes were less than the Tier III RBCs at the 90th percentile, for all exposure scenarios indicating that these slag constituents do not pose a potentially significant cancer risk or non-cancer hazard. Similarly, for the residential roadway scenario, the 95%UCL concentration of manganese did not exceed the Tier III RBC at the 90th percentile, indicating that manganese in BOF and EAF slags used as cover for unpaved roads does not pose a significant hazard. For the residential driveway scenario, the 95% UCL concentrations of manganese in BOF and EAF PS samples exceed their respective Tier III RBCs. However, inhalation and ingestion exposure to metals in PS, which is less than 1 inch in diameter, is not realistic due to the large particle size. The 95% UCL of manganese in the <300 µm size fractions and the <75 µm size fractions of both EAF and BOF slags are lower than the Tier III RBCs. The <300 µm size fraction is most representative of particles that could adhere to skin and be incidentally ingested, and therefore, comparison of manganese concentrations in the <300 µm size fraction with the Tier III RBCs is most appropriate. As the 95%UCL concentrations of manganese in the <300 µm size fractions of EAF and BOF slag are less than the PRA/RBCs, concentrations of manganese in EAF and BOF slags do not pose a hazard for these residential exposure scenarios.

The PRA allows one to compare the 95% UCL manganese concentrations to the RBC distribution, and determine the corresponding percentile. The 95% UCL concentrations of manganese in EAF and BOF PS samples are the 77th and 88th percentiles of their respective Tier III RBC distributions (Table 6.6).

Table 6.1
Childhood Soil Ingestion Rates and Associated Probabilities

Ingestion Rate (mg/d)	Percentile
0	5
0	10
0	25
16	50
45	75
67	90
110	95
1,391	100

Definition
mg/d = milligram per day

Table 6.2
PEF Triangular Distribution Parameters

Slag Type	Minimum PEF (m^3/kg)	Maximum PEF (m^3/kg)	Average PEF (m^3/kg)
EAF	1.6E+8	1.3E+9	7.0E+9
BOF	1.3E+8	1.1E+9	5.7E+9

Definitions
BOF = basic oxygen furnace, EAF = electric arc furnace, m^3/kg = cubic meter per kilogram, PEF = particulate emission factor

Table 6.3
B_{oral} Distribution Parameters for EAF and BOF[a]

PCOI	Minimum (as decimal percent)	Average (as decimal percent)	Maximum (as decimal percent)
EAF Slag			
Chromium	0.02	0.18	1.0
Manganese	0.03	0.27	0.50
Vanadium	0.09	0.59	0.83
BOF Slag			
Chromium	0.05	0.064	0.23
Manganese	0.14	0.16	0.59
Vanadium	0.44	0.12	0.74

Note

a Values expressed as decimal percent.

Definitions

BOF = basic oxygen furnace, B_{oral} = oral bioaccessibility factor, EAF = electric arc furnace, PCOI = constituent of interest for probabilistic analysis

Table 6.4
Results of the PRA, 50th and 90th Percentile Tier III RBCs

Risk/Hazard	Constituent	Slag Type	Percentiles	Tier III RBC (mg/kg)
Residential Driveway Scenario				
Hazard	Cr(VI)	BOF	50%	55,014
			90%	12,667
Risk	Cr(VI)	BOF	50%	731
			90%	153
Hazard	Manganese	BOF	50%	51,049
			90%	23,171
Hazard	Vanadium	BOF	50%	29,071
			90%	5,137
Hazard	Cr(VI)	EAF	50%	31,215
			90%	4,246
Risk	Cr(VI)	EAF	50%	316
			90%	50
Hazard	Manganese	EAF	50%	52,526
			90%	24,588
Hazard	Vanadium	EAF	50%	33,509
			90%	5,642
Residential Roadside Scenario				
Hazard	Manganese	BOF	50%	93,614
	(inhalation only)		90%	31,056
Hazard	Manganese	EAF	50%	115,491
	(inhalation only)		90%	38,725

Definitions
BOF = basic oxygen furnace, Cr(VI) = hexavalent chromium, EAF = electric arc furnace, mg/kg = milligram per kilogram, PCOI = constituent of interest for probabilistic analysis, PRA = probabilistic risk assessment

Table 6.5
Comparison of 90th percentile Tier III RBCs to 95% UCL Slag Constituent Concentrations

Risk/ Hazard	Constituent	Slag Type	90th percentile Tier III RBC (mg/kg)	95% UCL in Slag (mg/kg)	Particle Size Used for Comparison	Does 95% UCL Exceed Tier III RBC?
Residential Driveway						
Risk	Chromium (VI)	BOF	153	2.5	PS	No
Hazard	Manganese	BOF	23,171	21,882	<300 µm[a]	No
Hazard	Manganese	BOF	23,171	25,252	PS	Yes
Hazard	Vanadium	BOF	5,137	865	PS	No
Risk	Chromium (VI)	EAF	50	5.1	PS	No
Hazard	Manganese	EAF	24,588	23,300	<300 µm[a]	No
Hazard	Manganese	EAF	24,588	34,464	PS	Yes
Hazard	Vanadium	EAF	5,642	686	PS	No
Residential Roadside						
Hazard	Manganese	BOF	31,056	20,520	<75 µm[b]	No
Hazard	Manganese	EAF	38,725	20,018	<75 µm[b]	No

Notes

a Manganese concentrations in <300 µm are greater than the concentrations in <75 µm size samples, thus neither size fraction exceeds the Tier III RBC.

b The smallest size fraction characterized for this HHRA is used for the residential roadside scenario comparisons, as this scenario only evaluates inhalation exposure. 95% UCL concentrations of manganese in PS samples are also less than PRA RBCs.

Definitions

BF = blast furnace, BOF = basic oxygen furnace. chromium (VI) = hexavalent chromium, EAF = electric arc furnace, HHRA = human health risk assessment, mg/kg = milligram per kilogram, PRA = probabilistic risk assessment, PS = processed slag, RBC = risk-based concentration, UCL = upper confidence limit, µm = micrometer

Table 6.6
Comparison of 95% UCL Concentrations of Mn in Processed EAF and BOF Slag to the PRA RBC Distributions

Risk/Hazard	Constituent	Slag Type	95% UCL in PS (mg/kg)	Percentile of the PRA Distribution
Residential Driveway				
Hazard	Manganese	BOF	25,252	88
Hazard	Manganese	EAF	34,464	77

Definitions
BOF = basic oxygen furnace, EAF = electric arc furnace, mg/kg = milligram per kilogram, Mn = manganese, PRA = probabilistic risk assessment, PS = processed slag, RBC = risk-based concentration, UCL = upper confidence limit

7.0 Risk Characterization and Uncertainty Analysis

Risk characterization combines the results of the exposure and toxicity assessments to ascertain the potential health effects resulting from COI exposures in iron- and steel-making slag. For this HHRA, the risk characterization consists of comparing the RBCs to the 95% UCL and mean concentrations of COIs in slag by slag type and particle size.

As discussed in Sections 5 and 6, for both the DRA and PRA, non-cancer hazards are characterized by comparing the concentrations of COIs in slag to RBC concentrations derived to achieve non-cancer toxicity criteria (i.e., RfDs and RfCs), summed by all relevant exposure pathways. For both the DRA and PRA, RBCs protective of increased cancer risk are estimated in accordance with values that may trigger regulatory concern for environmental exposures. For the DRA, the RBCs were set at the lower bound of the acceptable risk range to achieve a one-in-a-million (10^{-6}) increased cancer risk, and in the PRA, the RBCs were set to achieve the mid-point of the acceptable risk range, or a ten-in-a-million (10^{-5}) increased cancer risk. This approach is consistent with the approach used in the recent USEPA Spent Foundry Sand risk assessment (USEPA 2009b), and is consistent with the USEPA target acceptable risk range of 10^{-4} to 10^{-6} (USEPA 1989a; 1991).

7.1 Comparison of the RBCs to Concentrations of COIs in Slag

Comparisons of the RBCs developed in the DRA and PRA to COI concentrations are provided below.

7.1.1 Deterministic Risk Assessment (DRA)

The Tier II RBCs were calculated using standard, default exposure parameters for both RME and MLE scenarios, and included slag-specific criteria where available. The purpose of the DRA was to provide a conservative screen of COIs to eliminate COIs from the PRA which did not pose a potential health risk, so that the PRA could focus on those COIs and scenarios which may pose a potential human health risk or hazard.

COIs with 95% UCL concentrations exceeding the Tier II RBCs for the RME are Cr(VI), manganese, and vanadium for the residential driveway receptor for both BOF and EAF slag. Manganese in EAF and BOF slags was the only COI exceeding the Tier II RBCs for the residential roadside scenario. The residential driveway scenario was the most sensitive (had the lowest RBCs). The Cr(VI) RME Tier II RBC for the residential driveway scenario was 5.2-fold higher than the 95% UCL for EAF slag. The manganese RME Tier II RBC for the residential driveway scenario was 3.6-fold higher than the 95% UCL for manganese in EAF slag. The vanadium RME Tier II RBC for the residential driveway scenario was 1.2-fold higher than the 95% UCL for vanadium in EAF slag. The 95%UCL concentration of iron did not exceed any Tier II RBCs. Concentrations of COIs in BF slag did not exceed the Tier II RBCs, and BF slag was not evaluated in the PRA.

For the industrial and maintenance worker and construction worker scenarios, all COIs and pathways had 95% UCL concentrations below the RME Tier II RBCs. Therefore, no COIs were carried into the PRA for the two worker scenarios, and the worker scenarios were not evaluated in the PRA.

7.1.2 Probabilistic Risk Assessment (PRA)

Tier III RBCs were calculated using a TRL of 10^{-5} and a HQ of 1.0. Similar to the approach taken in the USEPA's SFS risk assessment (2009b), risk or hazard percentiles determined using the slag-specific PRA were located on the respective distributions (the median and 90th percentile, Table 6.4), and the slag concentrations corresponding directly to the percentile of risks or hazards were back-calculated using a ratio. The PRA is inherently more refined and less uncertain than the DRA as distributions describing the full data set of available information are combined to construct a distribution of risk or hazard, rather than relying on compounding conservative assumptions as in the DRA.

Only the 95%UCL concentrations of manganese in EAF and BOF PS slag samples exceeded the 90th percentile of the Tier III RBC distributions for the residential driveway scenarios (Table 6.5). All other 95%UCL concentrations were below their respective RBCs. However, the 95% UCL concentrations of the more environmentally-relevant fraction size (<300 μm) for ingestion exposures, and the smallest size fraction (<75 μm), which is most representative of the fraction that could be inhaled, are below the 90th percentile Tier III RBCs for manganese in both BOF and EAF slag. For the residential driveway receptor, as shown in Table 6.6, percentile values of the PRA distribution for the respective manganese 95% UCL values are the 88th percentile for PS BOF slag, and the 77th percentile for PS EAF slag. Percentile values of the PRA distribution for the manganese 95% UCL values are the 91st percentile for <300 μm BOF slag, and the 92nd percentile for <300 μm EAF slag. Therefore, manganese is the only constituent with 95% UCL concentrations exceeding the Tier III RBC; and it occurs only for the residential driveway scenario and only for the PS size fraction. However, for the more relevant size fraction for human exposures, <300 μm and <75 μm, the 95% UCL manganese concentrations are below the respective Tier III RBCs at the 90th percentile. Overall, these findings indicate that environmental applications of steel-making slag for residential driveway scenarios are not expected to pose a meaningful human health risk from direct contact exposure.

The difference between the Tier II RME RBCs and the Tier III 90th percentile RBCs ranged from 10% (1.1-fold change) to 120% (12-fold change)—taking into account the different target risk levels used in the DRA and PRA for Cr(VI)—with the Tier III RBCs being higher in all cases (Table 7.1).

As noted above, the target theoretical increased cancer risk for the PRA was 10^{-5} and that for the DRA was 10^{-6}. Cr(VI) is not commonly measured in steel-making slag and was only measured in 23% of EAF samples and 17% of BOF samples, and at low concentrations, with a maximum and mean concentrations of 14.2 mg/kg and 1.9 mg/kg in EAF and 2.5 mg/kg and 0.83 mg/kg in BOF, respectively. Total Cr occurs at relatively low concentrations in BF slag, and Cr(VI) was not measured in any of the BF slag samples. For BOF slag, the difference between the 95%UCL concentration of Cr(VI) in slag and the residential driveway PRA RBC is 61-fold, indicating that the theoretical risk associated with Cr(VI) exposure is approximately 2×10^{-8}, and well below the acceptable risk range of 10^{-4} to 10^{-6}. For EAF slag, the difference between the 95%UCL concentration of Cr(VI) in slag and the residential driveway PRA RBC is 9.8-fold, indicating that the theoretical risk associated with Cr(VI) exposure is approximately 1×10^{-6}, which is consistent with the lower bound of the acceptable risk range. Thus, had a 1×10^{-6} target cancer risk been used to calculate the Tier III RBCs, the concentrations of Cr(VI) in both EAF and BOF slags would not have exceeded the RBCs.

7.2 Qualitative Uncertainty Analysis

Although this HHRA included many refinements and slag-application-specific data in order to reduce uncertainty, several sources of uncertainty still exist in the HHRA. Each parameter and assumption in the assessment introduces uncertainty into the quantitative risk and hazard estimates and resulting RBCs. In an effort to ensure that the conclusions of this HHRA have broad application for uses of iron- and steel-making slag and are sufficiently conservative, toxicity factors, assumptions, and exposure parameters were selected to overestimate, rather than underestimate, potential human exposures. Therefore, issues identified in this evaluation considering potential human exposures to slag applications generally reflect theoretical, upper-bound exposures. In addition, this HHRA is for expected environmental applications of iron- and steel-making slag, but do not include any information about the actual sites of application. Site-specific information could be used to further refine the exposure estimates to better depict the particular exposure scenarios for site-specific risk estimates.

7.2.1 Slag/Soil Characteristics

One uncertainty of this HHRA is that slag possesses characteristics similar to those of soil, and that exposure rates for slag and soil are similar. As examples, soil ingestion rates were used to represent slag ingestion rates, and particulate emissions/dispersion modeling was performed with models developed to evaluate soil particles. These assumptions are expected to overestimate exposure, as slag particles are generally larger and less likely to be incidentally ingested than soil.

Further, slag is cementitious and conglomerates and hardens with time in non-arid conditions.

The current HHRA uses new slag characterization data from three size fractions—PS (the primary commercial product), and two smaller particle sizes that have greater relevance for human exposures. These size fractions were collected by sieving PS slag samples, rather than by crushing it, such that the smaller size fractions are consistent with the smaller size fractions that may exist in the environment in association with a slag application.

The <75 µm size fraction was the smallest size fraction evaluated and used for comparisons with inhalation-based RBCs. The respirable fraction of particulate matter is <10 µm. The concentrations of manganese in this small size fraction of slag is not known; however, EAF and BOF slag demonstrate a trend of decreasing manganese concentrations with decreasing particle size (Figure 2.1). Thus, it is likely that manganese levels in respirable particles of slag would be lower than that in the <75 µm size fraction.

The current HHRA also uses a more robust data set for characterizing oral bioaccessibility including measures of bioaccessibility of all metals, with the exception of Cr(VI) in all samples from the < 300 µm size fraction. Cr(VI) was only characterized for PS slag samples because total chromium concentrations were highest in the PS size fraction.

7.2.2 Exposure Assessment

The exposure assessment quantifies a range of exposures, including the estimated average and upper-bound of exposures. Specific uncertainties are inherent in human exposure assessment for both scenarios. The manner in which several of these uncertainties are addressed in this HHRA are summarized below.

In the PRA, variability and uncertainty in the risk assessment parameters and models are quantified using probability distributions. The PRA includes distributions of information for each exposure parameter, which allows for characterization of uncertainty and variability based on all available information, and the results of the PRA are more certain than that of the DRA.

For all four exposure scenarios, even though slag becomes mixed with native soil and other materials over time, 100% of the soil was still assumed to be slag, with 100% of particulate emissions conservatively assumed to be derived from slag. Further, most road construction projects involve several steps, and incidental ingestion of slag may be anticipated only while workers are in contact with slag. However, the HHRA assumed that all road construction worker time involved contact with slag.

Exposure time (ET) for residents was conservatively assumed to be 100% in the DRA, which assumes that a child or adult resident is contacting slag for 350 days/year, and that exposures to slag replace exposures to soil. For the PRA, ET was assumed to be average hours per day spent in contact with sand and gravel. It was assumed that time spent in contact with sand or gravel was representative of time spent in contact with slag. This is a conservative assumption because slag is vitreous and cementitious and does not offer a desirable substrate for prolonged or frequent contact.

For construction worker inhalation exposure to slag, several conservative modeling assumptions were made, including: 1) workers are adjacent to the area where slag is applied and are always downwind, 2) no dust suppression measures are used, and 3) the daily road base area constructed is assumed to be 0.76 mile of 8-ft-wide road base applied per day. Based on professional judgment, this level of road base activity is likely an upper-bound overestimating activities for most construction projects, and 4) use of the box model is considered a conservative approach, as emissions are assumed to disperse only within the box and deposition within the box is not considered.

The USEPA preferred AERMOD air dispersion model was used for the residential roadside inhalation exposure pathway, replacing the previous evaluation using the older Industrial Source Complex (ISC) model, and new parameters from USEPA's 2009 Exposure Factors Handbook (USEPA 2009a) were incorporated. Use of the updated model should reduce uncertainty as compared to the approaches used in the earlier assessments.

For the residential roadside scenario, we estimated the level of traffic on an unpaved slag roadway. An unpaved roadway is not expected to support significant traffic. Based on data collected by state departments of transportation, the traffic assumptions are 162 and 60 vehicles per day for RME and MLE, respectively. Although, traffic on a given day might be greater or less than these values, these values were considered reasonable estimates for residential exposures. Further, no correction factors were included to differentiate indoor from outdoor exposures, essentially assuming indoor exposures to dust generated from a roadway are equal to the indoors.

7.2.3 Toxicity Criteria

Much of the conservatism in this HHRA, as in most, results from the inherent conservatism in the toxicity criteria. These criteria are specifically designed to be protective of sensitive human subpopulations and account for uncertainties through use of safety (or uncertainty and modifying) factors and conservative model extrapolation approaches. Therefore, the toxicity factors used in this risk assessment likely exaggerate potential risks and hazards due to COIs in slag. For example, with respect to the manganese RfD, EPA recommends an additional modifying factor for assessing potential hazards due to manganese in soil or groundwater, which was included in this evaluation. This additional factor is frequently deemed unnecessary, particularly for a type of material such as slag, because (1) manganese in slag is not anticipated to affect groundwater or drinking water due to its poor solubility, and (2) USEPA's rationale for this additional factor involves drinking-water exposures and exposures to neonates, which is also considered unlikely for slag. Had the additional modifying factor not been included in the derivation of manganese RBCs, all of the oral RBCs for manganese would be 3-times higher than that developed here.

The inhalation contribution to the manganese PRA RBC for the residential driveway scenario is approximately 3-fold higher than that for the oral exposure pathway (e.g., most of the hazard is associated with inhalation exposure to manganese). It is important to consider that the RBCs for manganese for inhalation exposure are based on the very conservative RfC for manganese. The IRIS RfC for manganese, which is used in this HHRA for assessment of the inhalation pathway, is based on early studies of battery manufacturing workers (USEPA 2010a). Recent evaluations of effects in these workers suggest that the manganese RfC could be increased by a factor of approximately 40-fold and still be sufficiently protective of adverse effects resulting from environmental exposures (Bailey et al. 2009). Further, although it is based on a human (occupational) study, the IRIS manganese RfC employs a large uncertainty factor (UF) of 1,000. This factor includes an UF of 10 for use of a LOAEL, 10 for sensitive subpopulations, and 10 for database limitations, included due to a lack of developmental data, less-than-chronic exposure periods for the worker population, and potential quantified differences in the toxicity resulting from exposure to the different forms of manganese. A subsequent reanalysis of the RfC by EPA determined that appropriate RfC values ranged from 0.09 - 0.2 μg/m^3, but the agency declined to update the IRIS database at that time. [59 Fed. Reg. 42,227, 42,242-42,245]. In December 2008, California adopted a revised chronic Reference Exposure Level ("REL") for manganese of 0.09 μg/m^3 under its air toxics hot spots program, which incorporates extra uncertainty factors to account for potential differential effects on the health of infants, children, and other sensitive subpopulations. The World Health Organization adopted an RfC for manganese of 0.15 μg/m^3 in 1999. Most recently, PBPK modeling developed under the auspices of the EPA Office of Research and Development demonstrates that the human body effectively processes manganese (both inhaled and ingested) at levels that are perhaps two to three orders of magnitude higher than the existing manganese RfC (Boyes, 2011). Accordingly, due to the use of highly conservative oral and inhalation toxicity criteria, the RBCs derived in this HHRA for manganese by inhalation, or for inhalation and oral exposure combined, are thought to be especially conservative.

As discussed in Section 4, the approach used for assessing risk from Cr(VI) is based on an external review draft of the USEPA Toxicological Review for Cr(VI) which was released September 30, 2010 (USEPA 2010c). As an external review draft, the values and approach for assessing Cr(VI) as a mutagen are more uncertain than for most constituents, because this position is not finalized and evidence supports a non-mutagenic MOA (Thompson et al. 2010). Although a risk assessment for Cr(VI) that is based on the information currently posted in IRIS would result in a much higher RBC (e.g., an EPA RSL for residential exposure of 230 mg/kg as compared to a Tier III RBC of 5 mg/kg), the USEPA draft assessment was used in order to ensure that this HHRA was consistent with the most current information and adequately conservative.

7.2.4 Risk Characterization

The risk characterization aspect of the HHRA is a result of combining the toxicity and exposure assessments. Therefore, the sources of conservatism inherent in multiple aspects of each stage are compounded in the risk characterization.

7.3 Quantitative Uncertainty Analysis (based on PRA)

As discussed above, there are multiple sources of uncertainty in the iron- and steel-making slag HHRA, as there are in any HHRA. By performing a PRA in addition to a DRA, and using slag-specific information to construct exposure scenarios, we aimed to reduce uncertainty and avoid some of the unnecessary overestimation of risks and hazards that is inherent in any risk assessment that follow USEPA guidance.

Table 7.1 below compares the DRA RBCs, generated using primarily conservative, single-value defaults, to the respective PRA RBCs, which were generated using distributions of several exposure and constituent parameters. It should be noted that B_{oral} values were included in both the PRA and DRA, and both rely on slag-specific information to inform the exposure assessment. The fold difference between Tier II and Tier III RBCs for Cr(VI) are divided by 10 because the PRA and DRA used a 10-fold different target risk level. Thus, in order to provide a true comparison of variability between DRA and PRA results, the fold differences for Cr(VI) were corrected.

As shown in Table 7.1, the Tier III RBCs range from 1.1- to 12-times higher than the Tier II RBCs. The values are most similar for the residential roadside scenario because it is based on inhalation exposure only, and the Tier II RBC is not impacted with the additional uncertainty and conservatism associated with quantifying exposure by the ingestion pathway. Also, for the roadside scenario in the DRA, a distance of 50 m from the road to the residence was selected, but for the PRA, distances between the road and the resident of 10, 20, 30, 40, 50, 100, 200, and 400 m were all considered in the PEF distribution.

Table 7.2 provides a comparison of the 95% UCL concentrations of PCOIs in PS to the PRA RBC distributions. 95%UCL concentrations of PCOIs in PS range from the 77th to >99th percentile of the RBC distributions, demonstrating that the upper-bound of concentrations of PCOIs in PS samples falls at the upper range of the RBC distribution.

Table 7.1
Comparison of Tier II RME and Tier 90th percentile Tier III RBCs

Risk/Hazard	Constituent	Slag Type	Tier II RBC (mg/kg)	Tier III RBC (mg/kg)	Fold Difference Between PRA RBC and DRA RBC
Residential Driveway					
Risk	Chromium (VI)	BOF	1.7	153	9[1]
Hazard	Manganese	BOF	1,949	23,171	12
Hazard	Vanadium	BOF	594	5,137	8.6
Risk	Chromium (VI)	EAF	1.0	50	5[1]
Hazard	Manganese	EAF	9,604	24,588	2.6
Hazard	Vanadium	EAF	589	5,642	9.6
Residential Roadside					
Hazard	Manganese	BOF	29,150	31,056	1.1
Hazard	Manganese	EAF	17,951	38,725	2.2

[1] The fold difference for Cr(VI) between the DRA RBCs and PRA RBCs was corrected in this table for the 10-fold difference in target risk values used in the assessments to provide a true measure of variability between the results of the PRA and DRA.

