

The Characterization of Trace Metals and Organics in Spent Foundry Sands Over a One-Year Period

ROBERT S. DUNGAN*

USDA-Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory, 3793 North 3600 East, Kimberly, Idaho 83341, USA

ABSTRACT: Millions of tons of spent sand, used to create metalcasting molds, are generated by the foundry industry each year in the United States. Not surprisingly, spent foundry sands (SFSs) are an excellent substitute for virgin sands that are currently used in manufactured soils and geotechnical applications. The purpose of this study was to characterize trace metals and EPA-priority polycyclic aromatic hydrocarbons (PAHs) and phenolics in ferrous and non-ferrous SFSs over a one-year period. Overall, the total metal concentrations in the SFSs were similar to those found in native soils, while the PAHs and phenolic concentrations were relatively low. Metal leaching tests were also performed, which revealed that the SFSs have a low metal leaching potential under the specific test conditions. The data from this study suggests that the majority of SFSs are not hazardous in nature, except those that use olivine sands or are from brass foundries, due to the presence of elevated concentrations of Ni or Cu, Pb, and Zn, respectively. This information will be useful to environmental regulators who are considering including SFSs in their beneficial use regulations.

INTRODUCTION

EACH year foundries in the U.S. discard about 10 million tons of spent sand in private and municipal landfills. The most commonly used molding process is green sand molding, which is used to produce 90% of the casting volume. Green sands are a mixture of sand (usually silica sand, 85–95% by weight) and lesser quantities of bentonite clay, carbonaceous additives, and water. Efforts to divert green sands and other molding sands (e.g. chemically bonded) from landfills, reduce disposal costs, and encourage their beneficial use are currently being encouraged by the U.S. EPA [16]. Although spent foundry sands (SFSs), such as green sands, are being successfully used in a few states as a component in manufactured soils and geotechnical applications [11,15], many states are reluctant to develop beneficial use regulations or relax current regulations due to a lack of detailed information on metals and organics.

The purpose of this study was to quantify trace metals and EPA-priority polycyclic aromatic hydrocarbons (PAHs) and phenolics in ferrous and non-ferrous SFSs

during three separate sampling events over a one-year period. Trace metal and organic data from the initial sampling event can be found in Dungan and Dees [7] and Dungan [5], respectively. In addition to quantifying total metals, a determination of Ag, As, Ba, Be, Cd, Cr, Cu, Ni, Pb, Sb, and Zn in toxicity characteristic leaching procedure (TCLP), synthetic precipitation leaching procedure (SPLP), and water extracts was performed. The results from this study will ultimately be used to assess the potential risks of using SFSs in manufactured soils for agricultural or horticultural applications. The results will also be of interest to state regulators who are developing or reviewing current beneficial use regulations.

MATERIALS AND METHODS

Spent Foundry Sands

In June 2005, September 2005, and July 2006 (which will be referred to as the first, second, and third sampling events, respectively), SFSs were collected from ferrous and non-ferrous foundries located in 13 states (Table 1). The June 2005 samples were collected as described by Dungan [5], while the remaining sets were collected by foundry personnel after receiving training

* Author to whom correspondence should be addressed.
E-mail: robert.dungan@ars.usda.gov

Table 1. Description of the Spent Foundry Molding Sands and Core Binder Systems.

Sand	State	Metal Poured	Molding Sand	Core Binder System and Process
1	PA	Iron	Green sand	PU coldbox, PU no-bake, shell, core oil
2	PA	Aluminum	Green sand [†]	Shell
3	PA	Iron	Green sand	Shell, furan warmbox
4	PA	Aluminum	Green sand	Shell
5	PA	Iron	Green sand	PU no-bake, shell, sodium silicate
6	PA	Steel	PU no-bake [†]	PU no-bake
7	PA	Iron	Green sand	PU no-bake
8	OH	Iron	Green sand	PU coldbox, PU hotbox
9	OH	Iron	Green sand	PU coldbox, PU hotbox
10	OH	Iron	Green sand	PU coldbox, PU hotbox
11	OH	Iron	Green sand	PU coldbox, PU no-bake, shell
12	IN	Iron	Shell	Shell
13	OH	Iron	Green sand	PU coldbox, PU no-bake, shell
14	OH	Aluminum	Green sand	PU no-bake, shell, core oil
15	IN	Iron	Green sand	PU coldbox, shell
16	OH	Iron	Green sand	PU coldbox, PU hotbox
17	OH	Iron	Green sand	PU coldbox, PU hotbox
18	IN	Iron	Green sand	PU coldbox, PU hotbox, shell
19	WI	Iron	Green sand	PU coldbox
20	OH	Aluminum	Green sand	Shell
21	IN	Iron	PU no-bake	PU coldbox, PU no-bake, furan warmbox
22	MI	Iron	Green sand	PU no-bake, shell
23	MI	Iron	Green sand	PU coldbox, shell
24	WI	Iron	Green sand	Shell
25	WI	Iron	Green sand	PU coldbox
26	MI	Iron	Green sand	none
27	OH	Iron	Green sand	PU no-bake, shell
28	TN	Iron	Green sand	none
29	WI	Steel	PU no-bake	PU no-bake
30	WI	Iron	Green sand	PU coldbox, shell
31	TN	Iron	Green sand	Shell, resin/CO ₂
32	TN	Iron	Green sand	PU coldbox
33	AL	No lead brass	PU no-bake	PU no-bake
34	AL	No lead brass	Green sand	PU no-bake
35	VA	Iron	Green sand	PU coldbox
36	GA	Iron	Green sand	PU coldbox, shell
37	SC	Iron	Green sand	PU coldbox, shell
38	IA	Steel	Phenolic ester-cured	PU coldbox, shell, resin/CO ₂
39	IA	Steel	Green sand	PU coldbox, shell, resin/CO ₂
40	NC	Iron	Green sand	PU coldbox, shell
41	IN	Steel	PU no-bake	PU no-bake
42	IN	Iron	Green sand	PU coldbox
43	WI	Steel	Green sand	PU no-bake, shell, core oil, resin/CO ₂

PU, phenolic urethane.

[†]Olivine sand utilized.

on sample collection. In brief, a clean section of PVC pipe (5.1 cm i.d.) was used to collect four samples from each waste sand pile. The samples were transferred into 500-mL I-CHEM glass jars with Teflon-lined polypropylene closures (Chase Scientific Glass Inc., Rockwood, TN), immediately shipped to our laboratory in coolers, and then stored at 4°C until processed.

Total Metal Analyses

The SFSs were digested according to U.S. EPA method 3050B [14]. Prior to digestion, each sample

was passed through a 0.5-mm sieve and homogenized. A 2.5 g sub-sample (dry wt.) was then refluxed in 10 mL of 8 M HNO₃ for 15 min. Afterwards, 5 mL of concentrated HNO₃ was added and samples were refluxed for 2 h. Two mL of DI water followed by 3 mL of 30% H₂O₂ were added to the samples, which were heated until effervescence subsided. Additional 1 mL aliquots of 30% H₂O₂ were added until effervescence was minimal. The samples were then refluxed for 15 min. in 10 mL of concentrated HCl. The digests were filtered through Whatman no. 40 paper layered with Whatman 2V fluted filters (Florham Park, NJ). The filtrate was di-

luted to 100 mL with 0.1 M HCl and analyzed by inductively coupled plasma-atomic emission spectrometry (ICP-AES). Blanks and standard reference material 2709 (San Joaquin Soil, National Institute of Standards and Technology, Gaithersburg, MD) were run regularly to ensure quality control.

Leach Tests

The TCLP and SPLP were conducted according to U.S. EPA methods 1311 and 1312 [14], respectively, but with modifications. Two g of spent sand was placed into a 50-mL polyethylene centrifuge tube (Fisher Scientific, Waltham, MA; Cat. No. 06-443-20), to which 40 mL of extraction fluid no. 1 (pH 4.9 for TCLP and pH 4.2 for SPLP) was added. The tubes were tightly capped and then tumbled at 30 rev min⁻¹ for 18 h on a rotary shaker (Appropriate Technical Resources Inc., Laurel, MD). The extracts were centrifuged for 10 min. at 3,000 × g and then filtered through a 0.7 μm glass fiber filter (Fisher Scientific; Cat. No. 09-804-142H). The pH of the recovered extracts was measured and recorded, after which they were acidified with HNO₃ to a pH < 2. The preserved samples were stored at 4°C until processed.

The water leach test was conducted according to ASTM International method D 3897 [1], except that a 2 g sample of spent sand was mixed with 40 mL of deionized (DI) water as described above. The aqueous extracts were centrifuged for 10 min. at 3,000 × g and then filtered through a 0.45 μm membrane filter. All extracts were analyzed for Ag, As, Ba, Be, Cd, Cr, Cu, Ni, Pb, Sb, and Zn by ICP-AES.

Extraction of Organics

A Dionex (Sunnyvale, CA) accelerated solvent extractor (ASE 200) was used to extract the PAHs and phenolics for analysis by gas chromatography-mass spectrometry (GC-MS). Twenty g of SFS as received was placed into the center of a 33-mL stainless steel extraction cell, which was then packed at each end with clean Ottawa sand (20–30 mesh, U.S. Silica Corp., Ottawa, IL) to fill the void. If the SFS was moist to the touch, anhydrous Na₂SO₄ was mixed with the sand prior to addition to the cells. The conditions of the ASE were as follows: solvent, dichloromethane/acetone (1:1); static extraction for 5 min at a pressure of 14 MPa (2000 psi) and an oven temperature of 100°C; flush volume, 60% of the cell volume; N₂ purge, 1 MPa (150 psi)

for 60 s. All extracts were collected in 40 mL I-CHEM vials. Immediately after the extraction, the extracts were evaporated to near dryness under N₂, then reconstituted with 2 mL of dichloromethane for GC-MS analysis.

Gas Chromatography—Mass Spectrometry

The GC was a Varian CP-3800 equipped with a Saturn 2200 ion trap MS (Varian Inc., Walnut Creek, CA). The GC capillary column was a VF-5ms (Varian Inc., 30 m × 0.25 mm × 0.25 μm) and helium was used as the carrier gas. For PAH analyses, the oven temperature program was 45°C for 2 min, then ramping at 10°C min⁻¹ to 325°C, then held at 325°C for 5 min. The temperature program for the phenolics analyses was 40°C for 4 min, then ramping at 12°C min⁻¹ to 260°C, then held for 1.67 min, followed by ramping at 10°C min⁻¹ to 280°C, then held at 280°C for 8 min. The injector temperature was 250°C for all analyses. The GC-MS transfer line temperature was 300°C and the ion trap temperature was 210°C. Mass spectra were obtained by electron impact at 70 eV from 50 to 300 m/z (1.7 scans s⁻¹).