Definitions
BF = blast furnace, BOF = basic oxygen furnace. chromium (VI) = hexavalent chromium, DRA = deterministic risk assessment, EAF = electric arc furnace, HHRA = human health risk assessment, mg/kg = milligram per kilogram, PRA = probabilistic risk assessment, RBC = risk-based concentration

Table 7.2
Comparison of 95% UCL Concentrations of COIs in Processed EAF and BOF Slag to the PRA RBC Distributions

Risk/Hazard	Constituent	Slag Type	95% UCL in PS (mg/kg)	Percentile of the PRA Distribution
Residential Driveway				
Risk	Chromium (VI)	BOF	2.5	>99
Hazard	Manganese	BOF	25,252	88
Hazard	Vanadium	BOF	865	97
Risk	Chromium (VI)	EAF	5.1	>99
Hazard	Manganese	EAF	34,460	77
Hazard	Vanadium	EAF	686	98
Risk/Hazard	**Constituent**	**Slag Type**	**95% UCL in**	**Percentile of the PRA**

			<75 µm (mg/kg)	Distribution
Residential Roadside				
Hazard	Manganese	BOF	20,520	95
Hazard	Manganese	EAF	20,018	97

Definitions

BOF = basic oxygen furnace, EAF = electric arc furnace, mg/kg = milligram per kilogram, Mn = manganese, PCOI = constituent of interest for probabilistic analysis, PRA = probabilistic risk assessment, PS = processed slag, RBC = risk-based concentration, UCL = upper confidence limit

8.0 Conclusions

This slag HHRA consists of hazard identification screening followed by extensive deterministic and probabilistic risk assessments conducted in a step-wise fashion to ensure conservative estimates of human health risks and hazards for two residential and two worker scenarios. These scenarios include residential driveway, residential roadside, industrial and maintenance worker, and construction worker receptors, and were selected for assessment based on prior risk assessments that identified these scenarios as those with the highest potential for direct contact human exposure based on the known environmental applications of iron- and steel-making slags. Twenty-six metals were analyzed in three different types of slag (EAF, BOF, BF) and three different particle sizes, and slag samples of <300 μm were analyzed for bioaccessibility. The risk assessment followed USEPA guidance and was conducted in a manner consistent with the USEPA Spent Foundry Sand risk assessment (USEPA 2009b).

After a screening procedure consisting of comparisons to US background concentrations and USEPA regional screening levels (RSL) (2010b), four constituents were identified as COIs and evaluated in the DRA: Cr(VI), iron, manganese, and vanadium for various receptor and slag types (see Table 3.6). In the DRA, RBCs were calculated for the COIs and compared to 95% UCL concentrations measured in slag. COIs with 95% UCL concentrations exceeding the RME Tier II RBCs were identified as COIs for the PRA (PCOIs) and evaluated using a probabilistic assessment. These include Cr(VI), manganese, and vanadium for the residential driveway receptor for both EAF and BOF slags. Manganese in both EAF and BOF slags was the only COI exceeding the Tier II RBCs for the residential roadside receptor. No COIs exceeded the Tier II RBCs for the industrial and maintenance worker or construction worker scenarios, therefore the worker scenarios were not evaluated in the PRA.

Only the 95%UCL concentrations of manganese in EAF and BOF PS slag samples exceeded the 90th percentile of the Tier III RBC distributions for the residential driveway scenarios. All other 95%UCL concentrations were below their respective Tier III RBCs. However, inhalation and incidental ingestion exposure to metals in PS, which is less than on inch in diameter, is not realistic due to the large particle size. Manganese concentrates in the larger particle sizes of slag. The 95% UCL concentrations of the more biologically relevant size fraction (<300 μm), which is more representative of the fraction that could be incidentally ingested, and the smallest size fraction (<75 μm), which is most representative of the fraction that could be inhaled, are below the Tier III RBCs for manganese in both BOF and EAF slags.

Therefore, after the generally standard DRA followed by a more robust but still conservative PRA, measured concentrations in slag are not considered to be of concern for human exposures by direct contact. This updated, thorough analysis demonstrates similar conclusions to the previous assessment that the environmental applications of iron- and steel-making slag are not considered to pose a hazard to human health.

9.0 References

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Appendix A

Results of 2008/2009 Slag Characterization Project

A.1 Metal concentrations (mg/kg) in processed slag (PS)

	Total Aluminum	Total Antimony	Total Arsenic	Total Barium	Total Beryllium	Total Cadmium	Total Calcium	Total Chromium	Hexavalent Chromium
Electric Arc Furnace (EAF) Slag									
830005*	16,000	0.5	2.2	640	1	0.27	140,000	4,300	--
830005* duplicate	34,000	< 0.3	1.5	54	< 0.2	0.1	250,000	1,700	--
~~830006*~~[1]	~~27,000~~	~~0.6~~	~~2.9~~	~~780~~	~~0.7~~	~~0.3~~	~~210,000~~	~~3,000~~	--
830006* resample 830104	32,000	0.33	2.4	890	0.54	0.17	230,000	2,600	--
830006* resample 830120	29,000	< 0.3	2	890	0.67	0.23	220,000	2,400	--
830006* resample 830121	36,000	0.34	1.7	1,100	0.72	0.25	260,000	2,600	--
830007*	36,000	0.5	2.1	240	1.5	0.17	160,000	2,000	--
830008*	20,000	2	8.5	180	1	2.3	170,000	2,900	--
830011*	16,000	< 0.3	4	87	< 0.2	0.12	230,000	2,900	--
839235/839236	21,000	0.85	4	1,000	4	0.97	200,000	1,500	--
839235/839236 duplicate	17,000	0.81	3.1	850	3.2	0.84	160,000	1,200	< 1
839237	49,000	2.1	7.5	480	0.91	0.71	210,000	3,100	--
839237 duplicate	40,000	1.8	6.5	410	0.78	0.56	180,000	2,600	< 1
839317	24,000	0.59	3.6	280	1.4	0.37	160,000	3,900	--
839317 duplicate	25,000	0.68	3.9	280	1.4	0.36	160,000	4,100	14.2
839318	23,000	1.3	4.5	420	0.71	1.3	260,000	3,300	--
839318 duplicate	20,000	1.2	3.6	370	0.62	1.1	220,000	2,700	2.9
839319	50,000	1.4	4.3	260	1.2	0.67	220,000	2,900	--
839319 duplicate	46,000	1.4	4.2	240	1	0.54	200,000	2,700	< 1
839320	29,000	0.19	3	380	0.66	0.34	210,000	4,500	--
839320 duplicate	25,000	0.18	2.4	310	0.56	0.3	180,000	3,900	5.7
839607	21,000	1.6	5.8	810	0.87	0.68	200,000	3,900	--
839607 duplicate	18,000	1.7	4.8	710	0.74	0.6	170,000	3,300	< 1
839191	40,000	0.53	3.7	340	1.5	0.47	200,000	3,100	--
839191 duplicate	36,000	0.55	3.5	310	1.4	0.52	180,000	2,900	< 1
839192	24,000	1.7	6.2	480	1.2	1.1	260,000	5,600	--
839192 duplicate	21,000	1.7	5.1	420	1	0.95	230,000	4,900	3.1
839193	37,000	2	6.5	410	1.7	0.37	170,000	2,300	--
839193 duplicate	35,000	2	5.9	370	1.5	0.3	170,000	2,200	< 1
839348	26,000	1.4	3.9	680	0.78	0.72	220,000	5,400	--
839348 duplicate	19,000	1.3	2.9	510	0.61	0.55	160,000	4,100	< 1

A.1 Metal concentrations (mg/kg) in processed slag (PS)

	Total Cobalt	Total Copper	Total Iron	Total Lead	Total Magnesium	Total Manganese	Total Mercury	Total Molybdenum	Total Nickel
Electric Arc Furnace (EAF) Slag									
830005*	9.7	250	270,000	10	50,000	37,000	< 0.05	41	51
830005* duplicate	5	22	200,000	3	54,000	25,000	< 0.05	8.6	8
~~830006*~~[1]	~~8~~	~~160~~	~~140,000~~	~~180~~	~~66,000~~	~~35,000~~	< 0.05	~~15~~	~~46~~
830006* resample 830104	7.4	140	140,000	21	62,000	33,000	< 0.05	13	24
830006* resample 830120	9.1	130	130,000	25	62,000	33,000	< 0.05	12	25
830006* resample 830121	10	130	140,000	14	64,000	39,000	< 0.05	12	18
830007*	4	39	170,000	1	41,000	14,000	< 0.05	5.5	9
830008*	18	130	170,000	90	52,000	20,000	0.069	270	230
830011*	6	53	290,000	2	60,000	33,000	< 0.05	9.2	20
839235/839236	13	180	150,000	6.6	52,000	51,000	< 0.01	30	63
839235/839236 duplicate	11	150	120,000	5.7	41,000	40,000	< 0.01	25	52
839237	9.6	190	190,000	8.4	55,000	36,000	< 0.01	88	76
839237 duplicate	8.1	160	160,000	7.2	46,000	30,000	< 0.01	74	63
839317	16	88	250,000	0.66	53,000	31,000	< 0.01	19	24
839317 duplicate	16	91	260,000	0.51	56,000	32,000	< 0.01	19	24
839318	10	170	190,000	7.8	45,000	33,000	< 0.01	39	33
839318 duplicate	8.6	160	160,000	7	39,000	28,000	< 0.01	35	29
839319	9.8	63	230,000	6.8	49,000	22,000	< 0.01	22	18
839319 duplicate	9.1	58	210,000	6.7	46,000	20,000	< 0.01	21	16
839320	10	72	300,000	0.32	72,000	42,000	< 0.01	21	11
839320 duplicate	8.7	63	260,000	0.29	62,000	36,000	< 0.01	18	9.2
839607	11	260	270,000	2.1	46,000	42,000	< 0.01	34	72
839607 duplicate	8.9	230	220,000	1.9	38,000	35,000	< 0.01	30	62
839191	13	62	210,000	7.1	65,000	27,000	< 0.01	19	41
839191 duplicate	12	57	190,000	6.5	59,000	25,000	< 0.01	18	38
839192	10	130	180,000	12	40,000	36,000	< 0.01	70	29
839192 duplicate	9	120	160,000	11	35,000	32,000	< 0.01	62	25
839193	15	100	190,000	4.6	62,000	17,000	< 0.01	14	34
839193 duplicate	14	100	180,000	4.5	58,000	16,000	< 0.01	13	33
839348	13	190	240,000	4.4	51,000	50,000	< 0.01	61	48
839348 duplicate	9.6	140	180,000	3.5	38,000	37,000	< 0.01	46	36

A.1 Metal concentrations (mg/kg) in processed slag (PS)

	Total Phosphorus	Total Selenium	Total Silicon	Total Silver	Total Thallium	Total Tin	Total Vanadium	Total Zinc
Electric Arc Furnace (EAF) Slag								
830005*	1,800	1.2	1,900	0.5	< 0.5	10	470	120
830005* duplicate	3,800	0.5	2,000	0.1	< 0.5	< 5	730	200
~~830006*~~[1]	~~2,000~~	~~0.7~~	~~2,200~~	~~0.5~~	< 0.5	< 5	~~1,300~~	~~88~~
830006* resample 830104	2,100	0.79	940	0.38	< 0.5	5.4	630	53
830006* resample 830120	2,200	0.72	1,000	0.44	< 0.5	< 5	600	56
830006* resample 830121	2,400	0.89	1,300	0.45	< 0.5	< 5	690	43
830007*	2,800	1.1	1,500	0.5	< 0.5	< 5	240	31
830008*	1,700	1.6	1,900	2.4	< 0.5	6.2	390	730
830011*	4,100	0.4	1,600	0.2	< 0.5	< 5	1,300	76
839235/839236	1,500	2.2	1,200	1.6	0.054	5	740	100
839235/839236 duplicate	1,500	1.9	1,200	1.3	0.041	4.5	610	86
839237	1,700	2.3	2,400	0.54	< 0.02	2.7	770	110
839237 duplicate	1,600	1.9	1,700	0.5	0.048	5	640	98
839317	2,100	0.79	850	0.38	< 0.02	2.7	460	67
839317 duplicate	2,300	0.85	1,000	0.44	< 0.02	< 2.5	480	70
839318	1,800	5.6	1,200	1.6	< 0.02	3.5	760	94
839318 duplicate	1,800	5.1	1,000	< 0.01	< 0.02	4.4	640	83
839319	2,400	0.77	450	0.78	< 0.02	8.9	830	120
839319 duplicate	2,200	0.74	4,600	0.56	< 0.02	3.2	770	120
839320	3,900	0.72	1,400	0.27	< 0.02	< 2.5	660	66
839320 duplicate	3,800	0.56	1,200	0.27	< 0.02	< 2.5	580	59
839607	2,000	0.64	1,200	0.96	0.3	15	860	88
839607 duplicate	1,900	0.57	1,600	0.85	0.3	14	730	78
839191	2,800	1.6	1,700	0.56	0.35	< 2.5	450	320
839191 duplicate	2,800	1.3	1,600	0.49	0.36	< 2.5	410	310
839192	2,200	1.3	2,200	1.1	0.33	4.1	670	160
839192 duplicate	2,300	1	1,300	0.92	0.33	3.7	590	150
839193	1,700	0.77	2,000	0.4	0.32	3.2	560	100
839193 duplicate	1,700	0.55	3,400	0.38	0.33	3.9	540	100
839348	2,100	0.63	830	0.79	< 0.02	5.7	930	100
839348 duplicate	2,000	0.48	750	0.62	< 0.02	2.5	700	83

A.1 Metal concentrations (mg/kg) in processed slag (PS)

	Total Aluminum	Total Antimony	Total Arsenic	Total Barium	Total Beryllium	Total Cadmium	Total Calcium	Total Chromium	Hexavalent Chromium
Electric Arc Furnace (EAF) Slag									
839210/839211	29,000	1.7	8.5	990	0.67	1.8	290,000	5,000	--
839210/839211 duplicate	27,000	1.7	7.2	900	0.63	1.6	270,000	4,600	< 1
839212	15,000	2.2	8	200	0.52	0.6	230,000	4,400	--
839212 duplicate	15,000	1.9	6.3	200	0.49	0.6	230,000	4,500	< 1
839224	18,000	1.7	6.6	980	2.5	1.6	190,000	2,200	--
839224 duplicate	12,000	1.3	4.1	620	1.7	1	130,000	1,400	< 1
839225	20,000	1.7	4.9	650	0.96	6.1	230,000	2,200	--
839225 duplicate	17,000	1.6	3.8	550	0.85	4.7	200,000	1,900	< 1
839226	54,000	1.6	5.1	270	1.1	0.63	240,000	2,600	--
839226 duplicate	46,000	1.5	4.2	230	0.94	0.51	210,000	2,200	< 1
839234	30,000	2.4	7.7	820	1.1	1.9	230,000	3,400	--
839234 duplicate	25,000	2.6	6.2	660	0.87	1.4	190,000	2,800	< 1
Minimum	15,000	< 0.3	1.85	87	< 0.2	0.12	160,000	1,350	< 1
Mean	27,561	1.26	4.7	478	1.08	0.97	203,258	3,136	1.9
Maximum	50,000	2.5	8.5	960	3.6	5.4	280,000	5,250	14.2
95% UCL	31,694	1.52	5.4	577	1.38	1.39	215,000	3,521	5.1

A.1 Metal concentrations (mg/kg) in processed slag (PS)

	Total Cobalt	Total Copper	Total Iron	Total Lead	Total Magnesium	Total Manganese	Total Mercury	Total Molybdenum	Total Nickel
Electric Arc Furnace (EAF) Slag									
839210/839211	16	180	180,000	32	63,000	47,000	< 0.01	25	49
839210/839211 duplicate	15	170	160,000	29	58,000	44,000	< 0.01	23	46
839212	12	150	250,000	2.6	70,000	31,000	< 0.01	51	74
839212 duplicate	11	140	220,000	3	70,000	31,000	< 0.01	45	62
839224	14	250	190,000	5.3	48,000	48,000	< 0.01	57	98
839224 duplicate	9.5	170	130,000	3.5	32,000	31,000	< 0.01	37	66
839225	11	110	110,000	35	58,000	25,000	< 0.01	31	54
839225 duplicate	9.5	100	99,000	30	50,000	22,000	< 0.01	28	47
839226	13	54	160,000	5.3	63,000	24,000	< 0.01	17	27
839226 duplicate	11	47	140,000	4.6	55,000	21,000	< 0.01	15	23
839234	17	400	190,000	40	63,000	35,000	< 0.01	38	90
839234 duplicate	14	330	150,000	34	53,000	29,000	< 0.01	32	74
Minimum	4	39	104,500	0.305	37,500	14,000	< 0.01	5.5	9
Mean	11.1	134	192,780	13.2	52,871	31,182	0.012	41.4	49
Maximum	18	365	290,000	90	70,000	45,500	0.069	270	230
95% UCL	12.3	166	210,500	21.5	56,292	34,460	NC	58.3	66

A.1 Metal concentrations (mg/kg) in processed slag (PS)

	Total Phosphorus	Total Selenium	Total Silicon	Total Silver	Total Thallium	Total Tin	Total Vanadium	Total Zinc
Electric Arc Furnace (EAF) Slag								
839210/839211	2,300	1.7	1,400	1.3	0.3	3.5	520	1,200
839210/839211 duplicate	2,200	1.5	1,900	1.2	0.34	3	480	1,200
839212	2,000	2	1,100	0.53	0.31	3.7	600	77
839212 duplicate	2,100	1.8	1,300	0.58	0.32	4.7	610	84
839224	1,600	1.4	1,200	2.6	0.31	4.9	500	150
839224 duplicate	1,300	0.82	1,300	1.5	0.32	4.2	330	110
839225	1,300	1.3	1,600	13	0.31	4.1	400	270
839225 duplicate	1,200	0.76	1,600	10	0.32	3.5	350	250
839226	2,000	1.4	2,000	0.94	0.33	< 2.5	440	340
839226 duplicate	2,000	1.5	3,100	0.76	0.32	< 2.5	390	300
839234	1,600	1	6,300	0.76	0.31	7.3	610	300
839234 duplicate	1,600	0.9	3,000	0.71	0.31	7.2	500	270
Minimum	1,250	0.4	790	0.2	< 0.02	< 2.5	240	31
Mean	2,195	1.31	1,742	1.29	0.21	4.3	601	209
Maximum	4,100	5.35	4,650	11.5	0.355	14.5	1,300	1200
95% UCL	2,463	1.66	2,041	3.47	0.22	5.5	686	309

NC = could not be calculated because of low number of detected samples; "--" = not analyzed; <LOD = less than the limit of detection

*2008 sample. All other samples were analyzed in 2009

Statistics were calculated on sample averages (averaging duplicates). Nondetects (<LOD) were assigned a value of 1/2LOD.

[1] Sample 830006 was determined to be a statistical outlier (p<0.01), not representative of slag from the facility, and excluded from the dataset. To obtain a representative sample, three "resamples" were taken from the facility and the results averaged for the risk assessment.

A.1 Metal concentrations (mg/kg) in processed slag (PS)

	Total Aluminum	Total Antimony	Total Arsenic	Total Barium	Total Beryllium	Total Cadmium	Total Calcium	Total Chromium	Hexavalent Chromium
Basic Oxygen Furnace (BOF) Slag									
830004*	11,000	< 0.3	1.8	97	0.3	0.11	230,000	1,900	--
830009*	13,000	0.4	3.1	55	0.3	0.4	240,000	1,700	--
830010*	16,000	< 0.3	2.1	60	1	0.12	260,000	1,300	--
830012*	31,000	< 0.3	2	57	0.6	0.09	220,000	1,000	--
830013*	34,000	< 0.3	1.8	61	0.3	0.09	250,000	1,600	--
839347	47,000	0.84	5.2	740	2.1	0.63	210,000	2,300	--
839347 duplicate	32,000	0.68	3.4	470	1.4	0.45	140,000	1,600	< 1
839232/839233	39,000	1.2	7.1	630	1.4	0.89	230,000	4,200	--
839232/839233 duplicate	32,000	1.3	5.5	540	1.2	0.71	190,000	3,400	< 1
839129/839135	21,000	0.28	6	95	0.54	1.4	330,000	2,100	--
839129/839135 duplicate	15,000	0.18	4.4	71	0.37	0.86	250,000	1,500	< 1
839138/839139	10,000	0.42	5.9	130	0.35	0.4	270,000	1,800	--
839138/839139 duplicate	9,100	0.42	4.7	110	0.3	0.27	240,000	1,600	2.5
839134/839140	23,000	0.52	8.8	110	0.38	0.52	260,000	2,100	--
839134/839140 duplicate	20,000	0.65	7.2	100	0.34	0.54	230,000	1,800	< 1
839145/839146	19,000	0.51	6.1	79	0.25	0.41	220,000	1,100	--
839145/839146 duplicate	19,000	0.47	4.9	76	0.25	0.45	220,000	1,100	< 1

Minimum	9,550	< 0.3	1.8	55	0.25	0.09	175,000	1,000	< 1
Mean	22,550	0.43	4.1	173	0.63	0.42	235,900	1,800	< 1
Maximum	39,500	1.25	8	605	1.75	1.13	290,000	3,800	2.5
95% UCL	28,355	0.64	5.3	449	0.96	0.60	252,400	2,228	NC

A.1 Metal concentrations (mg/kg) in processed slag (PS)

	Total Cobalt	Total Copper	Total Iron	Total Lead	Total Magnesium	Total Manganese	Total Mercury	Total Molybdenum	Total Nickel
Basic Oxygen Furnace (BOF) Slag									
830004*	5.9	37	180,000	4	42,000	23,000	< 0.05	7.9	13
830009*	6	34	210,000	22	50,000	25,000	< 0.05	91	31
830010*	3	23	170,000	3	43,000	23,000	< 0.05	30	14
830012*	4	26	180,000	3	48,000	17,000	< 0.05	5.9	9
830013*	5	21	190,000	3	53,000	24,000	< 0.05	8.8	7
839347	15	80	170,000	6.1	53,000	25,000	< 0.01	16	24
839347 duplicate	10	56	120,000	4.1	35,000	17,000	< 0.01	12	16
839232/839233	11	160	240,000	31	55,000	36,000	< 0.01	36	33
839232/839233 duplicate	9.5	140	200,000	27	46,000	30,000	< 0.01	31	28
839129/839135	10	22	130,000	52	54,000	30,000	< 0.01	96	44
839129/839135 duplicate	7.4	18	94,000	39	39,000	22,000	< 0.01	72	32
839138/839139	9.9	42	240,000	0.9	57,000	15,000	< 0.01	11	16
839138/839139 duplicate	8.6	38	210,000	0.8	50,000	13,000	< 0.01	9.3	14
839134/839140	6.3	35	190,000	2.4	58,000	24,000	< 0.01	8.9	17
839134/839140 duplicate	5.7	31	170,000	2.3	52,000	21,000	< 0.01	8.4	16
839145/839146	6.3	27	190,000	2.6	44,000	20,000	< 0.01	13	16
839145/839146 duplicate	6.1	26	180,000	2.5	43,000	19,000	< 0.01	12	15
Minimum	3	20	112,000	0.85	42,000	14,000	< 0.01	5.9	7
Mean	7.0	44	181,500	10.9	48,091	22,545	0.014	27.9	19
Maximum	12.5	150	225,000	45.5	55,000	33,000	0.025	91	38
95% UCL	8.5	93	199,300	30.3	50,618	25,252	NC	66.8	24

A.1 Metal concentrations (mg/kg) in processed slag (PS)

	Total Phosphorus	Total Selenium	Total Silicon	Total Silver	Total Thallium	Total Tin	Total Vanadium	Total Zinc
Basic Oxygen Furnace (BOF) Slag								
830004*	4,500	0.4	2,200	0.1	< 0.5	< 5	930	86
830009*	3,400	0.3	1,900	0.3	< 0.5	5.1	760	140
830010*	4,200	0.7	1,800	< 0.1	< 0.5	< 5	1,100	14
830012*	3,600	0.5	2,100	< 0.1	< 0.5	< 5	470	210
830013*	4,200	0.5	2,300	0.1	< 0.5	< 5	710	180
839347	2,000	1.9	900	0.88	< 0.02	< 2.5	530	160
839347 duplicate	2,100	1.4	880	0.61	< 0.02	< 2.5	360	120
839232/839233	2,200	1.8	13,000	0.72	0.38	4.2	840	540
839232/839233 duplicate	2,200	1.5	12,000	0.61	0.31	3.9	700	480
839129/839135	2,400	1	2,200	1.4	0.35	< 2.5	830	26
839129/839135 duplicate	2,400	0.67	2,400	0.99	0.33	< 2.5	610	21
839138/839139	2,800	0.65	3,300	0.26	0.36	< 2.5	830	37
839138/839139 duplicate	2,900	0.4	2,300	0.21	0.36	< 2.5	710	33
839134/839140	2,400	1.7	2,600	0.43	0.34	< 2.5	860	56
839134/839140 duplicate	2,500	1.9	2,800	0.38	0.35	< 2.5	770	54
839145/839146	3,700	0.3	2,200	0.34	0.31	< 2.5	910	130
839145/839146 duplicate	3,400	0.46	2,400	0.37	0.32	< 2.5	880	120
Minimum	2,050	0.3	890	< 0.1	< 0.02	< 2.5	445	14
Mean	3,218	0.84	3,072	0.38	0.27	< 2.5	762	138
Maximum	4,500	1.8	12,500	1.20	0.36	5.1	1,100	510
95% UCL	3,696	1.24	7,235	0.58	0.34	4.4	865	248

NC = could not be calculated because of low number of detected samples; "--" = not analyzed; <LOD = less than the limit of detection
*2008 sample. All other samples were analyzed in 2009
Statistics were calculated on sample averages (averaging duplicates). Nondetects (<LOD) were assigned a value of 1/2LOD.