RESULTS AND DISCUSSION

A total of 43 spent sands were collected from ferrous (iron and steel) and non-ferrous (aluminum and brass) foundries in 13 states mostly east of the Mississippi river (Table 1). Of the 43 sands, only 7 sands were from foundries that used chemically bonded molding sands; all others were green sands and 89% of the green sands were from ferrous foundries. Metal data from the initial sampling event, conducted in June 2005, is reported in Dungan and Dees [7]. Overall, the total metal concentrations in the SFSs (i.e. Ag, Al, As, B, Ba, Be, Co, Cr, Cu, Fe, Mg, Mn, Mo, Ni, Pb, Sb, V, and Zn) were within ranges found in native soils as determined by Smith et al. [13] and other similar reports (Table 2). Of the 19 metals quantified, only Ag, B, Cd, and Sb were not detected in any of the SFSs above the method detection limits (MDLs; i.e. 17.6, 19.2, 5.9, and 4.5 mg kg⁻¹, respectively). In a few spent sands, however, the metal concentrations were substantially higher than in most of the sands. For example, sand 34, a green sand from a non-leaded brass foundry, contained relatively high concentrations of Cu at 3318 mg kg⁻¹ and Zn at 1,640 mg kg⁻¹. As per the Smith et al. [13] dataset, the average

Table 2. Total Metal Concentrations in Soils and Other Surficial Materials.

Element	Concentration, mg kg ⁻¹														
	Spent Foundry Sands ¹			U.S. and Canadian Surface Soils ²			U.S. Soils and Other Surficial Materials ³			U.S. Surface Soils ⁴			U.S. Agricultural Soils ⁵		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Ag	<17.6			<1.0											
Al	<311	10048	1853	6900	87300	47597	700	>100000	72000						
As	0.04	4.8	1.0	<1.0	18.0	5.7	<0.1	97	7.2						
B	<19.2						<20	300	33						
Ba	<8.7	151	23.3	58.0	1800	529	10	5000	580						
Be	<1.2	3.1	08	0.2	4.0	1.3	<1	15	0.92						
Cd	<5.9			<0.1	5.2	0.29				<0.004	1.3	0.2	<0.01	2.0	0.18
Co	<0.84	95.3	3.7	0.9	143	8.9	<3	70	9.1	0.1	347	13.4			
Cr	<1.0	149	11.6	3.0	5320	71.3	1	2000	54	<0.007	3361	88.7			
Cu	<23.1	3318	97.1	<0.5	81.9	14.3	<1	700	25	0.3	201	24.7	<0.6	495	18
Fe	<352	44320	6115	3800	87700	20766	100	>10000	26000						
Hg				<0.02	0.71	0.04	<0.01	4.6	0.09	<0.001	2.0	0.04			
Mg	<720	51574	9119	400	173400	7409	50	>100000	9000						
Mn	<45.0	671	189	56.0	3120	610	<2	700	550	<0.01	3560	589			
Mo	<4.4	9.6	2.4	0.11	21.0	1.0	<3	15	0.97						
Ni	<1.2	2328	857	1.6	2314	35.1	<5	700	19	<0.027	3591	59.5	0.7	269	16.5
Pb	<7.7	25.7	5.0	5.3	319	23.3	<10	700	19	<0.034	164	12.7	<1.0	135	10.6
Sb	<4.5			0.14	2.3	0.64	<1	8.8	0.66						
Se				<0.2	2.3	0.38	<0.1	4.3	0.39						
Sn				0.3	8.6	1.4									
Sr				13.0	1382	184									
Ti				<0.1	1.8	0.46									
V	<7.4	9.1	3.8	7.0	380	59.6	<7	500	80						
W				0.1	3.5	0.71									
Zn	<33.4	1640	60.1	8.0	377	58.0	<5	2900	60	<0.16	216	62.6	<3.0	264	42.9

¹Dungan and Dees, 2008.²Smith et al., 2005; A horizon data.³Shacklette and Boerngen, 1984.⁴Burt et al., 2003.⁵Holmgreen et al., 1993.

Cu and Zn concentrations in U.S. and Canadian soils are 14 and 58 mg kg⁻¹, while maximum reported concentrations were 82 and 377 mg kg⁻¹, respectively (Table 2). The majority of the SFSs (i.e. 77%) contained respective Cu and Zn at concentrations of < 23.1 and < 33.4 mg kg⁻¹. Sand 2 (iron green sand) and sand 6 (steel phenolic urethane no-bake sand) contained the highest concentrations of Ni at 2,328 and 1,022 mg kg⁻¹, respectively. This can be attributed to the fact that these foundries use olivine sand instead of silica sand. The maximum determined concentrations for Ni in soils was 2,314 mg kg⁻¹ (Table 2). The average As concentration of the 43 sands was 1.0 mg kg⁻¹, and 91% of the sand samples contained < 7.7 mg Pb kg⁻¹. Arsenic and Pb were the greatest in sand 22 (iron green sand) at 4.8 and 26 mg kg⁻¹, respectively. These As and Pb concentrations, however, are close to average concentrations found in soils (Table 2). A comparison of the trace metal concentrations in SFSs to those in native soils is quite useful, since there is interest in using SFSs in

soil-related applications (e.g. manufactured soils). It also brings perspective to the metal concentrations found in the SFSs; demonstrating that trace metals in SFSs will present little risk to humans, wildlife, and the environment when used in manufactured soils. Due to physical limitations, most manufactured soils will contain no more than 30% SFS by weight.

For the second sampling event in September 2005, spent sands were received from all foundries except foundries 2, 15, 32, 38, and 39. Similarly, we did not receive sand samples from foundries 2, 5, 15, 32, 35, and 41 for the third sampling event in July 2006. Unlike the first sampling event, failure to receive samples during the subsequent sampling events occurred because the foundries themselves were responsible for collection. Regardless, participation in our study was quite high and the results for these sampling events can be found in Tables 3 through 10. A survey of the results in Tables 3 and 4 indicates that there was little overall change in the total metal composition of the SFSs over the one-year

Table 3. Total Metal Concentrations in the Spent Foundry Sands from the Second Sampling Event (September 2005).