A.1 Metal concentrations (mg/kg) in processed slag (PS)

	Total Aluminum	Total Antimony	Total Arsenic	Total Barium	Total Beryllium	Total Cadmium	Total Calcium	Total Chromium	Hexavalent Chromium
Blast Furnace (BF) Slag									
839130/839133	44,000	< 0.05	1.9	400	13	0.31	270,000	19	--
839130/839133 duplicate	27,000	< 0.05	1.3	240	8	0.23	180,000	14	< 1
839131/839132	48,000	< 0.05	1.9	910	13	0.56	260,000	54	--
839131/839132 duplicate	28,000	< 0.05	1.2	530	7.1	0.34	160,000	33	< 1
839136/839137	41,000	< 0.05	2	380	11	0.29	250,000	53	--
839136/839137 duplicate	27,000	< 0.05	1.2	260	7.5	0.19	170,000	39	< 1
839141/839142	45,000	< 0.05	2.7	830	10	0.36	230,000	55	--
839141/839142 duplicate	28,000	< 0.05	1.4	510	5.9	0.25	150,000	35	< 1
839143/839144	43,000	< 0.05	3.7	580	13	0.44	250,000	52	--
839143/839144 duplicate	26,000	< 0.05	1.6	320	6.7	0.22	150,000	31	< 1
839147/839148	37,000	< 0.05	4.6	560	12	0.49	230,000	77	--
839147/839148 duplicate	34,000	< 0.05	3.1	490	10	0.42	210,000	72	< 1
839154	41,000	< 0.05	3	530	12	0.35	230,000	15	--
839154 duplicate	43,000	< 0.05	2.1	580	12	0.35	230,000	18	< 1
839155	41,000	< 0.05	1.7	600	13	0.19	230,000	20	--
839155 duplicate	31,000	< 0.05	0.9	440	8.7	0.13	180,000	15	< 1

Minimum	34,000	< 0.05	1.3	320	7.95	0.16	190,000	16.5	< 1
Mean	36,500	< 0.05	2.1	510	10.2	0.32	211,300	38	< 1
Maximum	42,000	< 0.05	3.85	720	12	0.455	230,000	74.5	< 1
95% UCL	38,198	NC	2.7	607	11	0.39	220,200	51	NC

A.1 Metal concentrations (mg/kg) in processed slag (PS)

	Total Cobalt	Total Copper	Total Iron	Total Lead	Total Magnesium	Total Manganese	Total Mercury	Total Molybdenum	Total Nickel
Blast Furnace (BF) Slag									
839130/839133	8.9	1.5	3,200	< 0.02	59,000	2,300	< 0.01	0.19	4.1
839130/839133 duplicate	5.6	1	2,300	< 0.02	37,000	1,600	< 0.01	0.081	2.4
839131/839132	13	1.9	8,700	0.9	48,000	3,900	< 0.01	4	4.2
839131/839132 duplicate	7.8	1.2	5,200	0.46	28,000	2,400	< 0.01	2.5	2.5
839136/839137	9.6	2.1	7,000	0.3	54,000	3,400	< 0.01	0.28	4.5
839136/839137 duplicate	6.6	1.5	5,000	0.17	37,000	2,500	< 0.01	0.21	3
839141/839142	9.7	2.9	4,400	0.048	53,000	3,500	< 0.01	0.2	4.6
839141/839142 duplicate	6.2	1.8	2,900	< 0.02	34,000	2,300	< 0.01	0.098	2.9
839143/839144	5.8	3.3	5,400	0.31	56,000	3,100	< 0.01	0.26	5.6
839143/839144 duplicate	3.5	2	3,300	0.095	34,000	1,900	< 0.01	0.11	3.2
839147/839148	5.1	2.9	8,900	0.49	47,000	4,200	< 0.01	0.66	5.4
839147/839148 duplicate	4.5	2.6	8,600	0.4	43,000	3,800	< 0.01	0.58	4.7
839154	14	2.1	2,800	< 0.02	54,000	2,800	< 0.01	0.054	3.9
839154 duplicate	15	3.4	3,000	< 0.02	56,000	3,100	< 0.01	0.095	3.6
839155	8.8	1.2	1,600	0.04	51,000	3,000	< 0.01	< 0.05	1.9
839155 duplicate	6.7	0.98	1,300	0.026	39,000	2,300	< 0.01	< 0.05	1.5
Minimum	4.65	1.09	1,450	< 0.02	38,000	1,950	< 0.01	< 0.05	1.7
Mean	8.2	2.02	4,600	0.2	45,625	2,881	< 0.01	0.586	3.63
Maximum	14.5	2.75	8,750	0.68	55,000	4,000	< 0.01	3.25	5.05
95% UCL	10.3	2.5	6,239	0.4	48,801	3,273	NC	3.0	4.3

A.1 Metal concentrations (mg/kg) in processed slag (PS)

	Total Phosphorus	Total Selenium	Total Silicon	Total Silver	Total Thallium	Total Tin	Total Vanadium	Total Zinc
Blast Furnace (BF) Slag								
839130/839133	400	4.6	1,500	0.29	0.32	< 2.5	18	3.4
839130/839133 duplicate	420	2.6	1,600	0.2	0.3	< 2.5	13	2.3
839131/839132	490	5	1,700	1.2	0.31	< 2.5	33	5
839131/839132 duplicate	500	3	1,700	0.61	0.31	< 2.5	20	3.3
839136/839137	460	4.1	1,500	0.35	0.4	< 2.5	38	7.9
839136/839137 duplicate	460	2.4	1,700	0.26	0.4	< 2.5	27	5.9
839141/839142	440	4.6	2,000	0.61	0.34	< 5	39	9.6
839141/839142 duplicate	460	2.9	1,900	0.44	0.33	< 5	25	5.6
839143/839144	440	4.8	1,600	0.72	0.33	< 5	36	6.9
839143/839144 duplicate	410	3.7	2,000	0.41	0.32	< 5	22	4.1
839147/839148	430	3.5	2,000	0.79	0.36	< 2.5	32	8.2
839147/839148 duplicate	430	2.8	2,200	0.75	0.35	< 2.5	32	7.4
839154	390	3.9	1,700	0.61	0.32	< 2.5	28	10
839154 duplicate	410	3.8	1,800	0.51	0.34	< 2.5	31	13
839155	410	5.4	1,500	0.31	0.38	< 2.5	21	2.4
839155 duplicate	400	4.3	1,200	0.24	0.42	< 2.5	16	1.8

Minimum	400	3.15	1,350	0.245	0.31	< 2.5	15.5	2.1
Mean	434	3.84	1,725	0.52	0.35	< 2.5	27	6
Maximum	495	4.85	2,100	0.905	0.4	2.5	32.5	11.5
95% UCL	456	4.21	1,882	0.68	0.37	NC	31	8

NC = could not be calculated because of low number of detected samples; "--" = not analyzed; <LOD = less than the limit of detection
Statistics were calculated on sample averages (averaging duplicates). Nondetects (<LOD) were assigned a value of 1/2LOD.

A.2 Metal concentrations (mg/kg) in < 300 µm slag

	Total Aluminum	Total Antimony	Total Arsenic	Total Barium	Total Beryllium	Total Cadmium	Total Calcium	Total Chromium	Hexavalent Chromium
Electric Arc Furnace (EAF) Slag									
830005*	13,000	1.6	3	370	1	0.53	200,000	2,400	--
~~830006*~~[1]	~~18,000~~	~~2~~	~~4.3~~	~~390~~	~~1~~	~~1.1~~	~~220,000~~	~~1,400~~	--
830006* resample 830104	25,000	1.2	3.9	620	0.5	1	210,000	2,100	--
830006* resample 830120	25,000	1.4	4.1	620	0.63	1.3	220,000	2,000	--
830006* resample 830121	24,000	1	3.9	640	0.65	1.3	210,000	1,900	--
830007*	77,000	1.3	3.1	76	0.6	0.31	200,000	530	--
830008*	23,000	2.6	5.5	150	0.74	3	180,000	1,000	--
830011*	14,000	< 0.3	1.7	64	< 0.2	0.27	220,000	2,800	--
839235/839236	15,000	1	3.3	550	2	1.1	300,000	760	--
839237	70,000	1.8	9.2	330	0.64	0.96	220,000	1,300	--
839317	24,000	0.51	3.2	300	1.1	0.33	170,000	3,700	--
839318	15,000	1.2	2.5	230	0.44	1.7	390,000	660	--
839319	78,000	1.5	6.4	190	0.67	0.65	260,000	1,300	--
839320	22,000	0.057	1.6	330	0.52	0.27	180,000	4,200	--
839607	18,000	1.4	5.8	700	1.3	2.5	220,000	2,400	--
839191	35,000	0.71	3.7	160	0.59	1	140,000	1,100	--
839192	34,000	3.5	9.5	290	0.88	1.7	320,000	1,700	--
839193	60,000	1.7	9.8	240	0.91	0.59	210,000	1,100	--
839348	20,000	0.68	2	620	0.66	1.4	210,000	4,800	--
839210/839211	17,000	3.1	4.7	590	0.47	6.5	270,000	1,800	--
839212	7,600	0.44	1.9	120	0.33	0.37	340,000	1,300	--
839224	15,000	1.9	6.9	710	1.5	3.4	250,000	1,300	--
839225	14,000	2.1	3.2	470	0.77	12	230,000	770	--
839226	82,000	2.3	5.4	140	0.53	0.93	270,000	810	--
839234	20,000	2.5	5.6	580	0.84	10	150,000	2,100	--

Minimum	7,600	0.057	1.6	64	< 0.2	0.27	140,000	530	--
Mean	31,739	1.54	4.63	356	0.77	2.31	233,788	1,810	--
Maximum	82,000	3.5	9.8	710	1.8	12	390,000	4,800	--
95% UCL	54,285	1.87	5.70	434	0.93	3.58	256,600	2,288	--

A.2 Metal concentrations (mg/kg) in < 300 µm slag

	Total Cobalt	Total Copper	Total Iron	Total Lead	Total Magnesium	Total Manganese	Total Mercury	Total Molybdenum	Total Nickel
Electric Arc Furnace (EAF) Slag									
830005*	4.6	290	160,000	80	63,000	31,000	< 0.05	36	60
~~830006*~~[1]	~~3.2~~	~~210~~	~~74,000~~	~~930~~	~~97,000~~	~~19,000~~	~~< 0.05~~	~~9.4~~	~~49~~
830006* resample 830104	6.2	170	100,000	190	96,000	24,000	< 0.05	12	53
830006* resample 830120	7.2	190	100,000	240	99,000	24,000	< 0.05	12	52
830006* resample 830121	7	160	95,000	230	91,000	22,000	< 0.05	12	49
830007*	1	56	62,000	6	28,000	4,800	< 0.05	4.5	16
830008*	6	100	71,000	130	54,000	12,000	0.093	66	110
830011*	1	88	210,000	13	72,000	34,000	< 0.05	6	10
839235/839236	6.7	150	74,000	30	73,000	20,000	0.015	23	51
839237	7.5	190	98,000	51	57,000	15,000	0.024	64	73
839317	14	110	260,000	4.4	60,000	30,000	< 0.01	19	25
839318	4.6	97	46,000	22	38,000	8,000	< 0.01	15	18
839319	6.9	59	12,000	31	56,000	9,000	0.016	14	30
839320	7.5	74	290,000	2.7	76,000	37,000	< 0.01	17	11
839607	8.7	250	180,000	29	46,000	25,000	< 0.01	26	70
839191	17	100	97,000	32	140,000	10,000	< 0.01	29	230
839192	3.2	110	58,000	58	44,000	9,700	0.010	59	28
839193	9.8	87	89,000	21	93,000	8,000	< 0.01	9.6	83
839348	16	180	210,000	31	55,000	41,000	< 0.01	47	42
839210/839211	17	210	100,000	220	97,000	14,000	0.012	18	46
839212	6.5	47	63,000	5.8	61,000	8,600	< 0.01	16	29
839224	9	250	120,000	34	62,000	23,000	< 0.01	57	76
839225	14	110	49,000	98	65,000	9,300	< 0.01	32	53
839226	10	75	71,000	25	78,000	7,100	0.014	30	85
839234	23	480	210,000	280	89,000	25,000	0.011	43	140

Minimum	1	47	12,000	2.7	28,000	4,800	< 0.01	4.5	10
Mean	9.1	149	119,470	65	68,288	18,402	0.016	29.2	60.8
Maximum	23	480	290,000	280	140,000	41,000	0.093	66	230
95% UCL	11.2	188	154,100	101	77,208	23,272	0.022	38.1	81.7

A.2 Metal concentrations (mg/kg) in < 300 µm slag

	Total Phosphorus	Total Selenium	Total Silicon	Total Silver	Total Thallium	Total Tin	Total Vanadium	Total Zinc
Electric Arc Furnace (EAF) Slag								
830005*	1,200	2.5	1,900	0.6	< 0.5	19	270	350
~~830006*~~[1]	~~1,100~~	~~1.2~~	~~2,400~~	~~0.7~~	~~1.6~~	~~10~~	~~570~~	~~470~~
830006* resample 830104	1,600	0.8	1,100	0.68	< 0.5	9	530	360
830006* resample 830120	1,700	0.79	1,400	0.75	< 0.5	8.1	520	420
830006* resample 830121	1,600	0.79	1,300	0.77	< 0.5	8	500	420
830007*	1,300	1.5	1,500	0.9	< 0.5	< 5	59	46
830008*	940	2.1	2,500	3.9	< 0.5	6	130	1,200
830011*	3,900	0.3	2,200	0.1	< 0.5	< 5	1,100	200
839235/839236	680	5	2,900	1.1	< 0.02	3	320	170
839237	1,100	2.6	2,700	0.82	< 0.02	6.1	340	380
839317	1,900	0.47	3,100	0.45	< 0.02	4.7	440	140
839318	520	12	4,000	3	< 0.02	< 2.5	190	140
839319	1,100	1.1	6,300	0.36	< 0.02	3.9	290	370
839320	1,600	0.35	4,000	0.12	< 0.02	< 2.5	530	160
839607	1,400	0.99	2,400	4.4	< 0.02	16	580	280
839191	1,300	1	3,300	0.63	< 0.02	2.5	180	880
839192	860	1.8	2,400	2	0.051	5	170	380
839193	1,100	1.5	3,200	0.65	< 0.02	6.3	220	270
839348	1,700	0.44	2,100	2.3	< 0.02	5.2	750	280
839210/839211	1,500	2.1	2,200	2.7	< 0.02	7	180	4,000
839212	690	3	4,100	0.48	< 0.02	< 2.5	160	130
839224	1,000	2.8	2,400	5.6	< 0.02	6.8	290	460
839225	720	1.6	2,400	25	< 0.02	4.4	120	520
839226	1,100	1.8	5,300	1.2	< 0.02	4	150	670
839234	1,300	0.54	2,300	1.4	0.038	13	400	1,600
Minimum	520	0.3	1,267	0.1	< 0.02	< 2.5	59	46
Mean	1,297	2.1	2,930	2.63	0.07	5.88	336	592
Maximum	3,900	12	6,300	25	0.25	19	1,100	4,000
95% UCL	1,537	2.98	3,391	4.34	0.04	7.81	435	964

"--" = not analyzed; <LOD = less than the limit of detection

*2008 sample. All other samples were analyzed in 2009

Statistics were calculated on sample averages (averaging duplicates). Nondetects (<LOD) were assigned a value of 1/2LOD.

[1] Sample 830006 was determined to be a statistical outlier (p<0.01), not representative of slag from the facility, and excluded from the dataset. To obtain a representative sample, three "resamples" were taken from the facility and the results averaged for the risk assessment.

A.2 Metal concentrations (mg/kg) in < 300 µm slag

	Total Aluminum	Total Antimony	Total Arsenic	Total Barium	Total Beryllium	Total Cadmium	Total Calcium	Total Chromium	Hexavalent Chromium
Basic Oxygen Furnace (BOF) Slag									
830004*	9,300	< 0.3	2	87	0.4	0.25	250,000	2,000	--
830009*	16,000	0.6	3.2	48	0.2	0.63	250,000	1,700	--
830010*	12,000	< 0.3	1.8	54	1	0.13	250,000	1,200	--
830012*	26,000	< 0.3	1.2	49	0.4	0.44	220,000	1,100	--
830013*	20,000	< 0.3	1	44	< 0.2	0.23	240,000	1,700	--
830013* duplicate	15,000	0.6	3.1	45	< 0.2	0.72	230,000	1,600	--
839347	47,000	0.79	9.9	960	1.4	1.1	210,000	750	--
839232/839233	41,000	3.6	23	420	0.94	2.7	200,000	2,500	--
839129/839135	20,000	0.58	3.8	78	0.59	1.3	290,000	1,200	--
839138/839139	6,500	< 0.05	1.2	110	0.25	0.14	280,000	1,800	--
839134/839140	18,000	0.22	4.8	89	0.34	0.3	260,000	2,100	--
839145/839146	22,000	0.24	3.2	65	0.31	0.25	250,000	1,200	--
Minimum	6,500	< 0.05	1.2	44.5	< 0.2	0.13	200,000	750	--
Mean	21,391	0.63	5.1	182	0.54	0.70	245,000	1,564	--
Maximum	47,000	3.6	23	960	1.4	2.7	290,000	2,500	--
95% UCL	28,251	1.33	9.2	549	0.77	1.25	260,000	1,848	--

A.2 Metal concentrations (mg/kg) in < 300 µm slag

	Total Cobalt	Total Copper	Total Iron	Total Lead	Total Magnesium	Total Manganese	Total Mercury	Total Molybdenum	Total Nickel
Basic Oxygen Furnace (BOF) Slag									
830004*	2.8	53	190,000	18	55,000	24,000	< 0.05	8.3	17
830009*	3	39	190,000	59	66,000	23,000	< 0.05	67	29
830010*	0.9	30	140,000	8	49,000	21,000	< 0.05	24	6
830012*	1.3	68	160,000	19	62,000	17,000	< 0.05	6.4	10
830013*	1.1	48	170,000	11	64,000	23,000	< 0.05	8.7	7
830013* duplicate	2.9	38	170,000	51	62,000	22,000	< 0.05	63	26
839347	11	120	70,000	44	63,000	7,500	0.015	15	46
839232/839233	11	320	190,000	140	62,000	22,000	< 0.01	44	77
839129/839135	8.2	33	92,000	130	61,000	17,000	0.022	76	43
839138/839139	4.5	31	190,000	2.4	67,000	14,000	< 0.01	8.7	3.5
839134/839140	3.8	36	180,000	7.1	78,000	21,000	< 0.01	7.9	11
839145/839146	5.3	37	170,000	12	78,000	22,000	0.016	11	23
Minimum	0.9	30	70,000	2.4	49,000	7,500	< 0.01	6.4	3.5
Mean	4.9	74	158,400	42.8	64,000	19,182	0.018	27.7	26
Maximum	11	320	190,000	140	78,000	24,000	0.025	76	77
95% UCL	6.9	186	181,100	85.9	68,669	21,882	0.019	47.3	38

A.2 Metal concentrations (mg/kg) in < 300 µm slag

	Total Phosphorus	Total Selenium	Total Silicon	Total Silver	Total Thallium	Total Tin	Total Vanadium	Total Zinc
Basic Oxygen Furnace (BOF) Slag								
830004*	3,900	0.4	2,000	0.2	< 0.5	< 5	910	190
830009*	2,900	0.4	2,100	0.4	< 0.5	< 5	660	410
830010*	3,800	0.9	1,900	< 0.1	< 0.5	< 5	990	26
830012*	2,900	0.6	2,200	0.2	< 0.5	< 5	470	520
830013*	3,100	< 0.2	3,200	0.2	< 0.5	< 5	690	270
830013* duplicate	2,700	0.5	1,700	0.4	< 0.5	< 5	600	410
839347	980	3.4	1,900	1.4	< 0.02	< 2.5	200	610
839232/839233	1,700	1.9	2,300	2	< 0.02	8.3	470	2,300
839129/839135	1,700	1.3	1,500	1.9	< 0.02	< 2.5	460	48
839138/839139	2,800	0.43	1,900	0.21	< 0.02	< 2.5	800	40
839134/839140	2,400	2	1,800	0.36	< 0.02	< 2.5	720	88
839145/839146	3,100	0.54	1,900	0.23	< 0.02	< 2.5	900	260
Minimum	980	0.3	1,500	< 0.1	< 0.02	< 2.5	200	26
Mean	2,644	1.11	1,995	0.66	0.12	2.5	657	439
Maximum	3,900	3.4	2,450	2	0.25	8.3	990	2,300
95% UCL	3,131	1.80	2,137	1.62	NC	NC	788	949

NC = could not be calculated because of low number of detected samples; "--" = not analyzed; <LOD = less than the limit of detection

*2008 sample. All other samples were analyzed in 2009

Statistics were calculated on sample averages (averaging duplicates). Nondetects (<LOD) were assigned a value of 1/2LOD.

A.2 Metal concentrations (mg/kg) in < 300 µm slag

	Total Aluminum	Total Antimony	Total Arsenic	Total Barium	Total Beryllium	Total Cadmium	Total Calcium	Total Chromium	Hexavalent Chromium
Blast Furnace (BF) Slag									
839130/839133	37,000	< 0.05	1	420	6.4	0.17	240,000	21	--
839131/839132	41,000	< 0.05	1.2	450	7.5	0.56	250,000	30	--
839136/839137	36,000	< 0.05	1	400	6.2	0.22	240,000	37	--
839141/839142	39,000	< 0.05	1	750	6.6	0.31	210,000	55	--
839143/839144	41,000	< 0.05	1.1	600	8.6	0.28	250,000	50	--
839147/839148	36,000	< 0.05	1.2	500	8.2	0.33	250,000	53	--
839154	36,000	< 0.05	1.1	500	7.3	0.18	220,000	36	--
839155	39,000	< 0.05	1.1	420	8.2	0.23	260,000	55	--
Minimum	36,000	< 0.05	1	400	6.2	0.17	210,000	21	--
Mean	38,125	< 0.05	1.1	505	7.4	0.29	240,000	42	--
Maximum	41,000	< 0.05	1.2	750	8.6	0.56	260,000	55	--
95% UCL	39,577	NC	1.1	584	8.0	0.37	251,300	51	--

A.2 Metal concentrations (mg/kg) in < 300 µm slag

	Total Cobalt	Total Copper	Total Iron	Total Lead	Total Magnesium	Total Manganese	Total Mercury	Total Molybdenum	Total Nickel
Blast Furnace (BF) Slag									
839130/839133	4	14	2,900	1.3	60,000	2,500	< 0.01	0.31	1.6
839131/839132	27	19	4,900	3.9	54,000	3,200	< 0.01	1.1	3
839136/839137	5.9	17	7,000	3.8	60,000	3,500	0.013	0.45	2.5
839141/839142	5.1	20	4,900	2.1	56,000	3,500	< 0.01	0.49	1.4
839143/839144	12	15	6,400	2.5	67,000	3,200	< 0.01	0.56	2.5
839147/839148	3.9	28	6,400	4.9	54,000	4,500	< 0.01	0.63	5
839154	6	38	3,400	2.3	57,000	3,000	< 0.01	0.59	3.8
839155	5.7	100	3,700	6	59,000	3,400	0.012	1.2	6.2
Minimum	3.9	14	2,900	1.3	54,000	2,500	< 0.01	0.31	1.4
Mean	8.7	31.4	4,950	3.4	58,375	3,350	< 0.01	0.67	3.3
Maximum	27	100	7,000	6	67,000	4,500	0.013	1.2	6.2
95% UCL	20.8	54.2	5,981	4.4	61,215	3,731	0.012	0.88	4.4

A.2 Metal concentrations (mg/kg) in < 300 µm slag

	Total Phosphorus	Total Selenium	Total Silicon	Total Silver	Total Thallium	Total Tin	Total Vanadium	Total Zinc
Blast Furnace (BF) Slag								
839130/839133	360	5.6	1,600	0.38	< 0.02	< 2.5	19	8.1
839131/839132	370	6.6	1,500	1.2	< 0.02	< 2.5	14	16
839136/839137	400	4.9	1,500	0.47	< 0.02	< 2.5	30	28
839141/839142	420	6.6	1,400	0.65	< 0.02	< 5	37	15
839143/839144	460	5.8	1,400	0.65	< 0.02	< 5	28	16
839147/839148	390	5.2	2,300	0.65	0.1	< 2.5	28	37
839154	420	5.4	2,000	0.37	< 0.02	< 2.5	26	16
839155	390	6.3	2,100	0.5	0.05	< 2.5	28	25
Minimum	360	4.9	1,400	0.37	< 0.02	< 2.5	14	8.1
Mean	401	5.8	1,725	0.61	0.03	< 2.5	26	20.1
Maximum	460	6.6	2,300	1.2	0.1	2.5	37	37
95% UCL	423	6.2	1,962	0.81	0.07	NC	31	26.3

NC = could not be calculated because of low number of detected samples; "--" = not analyzed; <LOD = less than the limit of detection
Statistics were calculated on sample averages (averaging duplicates). Nondetects (<LOD) were assigned a value of 1/2LOD.

A.3 Metal concentrations (mg/kg) in < 75 µm slag

	Total Aluminum	Total Antimony	Total Arsenic	Total Barium	Total Beryllium	Total Cadmium	Total Calcium	Total Chromium	Hexavalent Chromium
Electric Arc Furnace (EAF) Slag									
830005*	11,000	1.8	4.5	350	1.1	0.87	230,000	1,700	--
~~830006*~~[1]	~~19,000~~	~~3.1~~	~~5.8~~	~~430~~	~~0.7~~	~~1.5~~	~~240,000~~	~~1,100~~	--
830006* resample 830104	28,000	2.2	5	600	0.55	1.8	230,000	1,400	--
830006* resample 830120	28,000	2.3	5.2	600	0.69	2	240,000	1,500	--
830006* resample 830121	29,000	2.3	5	640	0.65	1.8	230,000	1,500	--
830007*	73,000	1.3	3.8	76	0.8	0.36	210,000	410	--
830008*	25,000	2.5	6.7	210	1.1	3.5	210,000	720	--
830011*	14,000	< 0.3	2	77	0.2	0.5	250,000	2,800	--
839235/839236	14,000	1.7	7.6	430	1.4	0.92	300,000	560	--
839237	67,000	3.6	12	310	0.64	0.98	200,000	1,100	--
839317	26,000	1.4	5.8	320	1.5	0.29	170,000	3,400	--
839318	14,000	1.1	7	200	0.39	1.3	350,000	410	--
839319	69,000	3.1	10	160	0.68	1.3	230,000	1,100	--
839320	25,000	0.27	3.9	340	0.53	0.29	170,000	3,900	--
839607	21,000	3.4	11	710	1.8	2.9	240,000	2,000	--
839191	39,000	0.91	4.8	160	0.57	1.3	170,000	1,200	--
839192	35,000	4.9	13	290	1	1.5	310,000	1,500	--
839193	52,000	3.7	12	200	0.96	0.56	170,000	1,000	--
839348	20,000	1.4	4.9	640	0.76	1.6	210,000	4,300	--
839210/839211	15,000	3.8	7.3	510	0.48	6.6	260,000	1,100	--
839212	7,400	0.53	6.9	120	0.35	0.35	360,000	810	--
839224	15,000	3.5	11	590	1.3	3	270,000	940	--
839225	16,000	2.5	6.8	460	0.82	9.8	250,000	700	--
839226	66,000	4.3	7.6	110	0.53	0.82	210,000	690	--
839234	21,000	6.6	8.5	570	0.81	13	140,000	1,800	--

Minimum	7,400	< 0.3	2	76	0.2	0.29	140,000	410	--
Mean	30,624	2.49	7.4	338	0.83	2.44	233,788	1,528	--
Maximum	73,000	6.6	13	710	1.8	13	360,000	4300	--
95% UCL	39,358	3.09	8.5	412	0.98	4.91	255,100	1,980	--

A.3 Metal concentrations (mg/kg) in < 75 µm slag

	Total Cobalt	Total Copper	Total Iron	Total Lead	Total Magnesium	Total Manganese	Total Mercury	Total Molybdenum	Total Nickel
Electric Arc Furnace (EAF) Slag									
830005*	5	270	110,000	89	68,000	25,000	< 0.05	37	66
~~830006*~~[1]	~~3~~	~~230~~	~~54,000~~	~~1100~~	~~98,000~~	~~16,000~~	~~< 0.05~~	~~8~~	~~42~~
830006* resample 830104	4.9	170	72,500	330	97,000	18,000	< 0.05	11	35
830006* resample 830120	5.8	190	77,000	350	100,000	19,000	< 0.05	11	38
830006* resample 830121	5.4	180	70,000	340	100,000	18,000	< 0.05	11	34
830007*	1.3	85	44,000	9	27,000	3,800	< 0.05	5.6	18
830008*	3.5	83	45,000	130	52,000	10,000	0.13	58	58
830011*	1.1	53	190,000	13	70,000	31,000	< 0.05	6.5	7
839235/839236	7.1	160	48,000	31	71,000	13,000	0.012	22	42
839237	6.5	230	74,000	64	54,000	13,000	< 0.01	69	50
839317	12	120	240,000	4.3	54,000	29,000	< 0.01	19	26
839318	4.1	110	30,000	23	35,000	5,600	< 0.01	12	19
839319	5.5	110	99,000	45	54,000	8,200	0.045	13	34
839320	4.9	82	240,000	5.4	66,000	33,000	< 0.01	16	12
839607	7.6	260	140,000	34	47,000	21,000	< 0.01	24	65
839191	10	110	84,000	40	170,000	9,600	0.011	46	150
839192	4.2	100	47,000	56	42,000	8,600	< 0.01	61	25
839193	6	80	77,000	20	99,000	7,700	0.014	9.6	53
839348	12	200	180,000	38	51,000	38,000	< 0.01	42	50
839210/839211	5.9	170	64,000	170	93,000	9,700	0.021	14	36
839212	6	44	40,000	5.1	55,000	6,200	< 0.01	13	20
839224	8.6	270	92,000	43	64,000	18,000	< 0.01	57	73
839225	5.1	93	40,000	92	61,000	8,600	< 0.01	18	41
839226	7.3	55	50,000	25	71,000	5,400	0.02	56	110
839234	16	540	160,000	370	79,000	21,000	0.012	39	120

Minimum	1.1	44	30,000	4.3	27,000	3,800	< 0.01	5.6	7
Mean	7	155	98,508	75	67,364	15,624	0.019	29	50
Maximum	16	540	240,000	370	170,000	38,000	0.13	69	150
95% UCL	7.9	197	125,400	118	78,270	20,018	0.029	39.1	66

A.3 Metal concentrations (mg/kg) in < 75 µm slag

	Total Phosphorus	Total Selenium	Total Silicon	Total Silver	Total Thallium	Total Tin	Total Vanadium	Total Zinc
Electric Arc Furnace (EAF) Slag								
830005*	1,000	2.5	2,000	0.7	< 0.5	23	220	440
~~**830006***~~[1]	~~980~~	~~1.4~~	~~2,000~~	~~0.8~~	~~0.9~~	~~11~~	~~450~~	~~550~~
830006* resample 830104	1,300	0.91	850	0.8	< 0.5	9.4	400	590
830006* resample 830120	1,400	1	1,100	0.84	< 0.5	7.4	410	630
830006* resample 830121	1,500	1.1	1,400	0.55	< 0.5	9.9	410	610
830007*	1,000	2	1,600	1	< 0.5	5.6	50	61
830008*	1,200	2.8	2,800	5.3	< 0.5	7.1	98	1,200
830011*	3,800	0.4	2,100	0.2	< 0.5	6	1,100	190
839235/839236	590	6.2	2,500	0.91	< 0.02	3.4	200	190
839237	960	2.7	2,600	0.83	< 0.02	5.9	260	470
839317	1,800	1.1	18,000	0.42	< 0.02	5.9	410	190
839318	440	8.3	4,000	2.5	< 0.02	< 2.5	140	160
839319	990	0.84	4,500	1.2	< 0.02	6	250	500
839320	3,300	0.42	1,200	0.27	< 0.02	< 2.5	480	270
839607	1,300	1.2	1,500	4.6	< 0.02	20	510	380
839191	1,100	1.3	4,700	0.66	< 0.02	2.7	180	1,200
839192	810	1.6	2,300	1.4	0.038	4.5	150	390
839193	1,100	1.3	12,000	0.45	< 0.02	6.6	200	270
839348	1,800	0.72	1,900	2.9	< 0.02	5.9	690	370
839210/839211	1,300	2.2	2,600	2.9	< 0.02	5.4	120	4,000
839212	560	2.9	5,600	0.46	< 0.02	< 2.5	110	150
839224	850	4.2	2,500	5.3	< 0.02	8.3	220	610
839225	640	1.6	2,300	23	< 0.02	3.4	110	500
839226	1,000	1.7	17,000	1.2	< 0.02	3.8	120	730
839234	1,300	0.76	2,100	2.2	0.038	15	340	2,200
Minimum	440	0.4	1,117	0.2	< 0.02	< 2.5	50	61
Mean	1,284	2	4,405	2.7	0.07	6.9	289	686
Maximum	3,800	8.3	18,000	23	0.25	23	1,100	4,000
95% UCL	1,596	2.9	8,886	5.2	NC	12.14	384	1,115

NC = could not be calculated because of low number of detected samples; "--" = not analyzed; <LOD = less than the limit of detection

*2008 sample. All other samples were analyzed in 2009

Statistics were calculated on sample averages (averaging duplicates). Nondetects (<LOD) were assigned a value of 1/2LOD.

[1] Sample 830006 was determined to be a statistical outlier ($p<0.01$), not representative of slag from the facility, and excluded from the dataset. To obtain a representative sample, three "resamples" were taken from the facility and the results averaged for the risk assessment.

A.3 Metal concentrations (mg/kg) in < 75 µm slag

	Total Aluminum	Total Antimony	Total Arsenic	Total Barium	Total Beryllium	Total Cadmium	Total Calcium	Total Chromium	Hexavalent Chromium
Basic Oxygen Furnace (BOF) Slag									
830004*	9,100	< 0.3	1.9	97	0.3	0.32	270,000	2,000	--
830009*	14,000	0.7	3.3	58	0.4	0.83	280,000	1,700	--
~~830009* duplicate~~[2]	~~11,000~~	~~2.1~~	~~4.3~~	~~320~~	~~1.2~~	~~0.94~~	~~230,000~~	~~1,700~~	--
830010*	13,000	< 0.3	2.4	64	1.1	0.17	300,000	1,300	--
830012*	20,000	< 0.3	1.1	61	0.3	0.23	290,000	1,600	--
830013*	20,000	< 0.3	1.2	56	< 0.2	0.31	310,000	1,900	--
839347	45,000	1.9	12	1100	2.4	1.4	190,000	600	--
839232/839233	45,000	6.7	30	380	0.98	4.1	190,000	2,100	--
839129/839135	20,000	0.91	7.6	73	0.58	0.95	290,000	940	--
839138/839139	7,200	0.15	6.4	120	0.33	0.11	300,000	1,400	--
839134/839140	16,000	0.61	8.8	90	0.38	0.3	250,000	1,800	--
839145/839146	24,000	0.78	6.9	55	0.34	0.32	240,000	950	--

Minimum	7,200	< 0.3	1.1	55	< 0.2	0.11	190,000	600	--
Mean	21,209	1.12	7.4	196	0.66	0.82	264,500	1,481	--
Maximum	45,000	6.7	30	1,100	2.4	4.1	310,000	2,100	--
95% UCL	29,759	2.44	14	609	1.52	2.3	287,800	1748	--

A.3 Metal concentrations (mg/kg) in < 75 µm slag

	Total Cobalt	Total Copper	Total Iron	Total Lead	Total Magnesium	Total Manganese	Total Mercury	Total Molybdenum	Total Nickel
Basic Oxygen Furnace (BOF) Slag									
830004*	2	41	160,000	17	55,000	23,000	< 0.05	8.3	14
830009*	2.6	44	170,000	66	64,000	21,000	< 0.05	75	27
~~830009* duplicate~~[2]	~~5400~~	~~270~~	~~120,000~~	~~86~~	~~70,000~~	~~26,000~~	~~< 0.05~~	~~38~~	~~67~~
830010*	0.8	27	150,000	9	50,000	22,000	< 0.05	29	6
830012*	1	4.9	150,000	13	65,000	19,000	< 0.05	8.5	8
830013*	1	33	160,000	13	70,000	22,000	< 0.05	11	6
839347	8.2	98	61,000	50	58,000	6,400	0.024	13	49
839232/839233	9.8	350	160,000	170	68,000	20,000	0.018	44	82
839129/839135	3.4	52	63,000	170	61,000	14,000	0.026	70	25
839138/839139	2.7	30	140,000	2.6	45,000	11,000	< 0.01	9.3	5.4
839134/839140	2.7	34	150,000	7.3	68,000	19,000	< 0.01	8.4	9.7
839145/839146	3.1	56	120,000	13	84,000	17,000	0.022	12	16
Minimum	0.8	4.9	61,000	2.6	45,000	6,400	< 0.01	8.3	5.4
Mean	3	70	134,900	48	62,545	17,673	0.020	26	23
Maximum	9.8	350	170,000	170	84,000	23,000	0.026	75	82
95% UCL	5.5	196	155,900	104	68,351	20,520	0.023	60	39

A.3 Metal concentrations (mg/kg) in < 75 µm slag

	Total Phosphorus	Total Selenium	Total Silicon	Total Silver	Total Thallium	Total Tin	Total Vanadium	Total Zinc
Basic Oxygen Furnace (BOF) Slag								
830004*	3,800	0.6	2,100	0.2	< 0.5	< 5	1,000	200
830009*	2,700	0.4	6,900	1.1	< 0.5	< 5	690	480
~~830009* duplicate~~[2]	~~980~~	~~2.2~~	~~1,800~~	~~0.7~~	~~< 0.5~~	~~20~~	~~230~~	~~460~~
830010*	3,500	1	2,100	0.1	< 0.5	< 5	1,200	28
830012*	3,400	0.5	2,300	0.2	< 0.5	< 5	690	360
830013*	3,300	0.3	2,000	0.2	< 0.5	< 5	810	320
839347	940	3.6	1,600	1.1	< 0.02	< 2.5	180	720
839232/839233	1,500	2.1	3,200	3	0.054	7.6	420	3,500
839129/839135	1,300	1.6	2,500	1.7	0.2	< 2.5	420	66
839138/839139	3,000	0.58	3,200	0.15	0.026	< 2.5	860	40
839134/839140	2,000	1.7	6,500	0.31	0.036	< 2.5	700	100
839145/839146	2,100	0.67	11,000	0.24	< 0.02	< 2.5	770	300

	Total Phosphorus	Total Selenium	Total Silicon	Total Silver	Total Thallium	Total Tin	Total Vanadium	Total Zinc
Minimum	940	0.3	1,600	0.1	< 0.02	< 2.5	180	28
Mean	2,504	1.19	3,945	0.75	0.14	2.40	704	556
Maximum	3,800	3.6	11,000	3	0.25	7.6	1,200	3,500
95% UCL	3,042	1.89	6,210	1.96	0.12	4.10	859	1,281

"--" = not analyzed; <LOD = less than the limit of detection

*2008 sample. All other samples were analyzed in 2009

Statistics were calculated on sample averages (averaging duplicates). Nondetects (<LOD) were assigned a value of 1/2LOD.

[2] Results of duplicate were not included because the concentrations of some metals were not representative.

A.3 Metal concentrations (mg/kg) in < 75 µm slag

	Total Aluminum	Total Antimony	Total Arsenic	Total Barium	Total Beryllium	Total Cadmium	Total Calcium	Total Chromium	Hexavalent Chromium
Blast Furnace (BF) Slag									
839130/839133	36,000	< 0.05	4.5	430	12	0.17	220,000	16	--
839131/839132	36,000	< 0.05	4.7	1100	12	0.45	200,000	37	--
839136/839137	36,000	0.092	4.6	390	11	0.19	200,000	37	--
839141/839142	39,000	0.05	4.5	930	10	0.25	200,000	66	--
839143/839144	41,000	< 0.05	4.8	570	13	0.25	230,000	41	--
839147/839148	32,000	0.081	4.2	540	11	0.25	210,000	44	--
839154	39,000	< 0.05	2.1	570	8	0.28	250,000	37	--
839155	40,000	< 0.05	1.7	530	8.5	0.29	280,000	60	--
Minimum	32,000	< 0.05	1.7	390	8	0.17	200,000	16	--
Mean	37,375	< 0.05	3.9	633	11	0.27	223,800	42	--
Maximum	41,000	0.092	4.8	1,100	13	0.45	280,000	66	--
95% UCL	39,334	0.072	4.7	799	12	0.23	243,000	53	--

A.3 Metal concentrations (mg/kg) in < 75 µm slag

	Total Cobalt	Total Copper	Total Iron	Total Lead	Total Magnesium	Total Manganese	Total Mercury	Total Molybdenum	Total Nickel
Blast Furnace (BF) Slag									
839130/839133	3	21	2,800	1.8	50,000	2,600	< 0.01	0.3	3.9
839131/839132	3.8	19	5,500	5.1	41,000	2,900	< 0.01	1.2	6.1
839136/839137	5.1	20	5,600	3.5	50,000	3,400	< 0.01	0.55	5.6
839141/839142	5.7	15	6,300	2.2	48,000	3,600	< 0.01	0.29	3.4
839143/839144	5.8	14	7,800	3	58,000	3,200	< 0.01	0.57	4.6
839147/839148	2.5	29	6,600	5.9	41,000	3,900	0.015	0.65	6.9
839154	6.1	38	4,700	2	60,000	3,400	< 0.01	0.56	5.9
839155	3.6	170	3,700	7.8	58,000	3,700	< 0.01	2.6	12
Minimum	2.5	14	2,800	1.8	41,000	2,600	< 0.01	0.29	3.4
Mean	4.5	41	5,375	3.9	50,750	3,338	< 0.01	0.84	6.1
Maximum	6.1	170	7,800	7.8	60,000	3,900	0.015	2.6	12
95% UCL	5.9	83	6,455	5.4	55,747	3,624	NC	1.50	7.8

A.3 Metal concentrations (mg/kg) in < 75 µm slag

	Total Phosphorus	Total Selenium	Total Silicon	Total Silver	Total Thallium	Total Tin	Total Vanadium	Total Zinc
Blast Furnace (BF) Slag								
839130/839133	370	7.7	1,700	0.37	< 0.02	< 2.5	18	17
839131/839132	390	7	2,300	0.85	0.062	< 2.5	17	21
839136/839137	400	4.6	2,000	0.42	0.052	< 2.5	26	38
839141/839142	440	8	1,700	0.51	< 0.02	< 5	44	22
839143/839144	480	6.2	2,100	0.49	< 0.02	< 5	29	22
839147/839148	390	5.2	2,800	0.44	0.19	< 2.5	26	50
839154	400	6	1,800	0.6	< 0.02	< 2.5	31	24
839155	320	8.5	2,400	0.65	0.042	< 2.5	31	41
Minimum	320	4.6	1,700	0.37	< 0.02	< 2.5	17	17
Mean	399	6.7	2,100	0.54	0.05	1.56	28	29
Maximum	480	8.5	2,800	0.85	0.19	2.5	44	50
95% UCL	430	7.6	2,358	0.65	0.10	NC	33	37

NC = could not be calculated because of low number of detected samples; "--" = not analyzed; <LOD = less than the limit of detection

Statistics were calculated on sample averages (averaging duplicates). Nondetects (<LOD) were assigned a value of 1/2LOD.

Appendix B

Tier II Risk-Based Concentration Equations for the Deterministic Risk Assessment

Appendix B
Tier II Risk-Based Concentration Equations for the Deterministic Risk Assessment

Notes:

Slag risk-based concentration equations are based on the U.S. EPA Regional Screening Level equations (Available online at http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/equations.htm)

Acronyms are defined and numerical values provided in Table 5.1.

Residential Equations (Roadside)

Residential (Roadside) - Noncarcinogenic

Inhalation

$$Res.roadside.inh.RBC.nc\,(mg/kg) = \frac{THQ \; x \; ATnc.res.child}{EF.res \; x \; ED.res.child \; x \; ET.res \; x \; (1/RfC) \; x \; (1/PEF.res.roadside)}$$

Residential (Roadside) - Carcinogenic

Inhalation

$$Res.roadside.inh.RBC.c\,(mg/kg) = \frac{TR \; x \; ATc}{IUR \; x \; CF.2 \; x \; EF.res\,(1/PEF.res.roadside) \; x \; ED.res.adult \; x \; ET.res}$$

Residential (Roadside) – Mutagenic (Carcinogenic) – Applies to Chromium (VI) Only

Inhalation

$$Res.roadside.inh.RBC.c_{mut}\,(mg/kg) = \frac{TR \; x \; ATc}{EF.res \; x \; ET.res \; x \; CF.2} \; x$$

$$\frac{1}{[(ED.res.0\_2 \; x \; IUR \; x \; 10) + (ED.res.2\_6 \; x \; IUR \; x \; 3) + (ED.res.6\_16 \; x \; IUR \; x \; 3) + (ED.res.16\_30 \; x \; IUR \; x \; 1)] \; x \; (1/PEF.res.roadside)}$$

Residential Equations (Driveway)

Residential (Driveway) - Noncarcinogenic

Oral

$$Res.driveway.oral.RBC.nc\,({}^{mg}\!/\!_{kg}) = \frac{THQ\ x\ ATnc.res.child\ x\ BW.child}{EF.res\ x\ ED.res.child\ ({}^{1}\!/\!_{RfD})\ x\ IRsoil.res.child\ x\ CF.1}$$

Inhalation

$$Res.driveway.inh.RBC.nc\,({}^{mg}\!/\!_{kg}) = \frac{THQ\ x\ ATnc.res.child}{EF.res\ x\ ED.res.child\ x\ ET.res\ x\ ({}^{1}\!/\!_{RfC})\ x\ ({}^{1}\!/\!_{PEF.res.driveway})}$$

Total

$$Res.driveway.tot.RBC.nc\,({}^{mg}\!/\!_{kg}) = \frac{1}{\frac{1}{Res.driveway.oral.RBC.nc} + \frac{1}{Res.driveway.inh.RBC.nc}}$$

Residential (Driveway) - Carcinogenic

Oral

$$Res.driveway.oral.RBC.c\,({}^{mg}\!/_{kg}) = \frac{TR\ x\ ATc}{CSF\ x\ EF.res\ x\ IFS.adj\ x\ CF.1}$$

$$where:$$

$$IFS.adj = \frac{ED.res.child\ x\ IRsoil.res.child}{BW.child} + \frac{(ED.res.adult - ED.res.child)\ x\ IRsoil.res.adult}{BW.adult}$$

Inhalation

$$Res.driveway.inh.RBC.c\,({}^{mg}\!/_{kg}) = \frac{TR\ x\ ATc}{IUR\ x\ CF.2\ x\ EF.res\,({}^{1}\!/_{PEF.res.driveway})\ x\ ED.res.adult\ x\ ET.res}$$

Total

$$Res.driveway.tot.RBC.c\,({}^{mg}\!/_{kg}) = \frac{1}{\frac{1}{Res.driveway.oral.RBC.c} + \frac{1}{Res.driveway.inh.RBC.c}}$$

Residential (Driveway) – Mutagenic (Carcinogenic) – Applies to Chromium (VI) Only

Oral

$$Res.driveway.oral.RBC.c_{mut}\ ({}^{mg}\!/_{mg}) = \frac{TR\ x\ ATc}{CSF\ x\ EF.res\ x\ IFSM.adj\ x\ CF.1}$$

$$where:$$

$$\begin{aligned}IFSM.adj = {} & \left(\frac{ED.res.0\_2\ x\ IRsoil.res.child\ x\ 10}{BW.child}\right) + \left(\frac{ED.res.2\_6\ x\ IRsoil.res.child\ x\ 3}{BW.child}\right) + \\ & \left(\frac{ED.res.6\_16\ x\ IRsoil.res.adult\ x\ 3}{BW.adult}\right) + \left(\frac{ED.res.16\_30\ x\ IRsoil.res.adult\ x\ 1}{BW.adult}\right)\end{aligned}$$