Element	Concentration, mg kg ⁻¹																					
	1 [†]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Ag	<17.6 [‡]	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6
Al	3496	1740	1304	1482	353	<311	655	512	520	2114	2264	18.85	2206			1143	3173	1044	3574	6940	<311	3267
As	2.4	2.0	0.42	1.8			0.18	1.4	0.83	2.0	2.1	0.64	1.9	2.1		1.5	1.5	2.2	3.4	1.9	0.66	5.1
B	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2
Ba	38.2	23.7	<8.7	9.6	39.7	<8.7	<8.7	<8.7	<8.7	13.1	<8.7	15.1	<8.7			28.8	19.2	10.1	27.1	19.0	<8.7	20.4
Be	1.3	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	3.5	<1.2	<1.2	1.6
Cd	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9
Co	1.1	<0.84	<0.84	<0.84	9.10	<0.84	<0.84	<0.84	1.07	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	2.90	<0.84	<0.84	1.26
Cr	21.4	5.1	4.0	5.6	25.2	7.9	9.0	1.3	51.6	2.0	2.5	2.1	2.5			3.7	2.9	2.7	196	7.5	3.5	32.5
Cu	115	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	85.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	114	<23.1	<23.1	53.5
Fe	22989	5635	2516	5754	4558	727	4938	1071	21860	2073	904	4070	3357			2520	3942	2391	60020	3132	5386	20340
Mg	1295	1946	<720	<720	26994	<720	<720	<720	<720	<720	<720	<720	1678			<720	971	<720	1310	1267	<720	954
Mn	199	139	<45.0	121	184	<45.0	81.6	<45.0	149	<45.0	<45.0	<45.0	<45.0	<45.0	<45.0	45.1	94.6	<45.0	920	135	<45.0	458
Mo	<4.4	<4.4	<4.4	<4.4	<4.4	9.2	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	19.8	<4.4	<4.4	6.1
Ni	17.0	3.7	3.5	6.4	139	3.1	4.5	<1.2	18.0	2.0	<1.2	3.2	2.5			2.2	3.3	2.0	36.7	6.9	2.0	15.4
Pb	18.4	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	11.0	<7.7	<7.7	14.0
Sb	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5
V	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	19.3	<7.4	<7.4	<7.4
Zn	88.2	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	87.8
Element	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	
Ag	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6		<17.6	<17.6	<17.6	<17.6	<17.6			<17.6	<17.6	<17.6	<17.6	
Al	2705	2150	2103	1865	2431	2500	<311	2120	1213		<311	513	2072	2529	1811			1823	<311	1162	1856	
As	2.7	2.4	1.2	2.0	2.2	2.1	0.39	1.7	1.5		0.82	0.78	2.6	3.0	1.0			0.67	0.13	1.1	1.4	
B	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2		<19.2	<19.2	<19.2	<19.2	<19.2			<19.2	<19.2	<19.2	<19.2	
Ba	29.3	12.0	18.7	19.6	15.1	31.2	68.4	30.0	14.5		<8.7	<8.7	25.9	20.9	13.1			15.8	24.4	10.0	72.5	
Be	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2		<1.2	<1.2	<1.2	<1.2	<1.2			<1.2	<1.2	<1.2	<1.2	
Cd	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9		<5.9	<5.9	<5.9	<5.9	<5.9			<5.9	<5.9	<5.9	<5.9	
Co	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84		<0.84	<0.84	<0.84	<0.84	<0.84			<0.84	<0.84	<0.84	<0.84	
Cr	2.6	4.0	2.6	2.1	13.0	5.5	7.0	2.0	11.0		2.5	3.5	1.5	2.4	2.3			1.7	<1.0	1.7	5.7	
Cu	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1		14360	14220	<23.1	<23.1	<23.1			<23.1	<23.1	<23.1	<23.1	
Fe	3343	4031	2265	2793	10358	3810	1087	2704	3564		789	1704	4196	3962	3048			1760	4926	2743	2647	
Mg	1031	<720	<720	<720	979	813	<720	859	<720		<720	<720	807	<720	<720			<720	<720	<720	<720	
Mn	<45.0	62.2	<45.0	<45.0	89.9	57.0	<45.0	<45.0	<45.0		<45.0	<45.0	<45.0	50.6	67.1			<45.0	<45.0	<45	<45	
Mo	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4		<4.4	<4.4	<4.4	<4.4	<4.4			<4.4	<4.4	<4.4	<4.4	
Ni	2.8	3.7	1.9	2.4	20.6	3.0	15.7	1.9	14.0		34.5	21.1	2.1	2.6	2.1			<1.2	5.9	<1.2	7.4	
Pb	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7		20.6	28.9	<7.7	<7.7	<7.7			<7.7	<7.7	<7.7	<7.7	
Sb	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5		<4.5	<4.5	<4.5	<4.5	<4.5			<4.5	<4.5	<4.5	<4.5	
V	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4		<7.4	<7.4	<7.4	<7.4	<7.4			<7.4	<7.4	<7.4	<7.4	
Zn	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4		986	1732	<33.4	<33.4	<33.4			<33.4	<33.4	<33.4	<33.4	

<, Less than the method detection limit.

[†]Foundry identification number; refer to Table 1.[‡]Average of four replicates.

Table 4. Total Metal Concentrations in the Spent Foundry Sands from the Third Sampling Event (July 2006).