Inhalation

$$Res.driveway.inh.RBC.c_{mut}\ ({}^{mg}\!/_{kg}) = \frac{TR\ x\ ATc}{EF.res\ x\ ET.res\ x\ CF.2}\ x$$

$$\frac{1}{[(ED.res.0\_2\ x\ IUR\ x\ 10)+(ED.res.2\_6\ x\ IUR\ x\ 3)+(ED.res.6\_16\ x\ IUR\ x\ 3)+(ED.res.16\_30\ x\ IUR\ x\ 1)]\ x\ ({}^{1}\!/_{PEF.res.driveway})}$$

Total

$$Res.driveway.tot.RBC.c_{mut}\ ({}^{mg}\!/_{kg}) = \frac{1}{\frac{1}{Res.oral.RBC.c_{mut}} + \frac{1}{Res.inh.RBC.c_{mut}}}$$

Industrial/Maintenance Worker Equations

Industrial/Maintenance Worker - Noncarcinogenic

Oral

$$IWMW.oral.RBC.nc\,(mg/kg) = \frac{THQ \text{ x } ATnc.iwmw \text{ x } BW.adult}{EF.iwmw \text{ x } ED.iwmw\,(1/RfD) \text{ x } IRsoil.iwmw \text{ x } CF.1}$$

Inhalation

$$IWMW.inh.RBC.nc\,(mg/kg) = \frac{THQ \text{ x } ATnc.iwmw}{EF.iwmw \text{ x } ED.iwmw \text{ x } ET.res \text{ x } (1/RfC) \text{ x } (1/PEF.iwmw)}$$

Total

$$IWMW.tot.RBC.nc\,(mg/kg) = \frac{1}{\frac{1}{IWMW.oral.RBC.nc} + \frac{1}{IWMW.inh.RBC.nc}}$$

Industrial/Maintenance Worker - Carcinogenic

Oral

$$IWMW.oral.RBC.c\,(^{mg}/_{kg}) = \frac{TR \ x \ ATc \ x \ BW.adult}{EF.iwmw \ x \ ED.iwmw \ x \ CSF \ x \ \ x \ IRsoil.iwmw \ x \ CF.1}$$

Inhalation

$$IWMW.inh.RBC.c\,(^{mg}/_{kg}) = \frac{TR \ x \ ATc}{EF.iwmw \ x \ ED.iwmw \ x \ ET.iwmw \ x \ IUR \ x \ CF.2 \ x \ (^{1}/_{PEF.iwmw})}$$

Total

$$IWMW.tot.RBC.c\,(^{mg}/_{kg}) = \frac{1}{\frac{1}{IWMW.oral.RBC.c} + \frac{1}{IWMW.inh.RBC.c}}$$

Construction Worker Equations

Construction Worker - Noncarcinogenic

Oral

$$CW.oral.RBC.nc\,({}^{mg}\!/\!_{kg}) = \frac{THQ\ x\ ATnc.cw\ x\ BW.adult}{EF.cw\ x\ ED.cw\,({}^{1}\!/\!_{RfD})\ x\ IRsoil.cw\ x\ CF.1}$$

Inhalation

$$CW.inh.RBC.nc\,({}^{mg}\!/\!_{kg}) = \frac{THQ\ x\ ATnc.cw}{EF.cw\ x\ ED.cw\ x\ ET.res\ x\,({}^{1}\!/\!_{RfC})\ x\,({}^{1}\!/\!_{PEF.cw})}$$

Total

$$CW.tot.RBC.nc\,({}^{mg}\!/\!_{kg}) = \frac{1}{\frac{1}{CW.oral.RBC.nc} + \frac{1}{CW.inh.RBC.nc}}$$

Construction Worker - Carcinogenic

Oral

$$CW.oral.RBC.c\left({}^{mg}\!/_{kg}\right) = \frac{TR\ x\ ATc\ x\ BW.adult}{EF.cw\ x\ ED.cw\ x\ CSF\ x\ \ x\ IRsoil.cw\ x\ CF.1}$$

Inhalation

$$CW.inh.RBC.c\ \left({}^{mg}\!/_{kg}\right) = \frac{TR\ x\ ATc}{EF.cw\ x\ ED.cw\ x\ ET.cw\ x\ IUR\ x\ CF.2\ x\ \left({}^{1}\!/_{PEF.cw}\right)}$$

Total

$$CW.tot.RBC.c\left({}^{mg}\!/_{kg}\right) = \frac{1}{\frac{1}{CW.oral.RBC.c} + \frac{1}{CW.inh.RBC.c}}$$

Appendix C

Air Dispersion Modeling for Roadside Resident Scenario

Sullivan Environmental Consulting, Inc., 2010

An Air Quality Analysis of Predicted Normalized Annual Average Concentrations Of PM10 Emissions for Unpaved Road Sources

Submitted to:

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Introduction

The objective of this analysis is to estimate normalized annual average concentrations resulting from vehicular traffic moving over hypothetical road segments for six meteorological data sets across the U.S. Normalized modeling results were produced for the following distances: 10, 20, 30, 40, 50, 100, 200 and 400 meters from the road. This report is a follow-up to a similar modeling report that Sullivan Environmental Consulting, Inc. (Sullivan Environmental) compiled in 2006 for Exponent using the ISCST3 dispersion model.

The AERMOD model (version 09292) (EPA, 2009) was used for this analysis. These model runs are fully consistent with U.S. Environmental Protection Agency's (EPA) Model guidance (EPA, 2003) and is appropriate for this type of application. AERMOD has been thoroughly tested by the U.S. Environmental Protection Agency (see Appendix A). The AERMOD model (EPA, 2009; EPA, 2006; EPA, 2004) is a steady-state Gaussian plume model, which can be used to assess pollutant concentrations from a wide variety of sources such as stack, area, and volume sources. In this case, the roadway segments were represented using area sources with initial dispersion to account for the turbulent wake created by the vehicles. The model can be applied for areas of rural or urban areas, flat or rolling terrain, and for various averaging times ranging from 1-hour to annual. Receptor grids can be established in both a polar or discrete Cartesian format. In this modeling analysis, AERMOD was run with the FASTALL mode (optimized source calculations) with the rural control option. This optimized source option reduces model run times while the model results are not affected in any significant way to change the overall conclusions. Typically, the model results using these types of sources for the close-in receptors (<20 meter distance) do not vary more than ±7 percent and less than ±2 percent for the larger distances (>20 meters) using this optimized option compared to the much slower default option. The representative road source was modeled using the AREAPOLY source option.

This report summarizes the technical approach and results of the AERMOD modeling analysis that addresses the annual average concentrations resulting from these road PM10 emissions. All AERMOD model input/output files discussed in this report are provided in Appendix A.

1.0 Road Source

The road source was modeled as a series of 19 adjoining area sources (actually called AREAPOLY within AERMOD), each with a 6-meter width and 55-meter length for a total length of 1,045 meters. A base model run consisted of these area sources oriented in a north-south direction. Conservatively using an assumed physical height of 4 feet for the expected vehicles on the road, a modeled emission height of 0.6 meters and a sigma z (vertical distribution) height of 0.56 meters were used to represent the expected initial PM10 plume emitted behind the vehicles as they travel down an unpaved road.

A normalized emission rate of 0.0030303 grams/second per square meter was estimated by taking the ratio of the area of one of the individual area sources (i.e., 1 gram divided by (6-meters x 55-meters)). This normalized emission rate was applied to all nineteen individual area sources.

2.0 Meteorological Data

Six sets of 5-year processed hourly surface meteorological data in the form of wind direction vector, wind speed, temperature, stability, and mixing heights were used in this modeling analysis as the basis to represent various regions across the U.S. These six meteorological data sets were obtained for the following cities:

1. Austin, Texas (1983-1984; 1986-1988)
2. Bridgeport, Connecticut (2004-2008)
3. Charleston, South Carolina (2002-2006)
4. Des Moines, Iowa (2000-2004)
5. Detroit, Michigan (1986-1990)
6. Fresno, California (2004-2008)

With the exception for Detroit, Michigan data, these meteorological data sets were downloaded from each corresponding State regulatory agency web site as preprocessed, model-ready surface and upper air data files for AERMOD input. The Detroit data was processed by Sullivan Environmental using the AERMET preprocessor (EPA, 2006b; EPA, 2004b). These preprocessed files of hourly meteorological data are compiled in Appendix B.

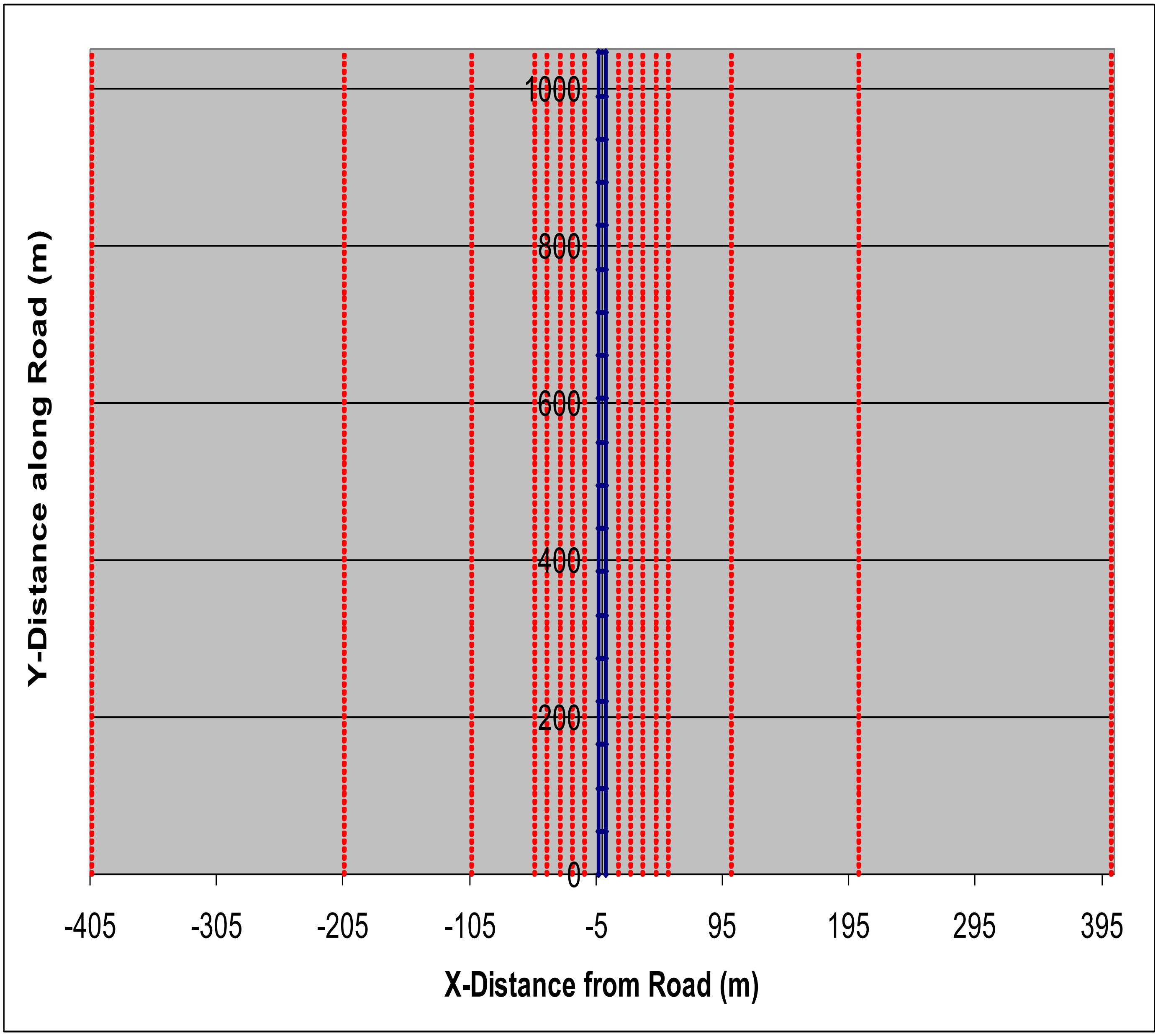
In order to properly account for different road orientations and, therefore, potentially different downwind impacts, the base north-south road orientation was maintained while the wind vectors within the meteorological data was rotated. This wind vector rotation is able to account for road orientations such as east-west (rotating the wind vector by positive 90 degrees), northeast-southwest (rotating the wind vector by positive 45 degrees), and northwest-southeast (rotating the wind vector by negative 45 degrees). This resulted in running four separate wind vector/road orientation scenarios.

3.0 Model Receptor Grid

A Cartesian model receptor grid was developed into 16 rows of receptors parallel to the modeled road source, with eight rows on each side of the road. The eight rows on each side of the road were placed at the specific distances from the edge of the road., i.e. 10, 20, 30, 40, 50, 100, 200, and 400 meters) at a receptor grid spacing of 10-meters between the receptors in each row. An example of the model receptor grid used is provided in Figure 1. Each receptor was modeled with a flagpole height of 2.0 meters (as requested by Exponent in the original 2006 modeling analysis).

Figure 1

Example Plot of the Model Receptor Grid of the Base North-South Oriented Road Source



5.0 Model Results

The model results, in the form of normalized annual average concentrations, for each of the four road-orientation scenarios and six meteorological data sites are provided in Appendix C as an Excel spreadsheet, with summary tables shown in the spreadsheet. These normalized concentrations are presented for each of the eight distances as defined earlier. Actual concentrations will need to be computed by multiplying these normalized concentrations by the ratio of the actual emission rates in the unit of grams/second-square meter over the modeled emission rate of 0.0030303 grams/second-square meter.

REFERENCES

EPA, 2003: Guideline on Air Quality Models (Revised). U.S. Environmental Protection Agency, 40 CFR 51 Appendix W, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

EPA, 2004: User's Guide for the AMS/EPA Regulatory Model - AERMOD. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, EPA-454/B-03-001, September 2004.

EPA, 2004b: User's Guide for the AERMOD Meteorological Preprocessor (AERMET). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, EPA-454/B-03-002, November 2004.

EPA, 2006: ADDENDUM - User's Guide for the AMS/EPA Regulatory Model - AERMOD. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, EPA-454/B-03-001, December 2006.

EPA, 2006b: ADDENDUM - User's Guide for the AERMOD Meteorological Preprocessor (AERMET). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, EPA-454/B-03-001, December 2006.

EPA, 2009: ADDENDUM - User's Guide for the AMS/EPA Regulatory Model - AERMOD. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, EPA-454/B-03-001, October 2009.

Appendix A

AERMOD Input Files

[APPENDIXA.ZIP]

1. BASERUN2.ZIP (North-South Road)
2. 90DEG2.ZIP (East-West Road)
3. 45DEG2.ZIP (Northeast-Southwest Road)
4. N45DEG2.ZIP (Northwest-Southeast Road)

Appendix B

Processed 5-Year Hourly Surface Meteorological Data

[APPENDIXB.ZIP]

1. AUSTIN.SFC (Austin, TX)
2. BRIDGEPORT.SFC (Bridgeport, CT)
3. CHARLESTON.SFC (Charleston, SC)
4. DES_MOINES.SFC (Des Moines, IA)
5. DETROIT.SFC (Detroit, MI)
6. FRESNO.SFC (Fresno, CA)

State Web Links Used to Download Preprocessed AERMOD-Ready Meteorological Data Files

Austin, TX
http://www.tceq.state.tx.us/permitting/air/modeling/aermod_datasets.html

Bridgeport, CT
http://www.ct.gov/dep/cwp/view.asp?a=2684&q=450396&depNav_GID=1619

Charleston, SC
http://infoweb01.dhec.sc.gov/aermod/app/aermod.html

Des Moines, IA
http://www.iowadnr.gov/air/prof/tech/AERMODMetData.html

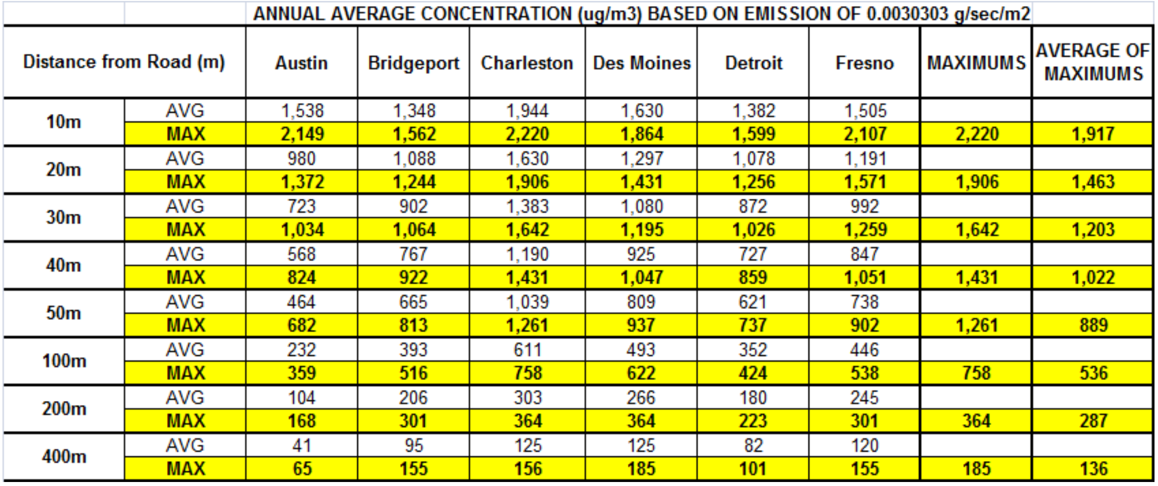
Fresno, CA
http://www.valleyair.org/busind/pto/Tox_Resources/AirQualityMonitoring.htm#met_section

Appendix C

Excel Spreadsheet
Summary Normalized Annual Average Concentrations

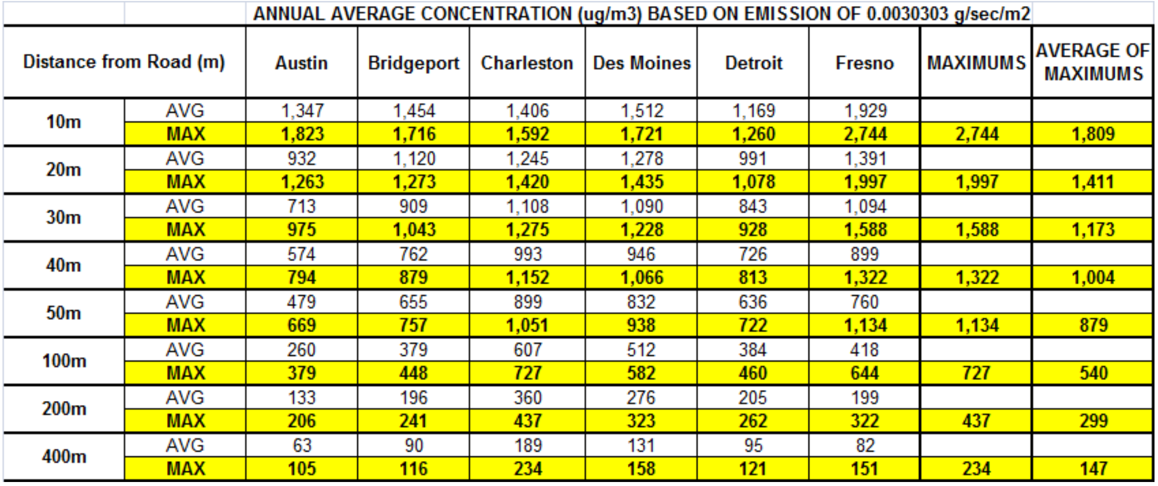
[APPENDIXC.ZIP]

North-South Road Orientation



		ANNUAL AVERAGE CONCENTRATION (ug/m3) BASED ON EMISSION OF 0.0030303 g/sec/m2							
Distance from Road (m)		**Austin**	**Bridgeport**	**Charleston**	**Des Moines**	**Detroit**	**Fresno**	**MAXIMUMS**	**AVERAGE OF MAXIMUMS**
10m	AVG	1,538	1,348	1,944	1,630	1,382	1,505		
	MAX	**2,149**	**1,562**	**2,220**	**1,864**	**1,599**	**2,107**	**2,220**	**1,917**
20m	AVG	980	1,088	1,630	1,297	1,078	1,191		
	MAX	**1,372**	**1,244**	**1,906**	**1,431**	**1,256**	**1,571**	**1,906**	**1,463**
30m	AVG	723	902	1,383	1,080	872	992		
	MAX	**1,034**	**1,064**	**1,642**	**1,195**	**1,026**	**1,259**	**1,642**	**1,203**
40m	AVG	568	767	1,190	925	727	847		
	MAX	**824**	**922**	**1,431**	**1,047**	**859**	**1,051**	**1,431**	**1,022**
50m	AVG	464	665	1,039	809	621	738		
	MAX	**682**	**813**	**1,261**	**937**	**737**	**902**	**1,261**	**889**
100m	AVG	232	393	611	493	352	446		
	MAX	**359**	**516**	**758**	**622**	**424**	**538**	**758**	**536**
200m	AVG	104	206	303	266	180	245		
	MAX	**168**	**301**	**364**	**364**	**223**	**301**	**364**	**287**
400m	AVG	41	95	125	125	82	120		
	MAX	**65**	**155**	**156**	**185**	**101**	**155**	**185**	**136**

East-West Road Orientation



		ANNUAL AVERAGE CONCENTRATION (ug/m3) BASED ON EMISSION OF 0.0030303 g/sec/m2							
Distance from Road (m)		**Austin**	**Bridgeport**	**Charleston**	**Des Moines**	**Detroit**	**Fresno**	**MAXIMUMS**	**AVERAGE OF MAXIMUMS**
10m	AVG	1,347	1,454	1,406	1,512	1,169	1,929		
	MAX	**1,823**	**1,716**	**1,592**	**1,721**	**1,260**	**2,744**	**2,744**	**1,809**
20m	AVG	932	1,120	1,245	1,278	991	1,391		
	MAX	**1,263**	**1,273**	**1,420**	**1,435**	**1,078**	**1,997**	**1,997**	**1,411**
30m	AVG	713	909	1,108	1,090	843	1,094		
	MAX	**975**	**1,043**	**1,275**	**1,228**	**928**	**1,588**	**1,588**	**1,173**
40m	AVG	574	762	993	946	726	899		
	MAX	**794**	**879**	**1,152**	**1,066**	**813**	**1,322**	**1,322**	**1,004**
50m	AVG	479	655	899	832	636	760		
	MAX	**669**	**757**	**1,051**	**938**	**722**	**1,134**	**1,134**	**879**
100m	AVG	260	379	607	512	384	418		
	MAX	**379**	**448**	**727**	**582**	**460**	**644**	**727**	**540**
200m	AVG	133	196	360	276	205	199		
	MAX	**206**	**241**	**437**	**323**	**262**	**322**	**437**	**299**
400m	AVG	63	90	189	131	95	82		
	MAX	**105**	**116**	**234**	**158**	**121**	**151**	**234**	**147**

Northeast-Southwest Road Orientation

		ANNUAL AVERAGE CONCENTRATION (ug/m3) BASED ON EMISSION OF 0.0030303 g/sec/m2							
Distance from Road (m)		Austin	Bridgeport	Charleston	Des Moines	Detroit	Fresno	MAXIMUMS	AVERAGE OF MAXIMUMS
10m	AVG	1,384	1,590	1,882	1,420	1,266	1,360		
	MAX	1,979	2,256	2,216	1,817	1,387	1,708	2,256	1,894
20m	AVG	936	1,213	1,534	1,199	1,033	1,161		
	MAX	1,344	1,757	1,809	1,435	1,132	1,441	1,809	1,486
30m	AVG	712	973	1,297	1,030	861	985		
	MAX	1,029	1,442	1,524	1,208	966	1,205	1,524	1,229
40m	AVG	571	808	1,122	900	733	849		
	MAX	835	1,209	1,309	1,032	833	1,034	1,309	1,042
50m	AVG	475	687	986	798	636	743		
	MAX	701	1,043	1,147	898	731	900	1,147	903
100m	AVG	254	379	601	508	374	455		
	MAX	393	602	694	584	448	546	694	545
200m	AVG	127	182	314	287	193	256		
	MAX	211	296	388	357	237	318	388	301
400m	AVG	58	74	135	144	87	132		
	MAX	106	111	186	189	115	177	189	147

Northwest-Southeast Road Orientation

		ANNUAL AVERAGE CONCENTRATION (ug/m3) BASED ON EMISSION OF 0.0030303 g/sec/m2							
Distance from Road (m)		Austin	Bridgeport	Charleston	Des Moines	Detroit	Fresno	MAXIMUMS	AVERAGE OF MAXIMUMS
10m	AVG	1,492	1,195	1,303	1,738	1,179	2,093		
	MAX	1,888	1,313	1,497	2,112	1,441	2,424	2,424	1,779
20m	AVG	971	986	1,232	1,380	1,011	1,436		
	MAX	1,221	1,094	1,398	1,710	1,260	1,775	1,775	1,410
30m	AVG	723	835	1,126	1,143	860	1,105		
	MAX	919	948	1,293	1,445	1,082	1,419	1,445	1,184
40m	AVG	572	721	1,024	973	741	892		
	MAX	735	832	1,186	1,246	942	1,178	1,246	1,020
50m	AVG	470	634	934	845	647	742		
	MAX	612	742	1,089	1,096	827	1,001	1,096	894
100m	AVG	241	394	635	497	387	382		
	MAX	331	487	768	676	515	563	768	557
200m	AVG	113	221	371	255	202	173		
	MAX	164	288	474	356	281	266	474	305
400m	AVG	47	111	187	113	92	66		
	MAX	72	149	247	152	125	115	247	143

Appendix D

Approach for calculating Tier III RBCs in the PRA

Approach for Calculating PRA RBCs

To calculate risk and hazard for PCOIs, the soil DRA/RBC equations were modified. Instead of calculating a soil concentration, the equations were configured to calculate risk and hazard. An example of this modification is provided below for soil ingestion, non-carcinogenic PCOIs in Equations D.1 (Tier II RBC equation), and D.2 (modified for hazard for Tier III RBC).