Element	Concentration, mg kg ⁻¹																					
	1 [†]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Ag	<17.6 [‡]	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6
Al	3431	1780	1072	<311	<311	816	370	650	2197	1416	1870	2086	981	3068	1044	2092	4680	<311	6189			
As	2.0	1.0	0.47	0.24	0.07	0.68	0.31	1.2	1.1	0.34	1.0	1.3	0.68	1.4	1.8	0.72	0.85	0.47	4.9			
B	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2
Ba	45.5	24.1	<8.7	<8.7	<8.7	<8.7	<8.7	<8.7	28.8	<8.7	23.0	9.5	19.4	53.1	12.3	25.5	12.9	<8.7	49.1			
Be	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2
Cd	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9
Co	<0.84	<0.84	<0.84	6.1	<0.84	<0.84	<8.4	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	2.2
Cr	5.0	<1.0	2.2	2.9	5.3	6.8	<1.3	30.5	2.1	1.6	<1.0	2.2	4.0	4.0	2.2	12.7	7.6	2.9	32.1			
Cu	31.3	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	78.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	47.0	<23.1	63.2	
Fe	5265	15.75	1542	4287	566	4549	931	15596	2530	710	1841	2970	2770	3751	2263	7727	2473	3760	25310			
Mg	<720	2218	<720	15990	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	906
Mn	80.7	46.5	<45.0	59.7	<45.0	62.8	<45.0	128	<45.0	<45.0	<45.0	<45.0	<45.0	<45.0	<45.0	81.4	<45.0	99.0	83.8	<45.0	483	
Mo	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4
Ni	3.2	<1.2	1.9	111	2.0	4.6	<1.2	10.5	3.4	<1.2	2.9	2.5	2.5	4.7	2.1	4.8	7.1	<1.2	17.7			
Pb	10.6	<7.7	<7.7	<7.7	<7.7	9.6	<7.7	19.6	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	12.8	<7.7	<7.7	62.6	
Sb	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5
V	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4
Zn	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	23.4	<33.4	352	
Element	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	
Ag	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.4	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6	<17.6
Al	2777	1936	2075	1592	2741	1795	387	1792	410	<311	1681	2739	1269	911	1298	1612	799	1092				
As	1.4	1.1	0.47	2.0	1.6	0.67	0.17	0.66	0.27	0.08	1.2	1.5	1.0	3.0	0.34	0.70	0.77	0.59				
B	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2	<19.2
Ba	27.1	<12.2	20.6	18.4	26.1	21.1	110	27.0	<8.7	<8.7	14.9	22.3	12.1	60.3	149	15.1	13.8	39.3				
Be	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	2.5	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2
Cd	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9	<5.9
Co	<0.84	<0.84	<0.84	<0.84	1.2	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84	9.1	<0.84	<0.84	<0.84	<0.84	<0.84	<0.84
Cr	2.7	3.0	2.4	1.9	8.5	4.5	8.0	1.9	2.5	<1.0	5.7	2.4	2.4	132	5.6	1.6	1.3	14.3				
Cu	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	38.5	4668	<23.1	<23.1	177	25.7	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1	<23.1
Fe	2999	3115	2209	2543	4748	4703	1047	2578	1696	<352	4339	2862	2281	45120	3162	1628	2787	1682				
Mg	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	<720	16566	<720	<720	<720	<720	<720	<720
Mn	<45.0	60.8	<45.0	<45.0	66.7	80.8	<45.0	<45.0	<45.0	<45.0	<45.0	50.6	<45.0	845	85.2	<45.0	<45.0	<45.0	<45.0	<45.0	<45.0	<45.0
Mo	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	54.6	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4	<4.4
Ni	3.3	3.6	2.6	2.6	7.0	3.1	8.6	2.1	3.0	<1.2	16.3	3.4	2.5	189	15.1	2.0	<1.2	3.9				
Pb	<7.7	8.2	<7.7	<7.7	9.0	8.1	<7.7	<7.7	<7.7	<7.7	212	<7.7	<7.7	46.6	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7	<7.7
Sb	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5	<4.5
V	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	9.7	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4	<7.4
Zn	<33.4	<33.4	<33.4	<33.4	<33.4	33.4	<33.4	<33.4	<33.4	<33.4	2829	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4	<33.4

<, Less than the method detection limit.

[†]Foundry identification number; refer to Table 1.[‡]Average of four replicates.

sampling period. Some of the largest fluctuations that did occur, occurred with Fe, but this was expected since most of the sands are from ferrous castings. In sand 27, for example, the Fe concentration decreased from 29,950 mg kg⁻¹ to 4,748 mg kg⁻¹ by the third sampling event. In sand 19, the Fe concentration increased to 60,020 mg kg⁻¹ by the second sampling, but then was lower at 7,727 mg kg⁻¹ by the third sampling. The average concentration of Fe in U.S. soils is 20,766 mg kg⁻¹, with a maximum concentration of 87,700 mg kg⁻¹ (Table 2). Iron is an essential nutrient for plants and animals, and phytotoxicity of Fe is not an agronomic problem [9]. While animals can tolerate higher concentrations of Fe than normally occur in feeds, chronic Fe toxicity is expressed as Fe-induced Cu deficiency only when Cu is low in the diet [3].

In the non-lead brass foundry sand (i.e., sand 34), the Pb concentration was 19 mg kg⁻¹ during the first sampling event [7], but surprisingly it increased to 29 and 212 mg kg⁻¹ by the second and third sampling events, respectively (Tables 3 and 4). In this sand the Cu concentration increased to 14,220 mg kg⁻¹ by the second sampling event, while Zn increased to 2,829 mg kg⁻¹ by the third sampling event. Sand 33, a chemically bonded sand from the same brass foundry, contained substantially less Cu, Pb, and Zn during the first and last sampling events; however, Cu was at a similar concentration during the second sampling event (Table 3). Since the concentrations of Cu, Pb, and/or Zn in brass foundry sands are generally at the high end of the range found in soils, they should not be considered for unconsolidated beneficial uses (e.g., manufactured soils). In two ferrous waste sands (i.e., 22 and 38), Pb was found to increase by the third sampling event; respective concentrations were as high as 63 and 47 mg kg⁻¹. Nickel which was at 1,022 mg kg⁻¹ in sand 6 during the first sampling [7], dropped to 139 and 111 mg kg⁻¹ by the second and third sampling events, respectively (Tables 3 and 4). No other dramatic fluctuations in the Pb and Ni concentrations were noted during the year-long study.