Eq. D.1

$$Csoil = \frac{THQ\ x\ AT\ x\ BW}{EF\ x\ ED\ x\ (\,{}^{1}\!/_{RfD})\ x\ IR_{soil}\ x\ B_{oral}}$$

Eq. D.2

$$THQ = \frac{Csoil\ x\ EF\ x\ ED\ x\ IR_{soil}\ x\ B_{oral}}{RfD\ x\ AT\ x\ BW}$$

where:

Csoil	concentration in soil (mg/kg)
THQ	target hazard quotient (1)
EF	exposure frequency (days per year)
ED	exposure duration (years)
IR_{soil}	ingestion rate of soil (kg/day)
RfD	oral reference dose (mg/kg-day)
AT	averaging time (days)
BW	body weight (kg)
B_{oral}	bioaccessibility (fractional percentage)

Equation D.2 was modified to include exposure time (ET), as illustrated below in Equation D.3. Exposure time represents the proportion of the day spent outdoors that could be spent in contact with slag. The USEPA Exposure Factors Handbook (USEPA 2009a) provides average hours per day spent outdoors and average hours per day spent in contact with sand or gravel by age. It was assumed that time spent in contact with sand or gravel was representative of time spent in contact with slag. This is expected to be a conservative assumption because slag is vitreous and cementitious and does not offer a desirable substrate for prolonged or frequent contact. We calculated the fraction of time that might be spent in contact with slag as a fraction using the hours per day spent in contact with sand or gravel divided by the hours per day spent outdoors, for each age group. The highest percentage (56%) was calculated for children 6 to 11 years old. To use these data in the PRA, a triangular distribution of ET was developed with a mean value of 56%, a maximum of 100%, and a minimum value of 0%. ET was not included in the DRA, thus in essence, it was assumed that 100% of soil ingestion is contributed by slag. This is a highly unlikely assumption, given that slag is not a desirable substrate for direct contact.

Eq. D.3

$$THQ = \frac{Csoil\ x\ EF\ x\ ED\ x\ IR_{soil}\ x\ B_{oral}\ x\ ET}{RfD\ x\ AT\ x\ BW}$$

The THQ for inhalation was calculated by rearranging the RSL equation presented in Equation D.4 as Equation D.5.

Eq. D.4

$$Csoil = \frac{THQ\ x\ AT\ x\ (PEF + VF)}{EF\ x\ ED\ x\ ET\ x\ (\ {}^{1}\!/_{RfC}\ )}$$

Eq. D.5

$$THQ = \frac{Csoil\ x\ EF\ x\ ED}{RfC\ x\ AT\ x\ (PEF + VF)}$$

where:

PEF particulate emission factor (m^3/kg)

VF vapor emission factor (equal to zero for slag)

RfC reference concentration (kg/m^3)

ET exposure time (fraction)

Equation D.5 was further modified to use an RfDi, the inhalation reference dose, instead of an RfC, so that distributions of BW and inhalation rate (Inh) might be included. The result is presented below in Equation D.6.

Eq. D.6

$$THQ = \frac{Csoil\ x\ EF\ x\ ED\ x\ ET}{(RfDi\ x\ BW)/(Inh\ x\ AT\ x\ PEF)}$$

For Cr(VI) in the DRA, the equations used to calculate risk due to oral exposure were consistent with those specified for chemicals that act by a mutagenic Mode of Action (MOA). The USEPA Preliminary Draft Toxicological Review classified Cr(VI) as a mutagen; however there is considerable uncertainty in this determination (Thompson et al. 2010). Special equations are used for mutagens which include Age –Dependent Adjustment Factors (ADAFs) to account for early life sensitivity. These equations, which invoke an age-dependent weighting scheme, are shown below in Equations D.7 and D.8.

Eq. D.7

$$Csoil = \frac{TRL\ x\ AT}{CSF\ x\ EF\ x\ IFSM}$$

Eq. D.8

$$IFSMo = (10\ x\ ED_{0\text{-}2}\ \ x\ [\ {}^{IRc}\!/_{BWc}]) + (3\ x\ ED_{2\text{-}6}\ \ x\ [\ {}^{IRc}\!/_{BWc}]) + (3\ x\ ED_{6\text{-}16}\ \ x\ [\ {}^{IRa}\!/_{BWa}]) + (ED_{16\text{-}30}\ \ x\ [\ {}^{IRa}\!/_{BWa}])$$

where:

CSF	cancer slope factor $(mg/kg\text{-}day)^{-1}$
BWc	body weight, child (kg)
BWa	body weight, adult (kg)
IRc	ingestion rate, child (kg/day)
IRa	ingestion rate, adult (kg/day)
$ED_{X\text{-}Y}$	exposure duration, from time period X to Y (years)

Because it was difficult to assess exposure duration in a probabilistic framework for four time periods, Equation D.8 was simplified to two time periods (0-6 years for child exposure, 6-30 years for adult exposure) and a multiplying factor for oral exposure (MFo). The multiplying factor is used to represent the age-dependent weighting described above in Equation D.8. MFo was determined by setting Equation D.8 equal to Equation D.9 since there is only one unknown parameter, and it was calculated to be 4.28. The two time period representation of the age-adjusted soil ingestion rate IFSMo is shown below in Equation D.9.

Eq. D.9

$$IFSMo = MFo\ x\ ([ED_{0\text{-}6}\ \ x\ \{\ {}^{IRc}\!/_{BWc}\} +\ \ [ED_{6\text{-}30}\ \ x\ \{\ {}^{IRa}\!/_{BWa}\})$$

Equation E.9 was then modified to calculate risk, including factors for B_{oral} and an ET. The resulting equation is shown below in Equation E.10.

Eq. D.10

$$Risk = \frac{Csoil\ x\ CSF\ x\ EF\ x\ B_{oral}\ \ x\ ET\ x\ IFSMo}{AT}$$

A similar approach was applied for calculating risk due to inhalation exposure to Cr(VI), assuming that it acts by a mutagenic MOA via inhalation. These equations are shown below in Equation D.11 and D.12 and invoke an age-dependent weighting scheme.

Eq. D.11

$$Csoil = \frac{TRL\ x\ AT}{CSF\ x\ EF\ x\ ET\ x\ IFSMi\ x\ (\ {}^{1}\!/_{PEF}\ +\ {}^{1}\!/_{VF}\ )}$$

Eq. D.12

$$IFSMi = (10\ x\ ED_{0\text{-}2}\ \ x\ IUR) + (3\ x\ ED_{2\text{-}6} x\ IUR) + (3\ x\ ED_{6\text{-}16} x\ IUR) + (ED_{16\text{-}30}\ \ x\ IUR)$$

where:

IUR inhalation unit risk factor $(mg/m^3)^{-1}$

VF vapor emission factor (equal to zero for slag)

Equation D.12 was modified to include the inhalation cancer slope factor (CSFi) instead of URF, so that the BW and Inh might be included explicitly. Both BW and Inh are treated as distributions in the PRA. The result is presented below in Equation D.13.

Eq. D. 13

$$IFSMi = \left(10\ x\ ED_{0-2}\ x\ CSFi\ x\ [{}^{Inhc}/_{BWc}]\right) + \left(3\ x\ ED_{2-6}\ x\ CSFi\ x\ \left[{}^{Inhc}/_{BWc}\right]\right) + (3\ x\ ED_{6-16}\ x\ CSFi\ x\ \left[{}^{Inha}/_{BWa}\right]) + (ED_{16-30}\ x\ CSFi\ x\ \left[{}^{Inha}/_{BWa}\right])$$

where:

Inha inhalation rate, adult (m^3/day)

Inhc inhalation rate, child (m^3/day)

Because it was difficult to assess exposure duration in a probabilistic framework for four time periods, the IFSMi equation was simplified to a two time period calculation (0-6 years for child exposure, 6-30 years for adult exposure) and a multiplying factor (MFi) was used. The two time period representation of IFSMi is shown below in Equation D.14.

Eq. D.14

$$IFSMi = MFi\ x\ ([ED_{0\text{-}6}\ x\ CSFi\ x\ \{{}^{Inhc}/_{BWc}\}] + [ED_{6\text{-}30}\ x\ CSFi\ x\ \{{}^{Inha}/_{BWa}\}])$$

MFi is used to represent the weights indicated above in Equation D.13. MFi was determined by setting Equation D.13 equal to Equation D.14 since there is only one unknown parameter, and was calculated to be 3.31. Equation D.11 was then modified to calculate risk. The resulting equation is shown below in Equation D.15.

Eq. D.15

$$Risk = \frac{Csoil\ x\ CSF\ x\ EF\ x\ ET\ x\ IFSMi}{AT\ x\ PEF}$$

Cumulative risk and hazard were calculated by adding oral and inhalation risks or hazards as appropriate. The risk or hazard equations above were solved using a Monte-Carlo analysis (MCA). MCA is a technique that repeatedly samples the probability distributions of the risk equation inputs and generates a range of risk values. The PRA was conducted using the software program Crystal Ball (v.

11.1.1.1) in Microsoft Excel. Distributions of inhalation risk/hazard, oral risk/hazard, and total risk/hazard were developed.

To calculate the Tier III RBCs, a point value of 1 mg/kg was used for the chemical concentration in soil (Csoil). This was done so that distributions of risk and hazard generated in the PRA represented a unit concentration. Then a risk or hazard percentile could be located on the distribution (the median and 90th percentile for our analysis), and a slag concentration that corresponds directly to the percentile of risk or hazard could be back-calculated using a simple ratio. This principle is demonstrated in Equations D.16 and D.17. A target risk level (TRL) of 10^{-5} and a target hazard quotient (THQ) of 1.0 were used. Equations D.16 and D.17 show the calculation for the 90th percentile.

Eq. D.16

$$Csoil_{TRL} = \frac{Csoil_{unity} \ x \ 10^{-5}}{Risk_{p=0.90}}$$

Eq. D.17

$$Csoil_{THQ} = \frac{Csoil_{unity} \ x \ 1.0}{HQ_{p=0.90}}$$

In these equations, $Csoil_{TRL}$ indicates the concentration in soil that corresponds to a risk of 10^{-5} at the 90th percentile in the risk distribution. Likewise, $Csoil_{THQ}$ indicates the concentration in soil that corresponds to a hazard quotient (HQ) of 1.0 at the 90th percentile in the distribution of hazard.

Appendix E

Ecological Risk Assessment (Section 3) from Exponent (2007): Human Health and Ecological Risk Assessment for Environmental Applications of Steel-making Slag: An Update*

*The human health risk assessment of the 2007 Exponent report is superseded by the current risk assessment in this document (ToxStrategies, 2011: Human Health Risk Assessment for Iron and Steel Slag).

Exponent®

Human Health and Ecological Risk Assessment for the Environmental Applications of Steel-Making Slag: An Update

November 8, 2007
(Update in progress;
completion anticipated in
2008)

Human Health and Ecological Risk Assessment for the Environmental Applications of Steel-Making Slag: An Update

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Acronyms and Abbreviations

ABS_{derm}	dermal absorption factor
ABS_{GI}	gastrointestinal absorption factor
ACR	acute-chronic ratio
ADD	average daily dose
ASTM	American Society for Testing and Materials
AWQC	ambient water quality criterion
B_{dermal}	dermal bioaccessibility factor
BF	blast furnace
BMD	benchmark dose modeling
BMDL	5% effect level of the benchmark dose (BMDL)
BOF	basic oxygen furnace
B_{oral}	oral bioaccessibility factor
CMC	criterion maximum concentration
COI	chemical of interest
CSL	cleanup screening levels
CT	central tendency
EAF	electric arc furnace
Eco-SSL	ecological soil screening level
EPA	U.S. Environmental Protection Agency
EPC	exposure-point concentration
ERL	effects range-low
ERM	effects range-median
ESL	ecological screening levels
ET	ecotox thresholds
FAV	final acute value
FCV	final chronic value
FTS	fraction of time spent in the area with exposed slag
GI	gastrointestinal
HHRA	human health risk assessment
HI	hazard index
IRIS	Integrated Risk Information System
K_d	water-to-solid partitioning coefficient
LADD	lifetime average daily dose
LC_{50}	lethal concentration affecting 50% of the test population
LEL	lowest effect level
LOAEL	lowest-observed-adverse-effect level
MLE	most likely exposure
NEC	no-effect concentration
NOAA	National Oceanic and Atmospheric Administration
NOAEL	no-observed-adverse-effect level
ORNL	Oak Ridge National Laboratory
PEC	probable effect concentration
PEF	particulate emission factors

PEL	probable effects level
PRG	preliminary remediation goal
RCRA	Resource Conservation and Recovery Act
RfC	reference concentration
RfD	reference dose
RME	reasonable maximum exposure
SEL	severe effect level
SF	slope factor
SQG	sediment quality guidelines
SQS	sediment quality standard
SSL	soil screening level
TCLP	toxicity characteristic leaching procedure
TEC	threshold effect concentration
TEL	threshold effects level
UCL	upper confidence limit

3 Evaluation of Potential Ecological Risks Related to Steel-Industry Slag

3.1 Introduction

The potential ecological risks posed by the use of steel-industry slags for various applications that result in exposure to the environment were evaluated in a risk assessment by Proctor et al. (2002). This evaluation is based on slag characterization data reported by Proctor et al. (2000). Ecological risk assessment is typically conducted on a site-specific basis, and most of the tools used by risk assessors are designed to determine chemicals of potential ecological interest for further field evaluation. This assessment attempts to investigate whether the uses of steel-making slag could potentially pose an ecological hazard, and to identify environmental conditions that may be affected. Field studies of actual slag applications were not conducted in this assessment, and the conclusions are based on screening-level approaches. The primary uses of steel-making slags that could potentially result in exposure of ecological receptors include bank stabilization in and along salt and freshwater bodies and the application of slag for agricultural amendments.

Potential risks to aquatic life were assessed using information from ASTM water leachate tests that had been conducted on representative slag samples for the original risk assessment (ChemRisk 1998; Proctor et al. 2002). This assessment found that aluminum was the only metal that posed a potential risk to aquatic receptors, based on exceedance of the EPA ambient water quality criterion (AWQC). Proctor et al. (2002) also concluded that high pH values associated with slag leachate may pose potential ecological risks in aquatic systems that have limited dilution volume (i.e., less than a 100-fold dilution of the leachate).

In this paper, we update and extend the evaluations of potential ecological risks associated with slag conducted by Proctor et al. (2002). Specifically, additional surface-water screening values were compiled for fresh and salt water to evaluate metals not addressed by the EPA AWQC. In addition, available screening values for sediments and soil were compiled to assess potential ecological risks posed by slag to aquatic invertebrates that live in both freshwater and saltwater sediments, as well as terrestrial organisms that commonly come into contact with upland soil where slag may be applied or that may ingest biota that live in or on such soil. In addition, bioavailability and alkalinity, both important factors for the ecological risk assessment of metals in slags, are evaluated in greater detail.

Available ecological screening values were compiled by conducting literature searches of the values frequently used by both state and federal agencies to evaluate potential ecological risks for surface water, sediments, and soil. The metals concentrations found in various types of steel slag presented by Proctor et al. (2000) were then compared with the screening values to identify any exceedances.

Proctor et al. (2000) evaluated the chemical characteristics of the three kinds of slag produced during the iron- and steel-making process (BF , BOF , and EAF) slag. For each kind of slag, the authors determined the concentrations of various metals in the slag, as well as in two kinds of leachate: from a TCLP test used to determine the mobility of slag under acidic conditions, and from an ASTM distilled-water leachate test (D-3987) used to determine metals mobility in water under neutral conditions (pH 7). The TCLP leachate data were considered by Proctor et al. (2000) to represent a worst-case scenario for evaluating metal leaching from slag to groundwater.

The ASTM water leachate data were used by Proctor et al. (2000) and in this assessment to evaluate worst-case conditions for metals leaching to ambient surface water. This is a highly conservative approach, because the ASTM test is an 18-hour shake (agitated extraction) test performed at a 20-to-1 water-to-slag ratio. Extraction using this procedure overestimates the concentrations of metals that are likely to be leached into ambient water under environmental conditions. The method states that the procedure is not intended to produce a leachate representative of leachate generated in the field or to simulate site-specific leachate conditions. This approach was applied in this screening-level assessment, because information on metals in leachate under field conditions at the site of slag application is not available.

For purposes of this evaluation, the following data from Proctor et al. (2000) were used:

- **Metals concentrations in slag:** This information was used to represent potential exposure to slag constituents in fresh and saltwater sediments, as well as upland soil. To be conservative, the 95% UCLs of the metals concentrations found in the three types of slag evaluated by Proctor et al. were used for these comparisons.

- **Metals concentrations in ASTM water leachate:** This information was used to represent potential exposure to slag constituents in surface water (i.e., both fresh and salt water). To be conservative, the maximum metals concentrations found in leachates of the three types of slag evaluated by Proctor et al. (2000) were used for these comparisons. Maximum values were used in these comparisons, because sufficient sample sizes were not available to calculate meaningful 95% UCLs.

The remainder of this section presents the available screening values that are commonly used by governmental agencies to evaluate potential ecological risks of metals in surface water, sediments, and soil. The results of the comparisons of those screening values with the metals concentrations found in representative slag samples by Proctor et al. (2000) are also presented. A final section discusses ecological considerations related to high pH values.

3.2 Summary of Screening Values

This section presents the available screening values for metals in surface water, sediments, and soil.

3.2.1 Surface Water

3.2.1.1 Fresh Water

Five sets of freshwater screening values for metals in surface water were available (Table 3-1). They included four sets developed by various groups within EPA and one set developed by researchers at the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee. The freshwater screening values included the following:

- **EPA (2002c) AWQCs:** These values were developed using extensive toxicological databases and were intended to be used for regulatory applications throughout the U.S. The current AWQCs include both chronic and acute values and are updated versions of earlier AWQCs developed by EPA (1976, 1986).

- **EPA (1996b) ecotox thresholds (ETs):** These values were developed for use in EPA's Superfund program. They are intended to serve as screening values to identify chemical concentrations that may pose ecological risks and therefore warrant additional evaluation during site investigations.

- **EPA (2001) Region IV screening values:** These values were developed by EPA Region IV for use as regional screening values to identify chemical concentrations associated with a low probability of unacceptable risks to ecological receptors. They include both chronic and acute values.

- **EPA (2003) Region V ecological screening levels (ESLs):** These values were developed by EPA Region V for use as regional screening values to identify chemical concentrations associated with potential ecological risks at sites covered under the Resource Conservation and Recovery Act (RCRA). They were developed as protective benchmarks and primarily address chronic effects.

- **ORNL toxicological benchmarks (Suter and Tsao 1996):** These values were developed for use as screening values to identify chemical concentrations that may result in aquatic ecological effects. They include both chronic and acute values.

3.2.1.2 Salt Water

Three sets of saltwater screening values for metals in surface water were available, all of which were developed by various groups within EPA (Table 3-2). The saltwater screening values included the following (described above):

- **EPA (2002c) AWQCs**
- **EPA (1996b) ETs**
- **EPA (2001) Region IV screening values.**

3.2.2 Sediments

3.2.2.1 Fresh Water

Eight sets of freshwater screening values were available for metals in sediments (Table 3-3). They included three sets developed by various groups within EPA and five sets developed by various researchers. The fresh-water sediment screening values included the following:

- **EPA (1996b) ETs**
- **EPA (2001) Region IV screening values**
- **EPA (2003) Region V ESLs**
- **Threshold and probable effect concentrations (TECs and PECs):** These values were developed by MacDonald et al. (2000) to represent sediment quality guidelines (SQGs) that predict the absence of sediment toxicity (TECs) and the presence of toxicity (PECs). The SQGs were not developed independently, but were calculated as geometric means of SQGs developed by others (e.g., EC and MENVIQ 1992; Long and Morgan 1991; Persaud et al. 1993; Ingersoll et al. 1996; Smith et al. 1996).

- **Lowest and severe effect levels (LELs and SELs):** These values were developed by Persaud et al. (1993) to represent SQGs that predict the absence of adverse effects on the majority of benthic macroinvertebrates (LELs) and the presence of adverse effects on the majority of those organisms (SELs). These SQGs were developed based on evaluations of the presence and absence of various benthic macroinvertebrate species in benthic communities sampled in the Great Lakes.

- **Effects range-lows and range-medians (ERLs and ERMs):** These values were developed by Long and Morgan (1991) to represent SQGs below which adverse effects would rarely be observed (ERLs), and above which adverse effects would occur frequently (ERMs). These SQGs were developed using sediment toxicity information collected for fresh and saltwater sediments throughout the United States.

- **Threshold and probable effects levels (TELs and PELs):** These values were developed by Smith et al. (1996) to represent SQGs below which adverse effects are expected to occur rarely (TELs), and above which adverse effects are expected to occur frequently (PELs). These SQGs were developed using sediment toxicity information collected for freshwater sediments throughout the United States.

- **Great Lakes SQGs:** These values were developed by Ingersoll et al. (1996) to represent SQGs based on toxicity data collected from the Great Lakes. The authors used that database to develop ERLs, ERMs, TELs, PELs, and no-effect concentrations (NECs). The first four SQGs were developed for the same uses as they were for the national databases described previously for Long and Morgan (1991) and MacDonald et al. (1996). The NECs were developed to represent chemical concentrations above which adverse ecological effects were always found.

3.2.2.2 Salt Water

Four sets of saltwater screening values were available for metals in sediments (Table 3-4). They included one set developed by EPA, one set developed by the Washington Department of Ecology, and two sets developed by other authors. The saltwater sediment screening values included the following:

- **EPA (1996b) ETs**
- **ERLs and ERMs:** These values were developed by Long et al. (1995) to represent SQGs below which adverse effects would rarely be observed (ERLs), and above which adverse effects would frequently occur (ERMs). These SQGs were developed based on sediment toxicity information collected for saltwater sediments throughout the U.S. and were developed in a manner consistent with the ERLs and ERMs for freshwater sediments by Long and Morgan (1991).
- **TELs and PELs:** These values were developed by MacDonald et al. (1996) to represent SQGs below which adverse effects are expected to occur rarely (TELs), and above which adverse effects are expected to occur frequently (PELs). These SQGs were developed based on sediment toxicity information collected for freshwater and saltwater sediments throughout the U.S. and were developed in a manner consistent with the TELs and PELs for freshwater sediments by Smith et al. (1996).
- **Washington State sediment management standards:** These values were developed by the Washington Department of Ecology (Ecology 1995). The sediment quality standards (SQS) represent SQGs below which no adverse effects are found. The cleanup screening levels (CSLs) represent the maximum allowable concentrations within authorized sediment impact zones. Both kinds of SQGs were developed using sediment toxicity data collected from Puget Sound, Washington.

3.2.3 Soil

Four sets of ecological screening values were available for metals in soil (Table 3-5). They included three sets developed by various groups within EPA and one set developed by various researchers. The soil screening values included the following:

- **EPA ecological soil screening levels (Eco-SSLs):** These values were developed for use in EPA's Superfund program. They were intended to be protective of ecological receptors that commonly come into contact with soil or ingest biota that live in or on soil. Depending on the available data for each chemical, Eco-SSLs were derived separately for four groups of receptors: plants, soil invertebrates, birds, and mammals. The Eco-SSLs are considered screening values that can be used to identify chemical concentrations that may warrant additional evaluation during site investigations.
- **EPA (2001) Region IV screening values**
- **EPA (2003) Region V ESLs**
- **ORNL toxicological benchmarks (Efroymson et al. 1997a,b):** These screening values were developed for use in identifying chemical concentrations that may result in aquatic ecological effects. They include values for protection of earthworms, soil microorganisms, and terrestrial plants.

3.3 Comparisons with Screening Values

The metals concentrations found in the representative slag samples evaluated by Proctor et al. (2000) were compared with their respective screening values for surface water, sediments, and soil. In making these comparisons, the various screening values available for each environmental medium were prioritized so that a single screening value was used for each metal. If the screening value with the highest priority was not available for a metal, then the value with the next-highest priority was used until an acceptable screening value was identified.

It is important to note that the only screening values that can be considered potentially predictive of adverse biological effects are the EPA AWQCs, because those values were based on single-chemical laboratory toxicity evaluations, and in most cases, were based on a relatively large number of toxicity tests. All of the other screening values were developed specifically for use as screening tools by their original authors, or were derived from field-collected data and were, therefore, subject to the uncertainties inherent in using such data (e.g., uncertain exposure regimes, multiple co-occurring chemicals that can contribute to any observed toxicity).

The screening values with the highest priority were those developed by EPA at the national level, because EPA is the lead environmental regulatory agency in the United States. The screening values with the next-highest priority were those developed by others but endorsed by EPA. The next-highest priority was given to screening values developed by ORNL, because of the extensive amount of toxicological information on which they were based. The next priority was given to screening values that are most commonly used by regulatory agencies when screening values developed by or endorsed by EPA or ORNL were not available. The prioritization scheme used for each set of screening values is discussed below, in conjunction with the comparisons to metals concentrations in slag.

In conducting the initial screening comparisons, the most conservative, undiluted metals concentrations in ASTM water leachate and pure slag were used. Further analysis included consideration of more realistic concentrations, accounting for reasonable levels of dilution in natural environments.

3.3.1 Fresh Water

For fresh water, the screening values with the highest priority were the EPA AWQCs, because they were developed by EPA using an extensive amount of toxicological information and are intended to be used throughout the United States. The screening values having the next-highest priority were the EPA-endorsed ecotox thresholds. Finally, the values having the third-highest priority were the toxicological benchmarks developed by ORNL. It was not necessary to use the screening values developed by EPA Region IV or Region V, because the higher priority screening values provided information for all of the metals leached from steel-making slags.

The initial screening-level comparisons showed that maximum concentrations of seven metals in the undiluted leachate of one or more types of steel-making slag exceeded the fresh-water screening values for aluminum, barium, chromium (both total and hexavalent chromium), lead, selenium, silver, and vanadium (Table 3-6). Exceedances were found for six metals in EAF slag, five metals in BF slag, and three metals in BOF slag. The greatest magnitudes of exceedance were found for aluminum and barium.

The findings described above are based on exposure to undiluted leachate. However, a more plausible exposure scenario was provided by Proctor et al. (2002), in which it was assumed that the leachate would be diluted by a factor of at least 100 with ambient water prior to ecological receptors being exposed. Applying a dilution factor of 100 is consistent with the dilution/attenuation ratio used by EPA for assessing the potential for TCLP leachate to influence groundwater. If this dilution factor is applied to the maximum metals concentrations presented in Table 3-6, the only concentrations that exceed the screening values are those for aluminum and barium in EAF slag. The maximum aluminum concentrations in leachate exceed both the acute and the chronic criteria, and the maximum barium concentration exceeds only the chronic criterion.

Because the screening values for aluminum and barium were exceeded in EAF slag when considering a plausible environmental exposure scenario, the screening values for those two metals were evaluated further to assess their underlying technical basis and better characterize any potential risks.

3.3.1.1 Aluminum

The screening values for aluminum are the EPA AWQCs, the development of which is described in U.S. EPA (1988). The acute criterion was developed using only 14 genera, including seven fishes, four benthic macroinvertebrates, two zooplankters, and a planarian. The zooplankter genus *Ceriodaphnia* proved to be the most sensitive taxon, with a genus mean acute value of 2,648 μg/L. The acute value for the brook trout (*Salvelinus fontinalis*) of 3,600 μg/L was slightly higher than that for *Ceriodaphnia*, but the acute values for the remaining 12 genera (i.e., 10,390–>79,900 μg/L) were substantially greater than that for *Ceriodaphnia*. However, because acute toxicity values were available for only 14 genera, the final acute value (FAV) was calculated as 1,496 μg/L (i.e., approximately half the acute value for the most sensitive genus). The FAV was then divided by an uncertainty factor of two to provide the criterion maximum concentration (CMC) of 748 μg/L, which forms the basis for the acute AWQC of 750 μg/L. EPA (1988) used the rationale that, because of the limited data set (i.e., only 14 genera), the FAV should be approximately one-half the acute value to capture any possible effects on a more sensitive organism than those tested.

The chronic AWQC was based on chronic toxicity information for only three species: the fathead minnow (*Pimephales promelas*) and the zooplanktors *Daphnia magna* and *Ceriodaphnia dubia*. The chronic value for the most sensitive species (i.e., the fathead minnow) was 742 μg/L, whereas the chronic values for the two zooplanktors ranged from 1,908 to 3,288 μg/L. These chronic values resulted in acute-chronic ratios (ACRs) of 1.0 to 51. Although EPA (1988) noted that the final ACR should be the lowest one identified (i.e., 1.0), the methods for calculating AWQC prohibit the ACR from being less than 2, because the final chronic value (FCV) would then be greater than the CMC. Therefore, the FAV (1,496 μg/L) was divided by 2 to produce an FCV of 748 μg/L. The FCV was then lowered to 87 μg/L, to protect brook trout and striped bass (*Morone saxatilis*), which in two unpublished manuscripts, were reported to be particularly sensitive to aluminum.

The aluminum criteria, particularly the chronic criterion, are likely to be overly protective. EPA (2002) acknowledges the questionable nature of the chronic criterion by noting that the agency is aware of field data indicating that many high-quality waters in the U.S. contain aluminum at concentrations greater than 87 μg/L. In addition, and particularly relevant to surface waters affected by steel-making slag, which is highly alkaline, the 87-μg/L value is based on a toxicity test with striped bass in water with pH of 6.5 to 6.6 and hardness of <10 mg/L. Data described in “Aluminum Water-Effect Ratio for the 3M Plant Effluent Discharge, Middleway, West Virginia” (May 1994), as cited in EPA (1988), demonstrate that aluminum is substantially less toxic at higher pH and hardness, but the effects of pH and hardness are not well quantified at this time. For this reason, the EPA criterion is likely to be overly conservative for aluminum leached from steel-making slag, and should be applied with caution. In realistic aquatic environments, particularly those that support the highly sensitive brook trout and striped bass, upon which the chronic AWQC is based, slag leachate will be sufficiently diluted such that aluminum levels are not expected to exceed water quality standards. Site-specific investigation is warranted in aquatic environments where dilution is limited and the slag-to-water ratio is low.

3.3.1.2 Barium

The screening value for barium was derived originally by Suter and Mabrey (1994) using the Tier II methodology developed for the Great Lakes Initiative (U.S. EPA 1995). The values were then adopted as ecotox thresholds by EPA (1996). The Tier II methodology was developed by EPA to allow water quality values to be calculated for chemicals that do not have a toxicity database sufficient for calculating Tier I criteria (the EPA AWQCs). Therefore, there is considerably more uncertainty associated with Tier II values than with Tier I criteria.

The Suter and Mabrey (1994) Tier II values for barium were developed using a minimal database composed of only two species: the zooplanktor *Daphnia magna* and the New Zealand mud snail *Potamopyrgus jenkinsi*. *D. magna* occurs naturally in many freshwater environments in the U.S., whereas *P. jenkinsi* is a non-native species. The lethal concentration affecting 50% of the population (LC50) reported for *D. Magna* by Suter and Mabrey was 410,000 μg/L, compared to a range of 330–1700 μg/L for *P. jenkinsi*, indicating that the snail was considerably more sensitive to barium than was the zooplankter. To obtain the Tier II value, the geometric mean of the LC50 values for *P. jenkinsi* (913 μg/kg) was divided by an EPA-recommended uncertainty factor of 13.0 (i.e., because information on only two species was available) and a default ACR of 17.9 (i.e., because a barium-specific ACR was not available in the literature). The result of these calculations was a Tier II value of 3.9 μg/L. Based on the methods used to develop this value, it is clear that there is considerable uncertainty associated with the barium AWQCs.

Suter and Tsao (1996) updated the toxicity database for barium and added two additional species: the non-native amphipod *Echinogammarus berilloni* and the native amphipod *Gammarus pulex*. The LC50 values for these two amphipod species were 122,000 μg/L and 238,000 μg/L, which are more closely in line with the LC50 value reported by Suter and Mabrey (1994) for *D. magna* than *P. jenkinsi*. If a Tier II value for barium were calculated based on the lowest LC50 value for the zooplankter and two amphipods (i.e., 122,000 μg/L), it would equal 539 μg/L, using an EPA-recommended uncertainty factor of 8.0 for three available species and the ACR of 28.3 estimated by Suter and Tsao (1996). Suter and Tsao (1996) also report a study on the chronic toxicity of barium, in which an LC50 value and 16% reproductive impairment value were observed for *D. magna* after exposure to barium for 21 days (Biesinger and Christensen 1972). The chronic 21-day LC50 value was 13,500 μg/L, and the 21-day 16% reproductive impairment value was 5,800 μg/L.

These additional studies reported by Suter and Tsao (1996) clearly demonstrate that the Tier II value of 3.9 μg/L for barium is unrepresentative and largely an artifact of the unusually high sensitivity of a non-native snail to barium. If the more appropriate test organisms are considered, such as daphnids and gammarid amphipods (both of which are considered sensitive test organisms by EPA), the Tier II value for barium would be 539 μg/L (i.e., much greater than the current Tier II value of 3.9 μg/L). Consequently, the leachate concentration observed for the EAF slag, when diluted 100-fold to reflect possible field conditions (8.3 μg/L) is well below that value.

3.3.2 Saltwater

For salt water, the screening values with the highest priority were the EPA AWQCs, followed by the EPA ecotox thresholds and the ORNL toxicological benchmarks. It was not necessary to use the screening values developed by EPA Region IV or Region V.

The initial screening-level comparisons showed that maximum concentrations of four metals (total chromium, copper, lead, and silver) in the undiluted leachate of one or more types of steel-making slag exceeded the saltwater screening values (Table 3-7). Exceedances were found for three metals in EAF slag, and for one metal in BF and BOF slags.

If a dilution factor of 100 is applied to the maximum leachate concentrations to provide a more plausible environmental exposure scenario (as described above for fresh-water environments), none of the maximum leachate concentrations exceeded their screening values. In fact, a dilution factor of only 5 would be required to ensure that none of the maximum leachate concentrations exceeded their screening values.

3.3.3 Freshwater Sediments

For freshwater sediments, the screening values with the highest priority were the TECs and PECs developed by MacDonald et al. (2000), because they were developed as geometric means of numerous other SQGs and, therefore, integrate the information provided by the other SQGs. The screening values with the second-highest priority were those developed by Long and Morgan (1991), because they were developed by the National Oceanic and Atmospheric Administration (NOAA) using extensive databases. Finally, the values with the third-highest priority were those developed by Persaud et al. (1993), because that study addressed iron and manganese using relatively extensive databases.

The results of the initial screening-level comparisons showed that 95% UCL concentrations of six metals (cadmium, total chromium, copper, iron, manganese, and silver) in one or more types of steel-making slag exceeded the freshwater sediment screening values (Table 3-8). Exceedances were found for six metals in EAF slag, four metals in BOF slag, and two metals in BF slag.

The initial screening evaluation is based on an unlikely scenario in which aquatic organisms are exposed to undiluted steel-making slag. This would occur only where slag was used as fill material in the sediments, which is rarely, if ever, done. More realistically, organisms would be exposed to slag that has eroded from upland areas or the banks of water bodies and has been subsequently deposited on natural sediments. Under this scenario, the slag particles would be substantially diluted by the native sediments. A dilution factor of only 40 would be required to ensure that the 95% UCL metals concentrations did not exceed sediment screening values. While an estimate of actual sediment dilution depends on site-specific factors, most erosion scenarios would likely result in a sediment-to-slag ratio of significantly more than 40.

3.3.4 Saltwater Sediments

For saltwater sediments, the screening values with the highest priority were the ERLs and ERMs, because they were developed by NOAA using extensive databases (Long et al. 1995). No other screening values were needed for saltwater sediments.

The initial screening-level comparisons showed that 95% UCL concentrations of only two metals (total chromium in BF, BOF, and EAF slags; and silver in BOF and EAF slags) exceeded the saltwater sediment screening values (Table 3-9).

As discussed above for freshwater sediments, the screening evaluation addresses an exposure scenario that is unlikely to be encountered in the environment. Instead, slag particles that are found in saltwater sediments would most likely have been transported from upland sources and would be substantially diluted by native sediments. A dilution factor of only 10 would be required to ensure that the 95% UCL metals concentrations did not exceed sediment screening values. While an estimate of actual sediment dilution depends on site-specific factors, most erosion scenarios would likely result in a sediment-to-slag ratio of significantly more than 10.

3.3.5 Soil

For soil, the screening values with the highest priority were the EPA Eco-SSLs, because they were developed by EPA using an extensive body of toxicological information and are intended to be used throughout the United States. The screening values with the next-highest priority were the toxicological benchmarks developed by ORNL. No other screening values were required for soil.

The results of the initial screening-level comparisons showed that 95%UCL concentrations of eight metals in one or more types of steel-making slag exceeded the soil screening values, including barium, total chromium, copper, iron, manganese, thallium, vanadium, and zinc (Table 3-10). Exceedances were found for four metals in BF slag, five metals in BOF slag, and eight metals in EAF slag.

The Eco-SSLs are very conservative and have only limited utility for risk assessment, because many of the values are lower than naturally occurring background concentrations of metals in soils. For example, the criteria for five metals (i.e., barium, chromium, lead, manganese, and vanadium) in slag that exceeded the Eco-SSLs are, in fact, lower than naturally occurring background levels in soils in the United States (U.S. EPA 2005a–j).

It is important to recognize that these findings are based on an assumption of exposure to undiluted slag, where no mixing with native soils occurs. Under such a scenario, there would be no expectation that the slag should provide a viable habitat for terrestrial organisms. Therefore, the screening evaluation described above should be considered only as a hypothetical worst-case scenario that has limited ecological relevance to actual application scenarios.

3.4 Summary of Screening Comparisons

The results of the initial screening-level evaluations indicate that, under very conservative scenarios based on a comparison of the maximum or 95% UCL concentrations of metals found in BF, BOF, and EAF slags and slag leachate, various metals exceed screening values for each of the environmental media evaluated (i.e., surface water, sediment, and soil). When plausible environmental conditions and application scenarios are considered, in which slag particles or leachate are naturally diluted by ambient water, sediment, or soil particles, no significant risk to ecological receptors is anticipated. The only potential caveat involves the need for sufficient dilution in scenarios where slag is applied in freshwater bodies, due to potential aluminum concentrations. In situations where dilution is limited and the slag-to-water ratio is low, site-specific evaluation of potential dilution, as well as the aluminum concentration of the slag and potentially affected ambient water, is recommended.

It is important to recognize that the screening levels used in this evaluation are, by design, based on highly conservative assumptions, and sometimes incorporate large uncertainty factors. Hence, the exceedance of a screening level should not be taken as evidence of an ecological hazard. As concluded by Proctor et al. (2002), this evaluation has found that the uses of steel-making slag are not likely to pose a hazard to ecological receptors. However, site-specific evaluation may be needed to judge the potential hazard in specific situations where dilution of slag with natural media is limited.

3.5 Bioavailability of Metal in Steel-Making Slag

A significant factor that mitigates the exposure of ecological receptors is the generally low bioavailability of metals within the slag matrix. The leachate tests reported by Proctor et al. (2000, 2002) document how resistant the metals are to leaching in the ASTM water leachate test, which conservatively represents the manner in which most slag leachate is formed in the environment. Even the TCLP leachate test, which was conducted under acidic conditions, showed that the metals in slag were generally resistant to leaching. As discussed in greater detail in the following section, slag is highly alkaline. This characteristic generally limits the release of metals from the slag matrix under environmental exposure conditions.

The two primary pathways through which organisms can be exposed to metals in slag are dermal contact and direct ingestion of slag particles (NRC 2003). For ingested particles, the gastrointestinal tract is the principal site for metals uptake. A prevailing assumption is that metals must be in a free-ion form before they can be transported across the cell membranes within the gastrointestinal tract. However, because the gut pH in most invertebrates ranges from near neutral to alkaline (NRC 2003), it is expected that the release of metals from slag in the digestive tract would be limited, resulting in low bioavailability and systemic absorption.

Digestion of materials in aquatic invertebrates can be relatively complex, and although few studies have addressed the transport mechanisms, it is known that they digest materials both externally (in the intestinal lumen) and, in some cases, within cells that engulf materials. Various compounds within the gut help determine which contaminants are available for transport into the organism. For example, high concentrations of amino acids are very effective in solubilizing sediment-associated metals. With respect to intracellular digestion, Luoma et al. (1992) found that marine bivalves with strong capabilities for intracellular digestion can assimilate metals with increased efficiency.

For soil invertebrates, the relative importance of dermal contact and direct ingestion as exposure pathways depends in large part on the physical characteristics of the organisms, as well as the physiology of the gut. Soft-bodied organisms, such as earthworms and some insect larvae, are thought to be exposed mainly by soil pore water (Saxe et al. 2001), whereas organisms with a hard cuticle or carapace (e.g., adult forms of many beetles, insects, and crustaceans) are thought to be exposed more through direct ingestion of contaminants. Saxe et al. (2001) modeled the body concentrations of several metals in the earthworm (*Eisenia andrei*) as a function of pH and soluble organic carbon. These authors assumed that metals that are soluble at the pH of soil pore water were available for dermal uptake. Gut exposure was estimated by determining the metal's availability in solution near neutral pH, which is the optimal pH for the earthworm enzymes associated with digestion. The authors found that the majority of metals uptake in the earthworm was through dermal exposure.

The above discussion on metals bioavailability indicates that, under normal environmental conditions, metals in steel slag would have low bioavailability, which would limit the exposure of organisms that live in or on soil and sediments associated with the slag. Because metals concentrations are very low in slag water leachate, there is limited risk of exposure via surface water or pore water. Because the latter medium appears to be the primary exposure pathway for most soft-bodied soil invertebrates, those organisms would have limited exposure to metals. For organisms in which direct ingestion of slag particles would be the primary exposure pathway, the fact that the gut pH of most invertebrates is neutral to alkaline indicates that substantial releases of metals in the gut would not occur and that metals from slag particles would therefore not be available for uptake.

3.6 Ecological Considerations Related to High pH Values

Leachate from steel-making slag can result in elevated pH levels in ambient water as a result of its generally alkaline nature. For example, Proctor et al. (2000) reported that the mean pH of the ASTM leachates ranged from 11.1 for BF slag to 11.8 for BOF and EAF slags. The potential ecological risks related to elevated pH in slag leachate were considered by Proctor et al. (2002), who concluded that most aquatic environments (e.g., rivers and lakes) would not be threatened by slag application along their banks, because any slag leachate would be sufficiently diluted by the relatively large amounts of ambient water. In contrast, it was suggested that only wetlands or very shallow water bodies would provide conditions under which slag leachate would pose potential ecological risks, largely due to the relatively low dilution capacities of those aquatic environments.

The EPA chronic AWQC for freshwater pH is 6.5–9, and for saltwater pH is 6.5–8.5 (U.S. EPA 2002c). Generally, values of pH below and above these ranges are thought to pose potential ecological risks. The AWQC for pH was developed in 1976 and has not changed since that time. When the AWQC were developed, the only extensive consideration of the effects of pH on aquatic life was a review conducted by the European Inland Fisheries Advisory Commission (EIFAC 1969). That report concluded that fisheries gradually deteriorate as pH values are further removed from the normal range, and that the pH range that is not directly toxic to fish is 5–9. However, the report noted that, because the toxicity of some chemicals (e.g., ammonia) increases as pH declines or increases, variations in pH can result indirectly in toxicity. EPA (1976) cites several studies that address the adverse effects of low pH, but does not present any studies that address effects due to high pH. In summary, the technical support for the AWQC for pH is relatively sparse in comparison to the AWQCs for many other chemicals. Nevertheless, the pH criteria have remained unchanged since 1976, so there likely would be considerable resistance to deviating from them without considerable supporting data.

Because steel-making slag leachate can result in pH values of approximately 11–12, the potential exists for the leachate to pose ecological risk if it is not sufficiently diluted by ambient water. However, predicting the pH of steelmaking slag leachate in the environment is difficult, because it is influenced by numerous factors.

By mass, steel-making slag consists of 30% to 50% calcium oxide (CaO). On hydration, calcium oxide spontaneously converts to calcium hydroxide [$Ca(OH)_2$], which is a strong base that dissociates in a two-step process as follows:

$$Ca(OH)_2 \xleftrightarrow{Pk_a=12.6} CaOH^+ + OH^- \xleftrightarrow{Pk_a=11.6} Ca^{2+} + 2OH^-$$

Similar reactions may occur with other slag constituents, including magnesium oxide, iron oxide, and others. The alkalinity of the slag is countered by the acidity of other slag constituents such as aluminum and phosphorus, which dissociate, and therefore are mobilized, as a result of the lime-based alkalinity:

$$CaOH^+ + OH^- + H_3AlO_{4(s)} \rightarrow Ca^{2+}HAlO^{-2}_{4(aq)} + 2H_2O$$

Predicting the pH of leachate from steel-making slag is therefore complicated, because the interaction between numerous slag constituents can result in highly variable pH values depending on the specific composition of the slag, as well as time.

Once an alkaline leachate enters the environment, it will interact with natural acids, resulting in its neutralization. The most ubiquitous buffer involved in this neutralization is carbonic acid, which is a natural constituent of water in equilibrium with carbon dioxide from the atmosphere. Carbon dioxide, when dissolved in water, will dissociate first to carbonic acid (H_2CO_3), and then to subsequent bicarbonate and carbonate species. These acid/base pairs buffer the water, with optimum capacity at pH 6.4 and pH 10.32:

$$CO_{2(aq)} + H_2O \xleftrightarrow{k=3.47\,x10^{-2}} H_2CO_3$$
$$H_2CO_3 \xleftrightarrow{pk=6.4} H^+ + HCO_3^-$$
$$HCO_3^- \xleftrightarrow{pk=10.32} H^+ + CO_3^{-2}$$

When ambient carbonates interact with the calcium hydroxide in the slag leachate, the result is a neutralization of the alkalinity and the production of insoluble calcium carbonate:

$$2H^+ + CO_3^{-2} + Ca^{+2} + 2OH^- \xleftrightarrow{K_{sp}=5x10^{-9}} 2H_2O + CaCO_{3(s)} \downarrow$$

The theoretical prediction of changes in solution pH with the dilution of the leachate is provided in Figure 3-1.