The SFSs were also subjected to the TCLP, SPLP, and the ASTM water leaching procedure. The metals quantified in the extracts were Ag, As, Ba, Be, Cd, Cr, Cu, Ni, Pb, Sb, and Zn. Leaching data from the first set of samples can be found in Dungan and Dees [7]. In brief, none of the 43 waste moldings sands failed the TCLP for elevated concentrations of Ag, As, Ba, Cd, Cr, and Pb. While Hg and Se are also required under SW-846 method 1311, they were not tested in our study.

Fahnlne and Regan [8] conducted the TCLP on 52 foundry sands and Hg and Se were ≤ 0.10 and ≤ 0.83 mg L⁻¹, respectively. These concentration are below the respective regulatory concentrations of 0.2 and 1.0 mg L⁻¹ [4]. The TCLP results from the second and third sampling events are shown in Tables 5 and 6, respectively. These results were markedly similar to the first sampling event and, as a result, they also would not exceed the TCLP regulatory concentrations for Ag, As, Ba, Cd, Cr, and Pb. Even sand 34 with a total Pb concentration of 212 mg kg⁻¹ (third sampling event only), contained 1.1 mg Pb L⁻¹ in the TCLP extracts, which is below the regulatory concentration of 5.0 mg L⁻¹. In addition, the SPLP and ASTM leach test results from the second and third sampling events were very similar to the first sampling event, with most concentrations being less than the MDL (data not shown). The TCLP, SPLP, and ASTM results indicate that the SFSs have a low metal leaching potential; however, the results should be used cautiously as they are not representative of leaching under field conditions.

The concentration of EPA-priority PAHs in the waste moldings sands are shown in Tables 7 and 8. As with the metals, the organic results from the second and third sampling events were very similar to the results obtained in June 2005 [5]. During the first sampling event, the 2-ring and 3-ring PAHs (i.e. acenaphthene, acenaphthylene, anthracene, fluorene, naphthalene, and phenanthrene) were generally detected at concentrations above the MDLs. Of these PAHs, anthracene, fluorene, naphthalene, and phenanthrene were the most abundant, as they were detected in > 79% of the SFSs. In the first set of samples, the average concentrations of these PAHs were 0.40, 0.34, 3.9, and 0.64 mg kg⁻¹, with high concentrations of 0.95, 2.6, 48, and 2.2 mg kg⁻¹, respectively. In sand 6, the naphthalene concentration declined from 48 mg kg⁻¹ to 8.3 and 0.16 mg kg⁻¹ by the second and third sampling events, respectively. Likewise, in sand 33 the naphthalene concentration decreased from 28 mg kg⁻¹ to about 10 mg kg⁻¹ during the last two sampling events. The average naphthalene concentrations, during the second and third sampling events, were 1.6 and 2.2 mg kg⁻¹, respectively. In sand 6 naphthalene increased about 10 times from the first sampling to 42 mg kg⁻¹ by the third sampling event. Aside from these major fluctuations with naphthalene, no other dramatic increases or decreases of anthracene, fluorene, naphthalene, and phenanthrene occurred over the course of this study. In the case of the 4-ring, 5-ring, and 6-ring PAHs, most were not detected a concentra-

Table 5. Metal concentrations in the TCLP Extracts from the Spent Foundry Sands from the Second Sampling Event (September 2005).

Element	Concentration, mg L ⁻¹																					
	1 [†]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Ag	<0.04 [‡]	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
As	<0.001	0.001	0.001	0.018	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.019	0.003	<0.001	0.002	0.001	0.013	0.001	<0.001	0.001	0.001	<0.001	<0.001
Ba	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86
Be	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cd	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cr	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46
Cu	0.14	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	0.14	<0.10	0.10	0.11
Ni	0.15	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	0.25	<0.14	<0.14	0.17
Pb	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.05	<0.05	<0.05
Sb	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Zn	9.6	<0.41	<0.41	<0.41	<0.41	<0.41	0.58	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	1.3
Element	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	
Ag	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	
As	0.007	0.002	0.003	0.008	<0.001	0.003	0.005	0.004	0.001	<0.001	<0.001	0.003	0.013	0.005	0.003	<0.001	0.001	0.006	0.003	<0.001	0.001	0.006
Ba	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86
Be	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cd	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cr	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	0.11	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46
Cu	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	43.9	0.65	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Ni	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	0.30	0.14	0.26	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Pb	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.24	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Sb	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Zn	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	6.5	40.3	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41

<, Less than the method detection limit.

[†]Foundry identification number; refer to Table 1.

[‡]Average of four replicates.

Table 6. Metal Concentrations in the TCLP Extracts from the Spent Foundry Sands from the Third Sampling Event (July 2006).