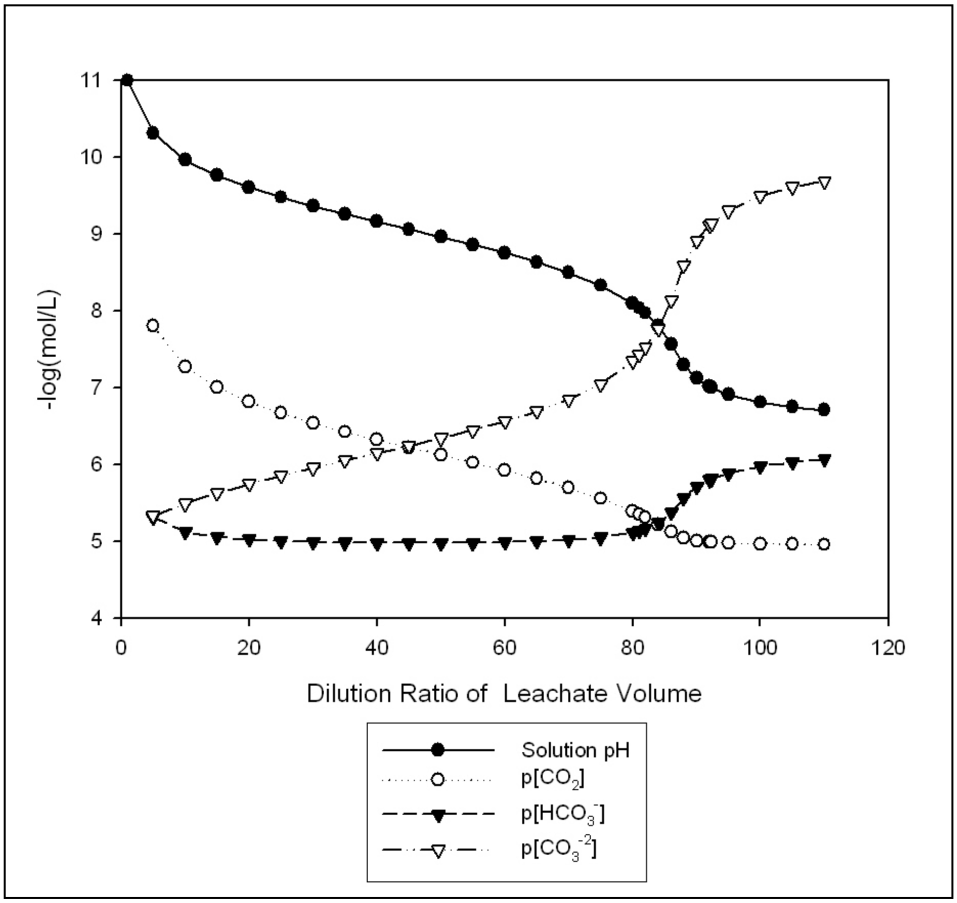

Figure 3-1. Change in carbonate species with the dilution of alkaline leachate from steel slag

Calcium carbonate has very low water solubility and, therefore, will precipitate with the neutralization of the leachate's alkalinity. Furthermore, other alkaline-soluble constituents, such as aluminum hydroxide, will also fall out of solution at the same time (see foregoing discussion regarding aluminum releases from slag).

$$Ca^{2+}HAlO_{4(aq)}^{-2} + H_2CO_{3(aq)} \rightarrow CaCO_{3(s)} \downarrow + H_3AlO_{4(s)} \downarrow$$

These neutralization reactions occur most quickly at locations where carbon dioxide and calcium hydroxide concentrations are the greatest. For atmosphere-equilibrated water such as shallow surface water or rainwater, the highest concentrations will occur at the surface interface of the calcium hydroxide with the water. This will result in precipitation of the calcium carbonate on the surface of the hydrated lime/calcium hydroxide constituent of the slag. The precipitation of calcium carbonate upon the calcium hydroxide introduces a diffusion barrier that isolates it from the water. This “armoring” process results in decreased alkalinity with time.

In considering potential ecological risks, the alkalinity of steel-making slag leachate may result in pH levels in downstream or downgradient areas that are, at least initially, higher than the EPA AWQC. To assess the impact of alkalinity from environmental applications of steel-making slag, it is recommended that users consider the scale of the potentially affected area, the potential for dilution, and the period of time during which the alkaline leachate is expected to continue (as the slag ages and the calcium hydroxide is armored). Laboratory studies of these environmental processes can provide additional information to assist in the evaluation of environmental applications. Accordingly, the potential for alkaline conditions should be considered for site-specific application scenarios where leachate from slag could reach ecological receptors. The alkalinity of slag leachate, however, is not expected to be a concern unless dilution with ambient water is less than approximately 100-fold, consistent with the conclusions of Proctor et al. (2002). Finally, it is important to recognize that the need for dilution is temporal, and that the alkalinity of slag leachate will decrease with time due to the “armoring” process described above.

3.7 Conclusions

The current uses of steel-making slag that are most likely to result in exposure of ecological receptors to metals in slag are bank stabilization and soil amendment. In both cases, it is unlikely that receptors will be exposed to pure slag or to the metals in undiluted leachate. Most slag applications (e.g., use as road base) do not result in exposure in natural habitats.

Evaluations of the potential for metals in steel-making slag to affect fresh and saltwater bodies, fresh and saltwater sediments, and soil were conducted by comparison of ecology-based screening levels to concentrations of metals in slag or in leachate from slag generated using the ASTM water leachate test (D-3987). The assessment further considered a reasonable level of dilution consistent with environmental conditions. With this approach, only the potential for aluminum and barium in EAF slag to leach from and affect freshwater bodies was identified as posing a potential ecological concern that warrants additional site-specific evaluation (see below). The leaching of metals into saltwater bodies, the erosion of slag into fresh and saltwater sediments, and the amendment of soils with slag for pH neutralization and agricultural conditioning were found to result in metal concentrations lower than ecological screening levels, assuming that the slag, and leachate from it, would be mixed or diluted as expected in typical environmental conditions (e.g., dilution of at least 100-fold).

Metal concentrations in ASTM water leach tests were conservatively used to assess whether leaching of metals from slag could affect ambient salt or freshwater bodies. This is a very conservative approach, because extraction of metals in the 18-hour shaking test will overestimate leaching under field conditions. The ASTM leachate test results for barium and aluminum from EAF slag, diluted 100-fold to account for natural environmental conditions, exceeded their AWQCs for freshwater. The AWQCs for both of these metals are based on relatively limited data sets and thus include large uncertainty factors. Our review of the toxicity data and methods used to set the criteria for both metals found that the EPA AWQCs for aluminum and barium are likely to be overly conservative and not predictive of toxicity. In realistic aquatic environments, it is not expected that the concentrations of these metals in slag leachate will pose an ecological concern. Nonetheless, care should be taken when EAF slag is used in freshwater habitats with limited dilution.

Steel-making slag is highly alkaline, and this property of slag limits the release of metals from the slag matrix. As a result, the bioavailability of metals in slag is highly limited. However, the pH levels in ASTM water leachate from all slag types range from 11.1 to 11.8 and exceed the AWQC for pH (upper bound of 9). Thus, the placement of slag in or along shallow water bodies could adversely affect pH, and care should be taken to ensure that there is adequate dilution of leachate with ambient water. A water-to-slag ratio of at least 2000:1should be applied to achieve a 100-fold or greater dilution of slag leachate). Leachate pH is likely to be high when slag initially reacts with environmental media, but the pH will become more neutral with time as the hydroxides react with natural carbonates to produce insoluble calcium

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Tables

Table 3-1. Summary of screening values for metals in fresh water

	U.S. EPA (2002)		U.S. EPA (1996)	U.S. EPA (2001)		U.S. EPA (2003)	ORNL (Suter and Tsao 1996)	
Metal	Chronic[a]	Acute[a]	ET[a]	Chronic	Acute	ESL	Chronic	Acute
Aluminum	87 [b]	750 [b]	--	160	1,300	--	87	750
Antimony	--	--	--	--	--	80	30	180
Arsenic	150	340	190	190	360	148	190	360
Barium	--	--	3.9	--	--	220	4.0	110
Beryllium	--	--	5.1	0.53	16	3.6	0.66	35
Cadmium	2.2 [c]	4.3 [c]	1.0 [c]	0.66 [d]	1.79 [d]	0.15	1.1	3.9
Chromium (total)	74 [c]	570 [c]	180 [c]	117	984	42	210	1,700
Chromium(VI)	11	16	10	11	16	--	11	16
Cobalt	--	--	3.0	--	--	24	23	1,500
Copper	9.0 [c]	13 [c]	11 [c]	6.54 [d]	9.22 [d]	1.58	12	18
Iron	1,000	--	1,000	--	--	--	1,000	--
Lead	2.5 [c]	65 [c]	2.5 [c]	1.32 [d]	33.8 [d]	1.17	3.2	82
Manganese	--	--	80	--	--	--	120	2,300
Mercury	0.77	1.4	1.3	0.012	2.4	0.0013	1.3	2.4
Molybdenum	--	--	240	--	--	--	370	16,000
Nickel	52 [c]	470 [c]	160 [c]	87.7 [d]	789 [d]	28.9	160	1,400
Selenium	5.0	--	5.0	5.0	20	5.0	5.0	20
Silver	--	3.4 [c]	--	0.012 [d]	1.23 [d]	0.12	0.36	4.1
Thallium	--	--	12	4.0	140	10	12	110
Tin	--	--	73	--	--	180	73	2,700
Vanadium	--	--	19	--	--	12	20	280
Zinc	120 [c]	120 [c]	100 [c]	58.9 [d]	65 [d]	65.7	110	120

Notes: All units are μg/L.

-- - no screening value available
EPA - U.S. Environmental Protection Agency
ESL - ecological screening level
ET - ecotox threshold
ORNL - Oak Ridge National Laboratory

[a] Screening values are expressed in terms of the dissolved metals in the water column for all metals except aluminum and selenium.

[b] Screening value is applicable for the pH range of 6.5–9.0.

[c] Screening value is a function of water hardness. Values in this table correspond to a hardness of 100 mg/L as calcium carbonate.

[d] Screening value is a function of water hardness. Values in this table correspond to a hardness of 50 mg/L as calcium carbonate.

Table 3-2. Summary of screening values for metals in salt water

	U.S. EPA (2002)		U.S. EPA (1996)	U.S. EPA (2001)	
Metal	Chronic[a]	Acute[a]	ET[a]	Chronic	Acute
Arsenic	36	69	36	36	69
Cadmium	8.8	40	9.3	9.3	43
Chromium (total)	--	--	--	103	1,030
Chromium(VI)	50	1,100	50	50	1,100
Copper	3.1	4.8	2.4	2.9	2.9
Lead	8.1	210	8.1	8.5	220
Mercury	0.94	1.8	1.1	0.025	2.1
Nickel	8.2	74	8.2	8.3	75
Selenium	71	290	71	71	300
Silver	--	1.9	--	0.23	2.3
Thallium	--	--	--	21.3	213
Zinc	81	90	81	86	95

Note: All units are µg/L.

--	-	no screening value available
EPA	-	U.S. Environmental Protection Agency
ET	-	ecotox threshold

[a] Screening values are expressed in terms of the dissolved concentration in the water column.

Table 3-3. Summary of screening values for metals in freshwater sediments

	U.S. EPA (1996)	U.S. EPA (2001)	U.S. EPA (2003)	MacDonald et al. (2000)		Persaud et al. (1993)		Long and Morgan (1991)		Smith et al. (1996)		Ingersoll et al. (1996)				
Metal	ET			TEC	PEC	LEL	SEL	ERL	ERM	TEL	PEL	ERL	ERM	TEL	PEL	NEC
Aluminum	--	--	--	--	--	--	--	--	--	--	--	14,000	58,000	26,000	60,000	73,000
Antimony	--	12	--	--	--	--	--	2.0	25	--	--	--	--	--	--	--
Arsenic	8.2	7.24	9.79	9.79	33.0	6.0	33	33	85	5.9	17	13	50	11	48	100
Cadmium	1.2	1.0	0.99	0.99	4.98	0.6	10	5.0	9.0	0.60	3.53	0.70	3.9	0.58	3.2	8.0
Chromium (total)	81	52.3	43.4	43.4	111	26	110	80	145	37.3	90	39	270	36	120	95
Cobalt	--	--	50	--	--	--	--	--	--	--	--	--	--	--	--	--
Copper	34	18.7	31.6	31.6	149	16	110	70	390	35.7	197	41	190	28	100	580
Iron	--	--	--	--	--	20,000	40,000	--	--	--	--	20,000	28,000	19,000	25,000	29,000
Lead	47	30.2	35.8	35.8	128	31	250	35	110	35	91.3	55	99	37	82	130
Manganese			--			460	1,100				--	730	1,700	630	1,200	4,500
Mercury	0.15	0.13	0.17	0.18	1.06	0.2	2.0	0.15	1.3	0.17	0.49	--	--	--	--	--
Nickel	21	15.9	22.7	22.7	48.6	16	75	30	50	18	36	24	45	20	33	43
Silica	--	--	0.5	--	--	--	--	--	--	--	--	--	--	--	--	--
Silver	--	2.0	--	--	--	--	--	1.0	2.2	--	--	--	--	--	--	--
Zinc	150	124	121	121	459	120	820	120	270	123	315	110	550	98	540	1,300

Note: All units are mg/kg dry weight.

-- - no screening value available
EPA - U.S. Environmental Protection Agency
ERL - effects range-low
ERM - effects range-median
ESL - ecological screening level
ET - ecotox threshold
LEL - lowest effect level
NEC - no effect concentration
PEC - probable effect concentration
PEL - probable effect level
SEL - severe effect level
TEC - threshold effect concentration
TEL - threshold effect level

Table 3-4. Summary of screening values for metals in saltwater sediments

	U.S. EPA (1996)	Long et al. (1995)		Long and Morgan (1991)		MacDonald et al. (1996)		Ecology (1995)	
Metal	ET	ERL	ERM	ERL	ERM	TEL	PEL	SQS	CSL
Antimony	--	--	--	2.0	25	--	--	--	--
Arsenic	8.2	8.2	70	33	85	7.2	41.6	57	93
Cadmium	1.2	1.2	9.6	5.0	9.0	0.68	4.21	5.1	6.7
Chromium (total)	81	81	370	80	145		160	260	270
Copper	34	34	270	70	390	18.7	108	390	390
Lead	47	46.7	218	35	110	30.2	112	450	530
Mercury	0.15	0.15	0.71	0.15	1.3	0.13	0.7	0.41	0.59
Nickel	21	20.9	51.6	30	50	15.9	42.8	--	--
Silver	--	1.0	3.7	1.0	2.0	0.73	1.77	6.1	6.1
Zinc	150	150	410	120	270	124	271	410	960

Note: All units are mg/kg dry weight.

-- - no screening value available
CSL - cleanup screening level
ERL - effects range-low
ERM - effects range-median
ET - ecotox threshold
PEL - probable effect level
SQS - sediment quality standard
TEL - threshold effect level

Table 3-5. Summary of screening values for metals in soil

	ORNL					EPA Eco-SSL			
Metal	Ew	Mic	Plt	U.S. EPA (2001)	U.S. EPA (2003)	Inv	Plt	WI-Av	WI-Ma
Aluminum[a]	--	600	50	50	--	--	--	--	--
Antimony	--	--	5.0	3.5	0.142	78	--	--	0.27
Arsenic	60	100	10	10	5.7	--	18	43	46
Barium	--	3,000	500	165	1.04	330	--	--	2,000
Beryllium	--	--	10	1.1	1.06	40	--	--	21
Cadmium	20	20	4.0	1.6	0.002	140	32	0.77	0.36
Chromium (total)	0.4	10	1.0	0.4	0.4	--	--	26	34
Chromium(VI)	--	--	--	--	--	--	--	--	81
Cobalt	--	1,000	20	20	0.14	--	13	120	230
Copper	60.0	100	100	40	5.4	--	--	--	--
Iron	--	200	--	200	--	--	--	--	--
Lead	500	900	50	50	0.054	1,700	110	11	56
Manganese	--	100	500	100	--	--	--	--	--
Mercury	0.1	30	0.3	0.1	0.1	--	--	--	--
Molybdenum	--	200	2.0	2.0	--	--	--	--	--
Nickel	200	90	30	30	13.6	--	--	--	--
Selenium	70	100	1.0	0.81	0.028	--	--	--	--
Silver	--	50	2.0	2.0	4.04	--	--	--	--
Thallium	--	--	1.0	1.0	0.057	--	--	--	--
Tin	--	2,000	50	53	7.62	--	--	--	--
Vanadium	--	20	2.0	2.0	1.59	--	--	7.8	280
Zinc	100	100	50	50	6.62	--	--	--	--

Note: All units are mg/kg dry weight.

-- - no screening value available
Eco-SSL - ecological soil screening level
EPA - U.S. Environmental Protection Agency
ESL - ecological screening levels
Ew - earthworm
Inv - invertebrate
Mic - microorganism
ORNL - Oak Ridge National Laboratory
Plt - plant
WI-Av - wildlife, avian
WI-Ma - wildlife, mammalian

[a] The Eco-SSL for aluminum is based on measured soil pH. Aluminum is a potential problem only where soil pH is less than 5.5

Table 3-6. Comparison of maximum metal concentrations in ASTM water leachate with freshwater screening values

	Maximum Leachate Concentration			Screening Value		
Metal	BF	BOF	EAF	Chronic	Acute	Source
Aluminum	7,500 [a]	5,600 [a]	91,000 [a]	87	750	U.S. EPA (2002)
Antimony	--	--	17	30	180	Suter and Tsao (1996)
Arsenic	3.1	3.0	4.2	150	340	U.S. EPA (2002)
Barium	380 [a]	220 [a]	830 [a]	4.0	110	Suter and Tsao (1996)
Beryllium	--	--	--	0.7	35	Suter and Tsao (1996)
Cadmium	--	--	--	2.2	4.3	U.S. EPA (2002)
Chromium (total)	13	--	240 [b]	74	570	U.S. EPA (2002)
Chromium(VI)	--	--	29 [a]	11	16	U.S. EPA (2002)
Copper	--	--	5.5	9.0	13	U.S. EPA (2002)
Iron	--	--	--	1,000	NA	U.S. EPA (2002)
Lead	--	27 [b]	40 [b]	2.5	65	U.S. EPA (2002)
Manganese	2.8	2.2	5.3	80	2,300	U.S. EPA (1996); Suter and Tsao (1996)
Mercury	--	--	--	0.77	1.4	U.S. EPA (2002)
Molybdenum	--	8.0	77	240	16,000	U.S. EPA (1996); Suter and Tsao (1996)
Nickel	--	--	--	52	470	U.S. EPA (2002)
Selenium	12 [b]	--	16 [b]	5.0	20	U.S. EPA (2002); Suter and Tsao (1996)
Silver	8.5 [a]	--	--	0.4	4.1	Suter and Tsao (1996); U.S. EPA (2002)
Thallium	--	--	--	12	110	Suter and Tsao (1996)
Tin	--	--	--	73	2,700	Suter and Tsao (1996)
Vanadium	32 [b]	8.7	39 [b]	19	280	U.S. EPA (1996); Suter and Tsao (1996)
Zinc	--	--	--	120	120	U.S. EPA (2002)

Notes: -- - metal not detected; all unit are μg/L.
ASTM - American Society for Testing and Materials
BF - blast furnace
BOF - basic oxygen furnace
EAF - electric arc furnace
NA - screening value not available

[a] Concentration exceeds acute screening value.

[b] Concentration exceeds chronic screening value.

Table 3-7. Comparison of maximum metal concentrations in ASTM water leachate with saltwater screening values

	Maximum Leachate Concentration			Screening Value		
Metal	BF	BOF	EAF	Chronic	Acute	Source
Arsenic	--	3.0	4.2	36	69	U.S. EPA (2002)
Cadmium	--	--	--	8.8	40	U.S. EPA (2002)
Chromium (total)	13	--	240 [b]	103	1,030	U.S. EPA (2001)
Chromium(VI)	--	--	29	50	1,100	U.S. EPA (2002)
Copper	--	--	5.5 [a]	3.1	4.8	U.S. EPA (2002)
Lead	--	27 [b]	40 [b]	8.1	210	U.S. EPA (2002)
Mercury	--	--	--	0.94	1.8	U.S. EPA (2002)
Nickel	--	--	--	8.2	74	U.S. EPA (2002)
Selenium	12	--	16	71	290	U.S. EPA (2002)
Silver	8.5 [a]	--	--	NA	1.9	U.S. EPA (2002)
Thallium	--	--	--	21	213	U.S. EPA (2001)
Zinc	--	--	--	81	90	U.S. EPA (2002)

Notes:

--	-	metal not detected; all unit are μg/L.
ASTM	-	American Society for Testing and Materials
BF	-	blast furnace
BOF	-	basic oxygen furnace
EAF	-	electric arc furnace
NA	-	screening value not available

[a] Concentration exceeds acute screening value.

[b] Concentration exceeds chronic screening value.

Table 3-8. Comparison of 95% UCL slag concentrations with screening values for freshwater sediments

	95% UCL slag concentration			Screening	
Metal	BF	BOF	EAF	Value	Source
Antimony	--	4.2	4.9	25	Long and Morgan (1991)
Arsenic	1.9	--	2.2	33	MacDonald et al. (2000)
Cadmium	--	4.2	9.1 [a]	5.0	MacDonald et al. (2000)
Chromium (total)	600 [a]	1,400 [a]	3,400 [a]	111	MacDonald et al. (2000)
Copper	8.7	38	202 [a]	149	MacDonald et al. (2000)
Iron	34,000	200,000 [a]	210,000 [a]	40,000	Persaud et al. (1993)
Lead	8.6	88	38	128	MacDonald et al. (2000)
Manganese	8,200 [a]	39,000 [a]	41,000 [a]	1,100	Persaud et al. (1993)
Mercury	--	0.1	0.04	1.06	MacDonald et al. (2000)
Nickel	1.9	6.0	42	48.6	MacDonald et al. (2000)
Silver	--	19 [a]	13 [a]	2.2	Long and Morgan (1991)
Zinc	41	63	210	459	MacDonald et al. (2000)

Notes:

--	-	metal not detected; all units are mg/kg dry weight.
BF	-	blast furnace
BOF	-	basic oxygen furnace
EAF	-	electric arc furnace
UCL	-	upper confidence limit

[a] Concentration exceeds screening value.

Table 3-9. Comparison of 95% UCL slag concentrations with screening values for saltwater sediments

	95% UCL Slag Concentration			Screening	
Metal	BF	BOF	EAF	Value	Source
Antimony	--	4.2	4.9	25	Long et al. (1995)
Arsenic	1.9	--	2.2	70	Long et al. (1995)
Cadmium	--	4.2	9.1	9.6	Long et al. (1995)
Chromium (total)	600 [a]	1,400 [a]	3,400 [a]	370	Long et al. (1995)
Copper	8.7	38	200	270	Long et al. (1995)
Lead	8.6	88	38	218	Long et al. (1995)
Mercury	--	0.1	0.04	0.71	Long et al. (1995)
Nickel	1.9	6.0	42	51.6	Long et al. (1995)
Silver	--	19 [a]	13 [a]	3.7	Long et al. (1995)
Zinc	41	63	210	410	Long et al. (1995)

Notes:		
--	-	metal not detected; all units are mg/kg dry weight.
BF	-	blast furnace
BOF	-	basic oxygen furnace
EAF	-	electric arc furnace
UCL	-	upper confidence limit

[a] Concentration exceeds screening value.

Table 3-10. Comparison of 95% UCL slag concentrations with soil screening values

	95% UCL Slag Concentration			Screening	
Metal	BF	BOF	EAF	Value	Source
Aluminum[a]	44,000	36,000	38,000	pH < 5.5	U.S. EPA (2005a)
Antimony	--	4.2	4.9	78	U.S. EPA (2005b)
Arsenic	1.9	--	2.2	18	U.S. EPA (2005c)
Barium	310	103	640 [b]	330	U.S. EPA (2005d)
Beryllium	9.2	1.0	1.4	40	U.S. EPA (2005e)
Cadmium	--	4.2	9.1	140	U.S. EPA (2005f)
Chromium (total)	600 [b]	1,400 [b]	3,400 [b]	26	U.S. EPA (2005g)
Chromium(VI)	--	--	1.5	81	U.S. EPA (2005g)
Copper	8.7	38	200 [b]	60	Efroymson et al. (1997)
Iron	34,000 [b]	200,000 [b]	210,000 [b]	200	U.S. EPA (2005i)
Lead	8.6	88	38	1,700	Efroymson et al. (1997)
Manganese	8,200 [b]	39,000 [b]	41,000 [b]	100	Efroymson et al. (1997)
Mercury	--	0.1	0.04	0.1	Efroymson et al. (1997)
Molybdenum	1.6	140	35	200	Efroymson et al. (1997)
Nickel	1.9	6.0	42	90	Efroymson et al. (1997)
Selenium	5.1	18	20	70	Efroymson et al. (1997)
Silver	--	19	13	50	Efroymson et al. (1997)
Thallium	--	10 [b]	14 [b]	1.0	Efroymson et al. (1997)
Tin	2.1	8.2	12	2,000	Efroymson et al. (1997)
Vanadium	150 [b]	1,100 [b]	580 [b]	20	Efroymson et al. (1997)
Zinc	41	63	210 [b]	100	Efroymson et al. (1997)

Notes: -- - metal not detected; all units are mg/kg dry weight.
BF - blast furnace
BOF - basic oxygen furnace
EAF - electric arc furnace
UCL - upper confidence limit

[a] The ecological soil screening level for aluminum is based on measured soil pH. Aluminum is a potential problem only where soil pH is less than 5.5.

[b] Concentration exceeds screening value.