Element	Concentration, mg L ⁻¹																					
	1 [†]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Ag	<0.04 [‡]		<0.04	<0.04		<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04		<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
As	0.004		0.003	<0.001		<0.001	<0.001	<0.001	0.001	<0.001	0.004	0.001	0.004	0.006		<0.001	0.007	0.001	<0.001	0.001	<0.001	<0.001
Ba	<0.86		<0.86	<0.86		<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86		<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86
Be	<0.01		<0.01	<0.01		<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01
Cd	<0.01		<0.01	<0.01		<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.03	<0.01
Cr	<0.46		<0.46	<0.46		<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46		<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46
Cu	<0.10		<0.10	<0.10		<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10		<0.10	<0.10	<0.10	<0.10	<0.10	0.10	<0.10
Ni	<0.14		<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	0.27
Pb	<0.05		<0.05	<0.05		<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05		<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Sb	<0.02		<0.07	<0.07		<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07		<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07
Zn	<0.41		<0.41	<0.41		<0.41	<0.41	0.68	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41		<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	4.5
Element	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	
Ag	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04		<0.04	<0.04		<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
As	0.005	0.003	0.003	0.012	<0.001	<0.001	0.002	0.001	<0.001		<0.001	0.001		0.017	0.001	0.007	0.004	0.001		<0.001	0.005	
Ba	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86		<0.86	<0.86		<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86	<0.86
Be	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01		<0.01	<0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cd	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01		<0.01	<0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cr	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46		<0.46	<0.46		<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46	<0.46
Cu	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10		<0.10	5.4		<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Ni	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	0.20	<0.14	<0.14		<0.14	0.23		<0.14	<0.14	1.71	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Pb	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05		<0.05	1.1		<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Sb	<0.02	<0.07	<0.07	<0.07	<0.07	<0.02	<0.07	<0.07	<0.07		<0.07	<0.07		<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07
Zn	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41		<0.41	42.5		<0.41	<0.41	0.71	<0.41	<0.41	<0.41	<0.41	<0.41	<0.41

<, Less than the method detection limit.
[†]Foundry identification number; refer to Table 1.
[‡]Average of four replicates.

Table 7. Concentration of polycyclic Aromatic Hydrocarbons in the Spent Foundry Sands from the Second Sampling Event (September 2005).

Compound	Concentration, mg kg ⁻¹																					
	1 [†]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Acenaphthene	<0.04 [‡]	<0.04	<0.04	0.06	<0.04	0.09	0.05	<0.04	<0.04	0.11	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	0.09	<0.04	<0.04
Acenaphthylene	0.17	<0.03	<0.03	0.06	0.28	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.03	<0.03	<0.03	<0.03	0.08	<0.03	<0.03	<0.03	0.04
Anthracene	0.24	0.18	0.33	0.62	0.38	0.27	0.52	0.69	<0.03	0.99	<0.03	0.43	0.84		0.49	0.44	<0.03	0.36	0.83	0.23	0.62	
Benz[a]anthracene	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	0.20	0.13	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	0.10
Benzo[b]fluoranthene	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
Benzo[k]fluoranthene	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13
Benzo[ghi]perylene	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Benzo[a]pyrene	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Chrysene	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	0.11	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08
Dibenz[a,h]anthracene	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16
Fluoranthene	<0.06	<0.06	<0.06	0.10	0.06	<0.06	1.03	0.11	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06
Fluorene	0.25	<0.04	<0.04	0.50	0.38	0.25	0.11	0.47	<0.04	0.55	<0.04	0.44	0.53		0.36	0.11	0.36	0.25	0.56	<0.04	0.45	
Indeno[1,2,3-cd]pyrene	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Naphthalene	1.60	0.26	0.34	0.84	8.33	0.43	0.16	0.38	0.39	1.49	<0.03	1.87	0.59		0.55	0.34	0.27	0.51	0.66	<0.03	0.81	
Phenanthrene	1.36	0.18	0.37	0.62	0.43	0.29	1.29	0.94	0.94	1.40	<0.03	0.91	1.01		0.77	0.39	1.10	0.40	0.97	0.20	0.64	
Pyrene	0.06	<0.03	<0.03	0.24	<0.03	0.06	0.86	0.20	<0.03	0.18	<0.03	0.12	0.47		<0.03	<0.03	0.16	0.07	0.47	<0.03	0.23	
Compound	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	
Acenaphthene	0.17	<0.04	<0.04	<0.04	<0.04	<0.04	0.06	<0.04	<0.04		<0.04	<0.04	<0.04	0.12	<0.04			0.18	<0.04	0.04	<0.04	
Acenaphthylene	0.10	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03		0.32	0.25	0.11	<0.03	0.12			0.09	<0.03	<0.03	0.20	
Anthracene	0.54	0.97	0.33	0.33	0.28	0.14	0.35	<0.03	0.06		0.46	0.45	0.36	0.35	0.66			0.48	0.53	0.53	0.05	
Benz[a]anthracene	<0.10	<0.10	<0.10	<0.10	<0.10	<0.01	<0.10	<0.10	<0.10		<0.10	<0.10	<0.10	<0.10	<0.10			<0.10	<0.10	<0.10	<0.10	
Benzo[b]fluoranthene	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12		<0.12	<0.12	<0.12	<0.12	<0.12			<0.12	<0.12	<0.12	<0.12	
Benzo[k]fluoranthene	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13		<0.13	<0.13	<0.13	<0.13	<0.13			<0.13	<0.13	<0.13	<0.13	
Benzo[ghi]perylene	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14			<0.14	<0.14	<0.14	<0.14	
Benzo[a]pyrene	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20		<0.20	<0.20	<0.20	<0.20	<0.20			<0.20	<0.20	<0.20	<0.20	
Chrysene	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08		<0.08	<0.08	<0.08	<0.08	<0.08			<0.08	<0.08	<0.08	<0.08	
Dibenz[a,h]anthracene	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16		<0.16	<0.16	<0.16	<0.16	<0.16			<0.16	0.17	<0.16	<0.16	
Fluoranthene	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06		<0.06	<0.06	<0.06	<0.06	0.23			<0.06	<0.06	<0.06	<0.06	
Fluorene	0.41	1.19	0.19	0.49	0.10	0.08	0.16	0.71	0.11		0.54	0.84	0.26	<0.04	0.88			0.41	0.38	0.24	0.16	
Indeno[1,2,3-cd]pyrene	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.04	<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14			<0.14	<0.14	<0.14	<0.14	
Naphthalene	0.09	1.37	0.43	0.89	0.19	0.95	<0.03	0.74	0.36		9.76	0.74	0.29	1.12	2.20			1.10	14.6	0.68	0.10	
Phenanthrene	0.57	1.91	0.45	1.28	0.54	0.14	0.29	1.07	0.26		0.66	0.90	0.57	0.88	1.68			0.77	0.65	0.55	0.23	
Pyrene	0.22	0.80	0.09	0.33	<0.03	0.07	<0.03	0.49	<0.03		0.23	0.27	<0.03	0.10	0.16			0.04	0.13	<0.03	<0.03	

<, Less than the method detection limit.

†Foundry identification number; refer to Table 1.

‡Average of four replicates.

Table 8. Concentration of polycyclic Aromatic Hydrocarbons in the Spent Foundry Sands from the Third Sampling Event (July 2006).

Compound	Concentration, mg kg ⁻¹																					
	1 [†]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Acenaphthene	<0.04 [‡]		<0.04	<0.04		<0.04	<0.04	<0.04	<0.04	<0.04	0.11	<0.04	0.10	0.11		<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Acenaphthylene	0.03		<0.03	<0.03		<0.03	<0.03	<0.03	<0.03	<0.03	0.14	<0.03	0.07	<0.03		<0.03	<0.03	0.25	<0.03	<0.03	<0.03	<0.03
Anthracene	0.09		0.10	0.10		0.11	<0.03	0.25	0.13	0.07	0.69	<0.03	0.25	0.18		0.16	0.10	0.60	0.13	0.37	<0.03	0.17
Benz[a]anthracene	<0.10		<0.10	<0.10		<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10		0.15	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Benzo[b]fluoranthene	<0.12		<0.12	<0.12		<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12		<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
Benzo[k]fluoranthene	<0.13		<0.13	<0.13		<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13		<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13
Benzo[ghi]perylene	<0.14		<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Benzo[a]pyrene	<0.20		<0.20	<0.20		<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20		<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Chrysene	<0.08		<0.08	<0.08		<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08		<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08
Dibenz[a,h]anthracene	<0.16		<0.16	<0.16		<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16		<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16
Fluoranthene	<0.06		<0.06	<0.06		<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06		0.10	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06
Fluorene	0.14		0.14	<0.04		0.39	0.06	0.28	<0.04	0.08	0.64	<0.04	0.32	0.24		0.14	0.07	0.56	0.30	0.30	<0.04	0.17
Indeno[1,2,3-cd]pyrene	<0.14		<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Naphthalene	0.65		0.67	0.07		42.2	0.16	0.35	<0.03	0.03	2.80	<0.03	0.63	0.14		0.50	0.17	0.21	0.43	0.64	<0.03	0.64
Phenanthrene	0.30		0.39	0.18		0.18	0.09	0.43	<0.03	0.19	1.86	<0.30	0.80	0.64		0.43	0.22	0.80	0.43	1.43	0.09	0.61
Pyrene	0.07		0.09	0.06		0.06	<0.03	0.19	<0.03	0.06	0.29	<0.30	0.11	0.11		0.10	0.06	0.09	0.10	0.27	0.04	0.12

Compound	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
Acenaphthene	<0.04	0.40	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04		<0.04	0.06		<0.04	0.05	<0.04	<0.04	0.25		0.04	<0.04
Acenaphthylene	0.07	0.16	<0.03	0.05	0.04	<0.03	<0.03	<0.03	0.05		0.08	0.10		<0.03	0.07	<0.03	<0.03	0.33		<0.03	<0.03
Anthracene	0.19	0.56	0.04	0.23	0.15	<0.03	0.17	<0.03	0.05		0.20	0.35		<0.03	0.27	0.10	0.07	0.60		0.46	0.10
Benz[a]anthracene	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10		<0.10	<0.10		<0.10	<0.10	<0.10	<0.10	<0.10		<0.10	<0.10
Benzo[b]fluoranthene	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12		<0.12	<0.12		<0.12	<0.12	<0.12	<0.12	<0.12		<0.12	<0.12
Benzo[k]fluoranthene	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13		<0.13	<0.13		<0.13	<0.13	<0.13	<0.13	<0.13		<0.13	<0.13
Benzo[ghi]perylene	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14		<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14		<0.14	<0.14
Benzo[a]pyrene	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20		<0.20	<0.20		<0.20	<0.20	<0.20	<0.20	<0.20		<0.20	<0.20
Chrysene	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08		<0.08	<0.08		<0.08	<0.08	<0.08	<0.08	<0.08		<0.08	<0.08
Dibenz[a,h]anthracene	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16		<0.16	<0.16		<0.16	<0.16	<0.16	<0.16	<0.16		<0.16	<0.16
Fluoranthene	<0.06	<0.06	<0.06	<0.06	0.06	<0.06	<0.06	<0.06	<0.06		<0.06	<0.06		<0.06	<0.06	<0.06	<0.06	0.09		<0.06	<0.06
Fluorene	0.12	1.05	0.06	0.42	0.14	0.05	0.07	0.07	0.04		0.46	0.83		0.22	0.41	<0.04	<0.04	0.41		0.18	<0.04
Indeno[1,2,3-cd]pyrene	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14		<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14		<0.14	<0.14
Naphthalene	0.30	1.88	0.08	0.89	1.00	0.53	0.08	0.12	0.17		9.60	1.96		5.77	0.67	0.03	0.05	0.54		0.41	0.03
Phenanthrene	0.31	1.14	0.37	0.44	0.44	0.74	0.18	0.25	0.10		0.46	1.58		0.48	0.81	0.11	0.21	0.73		0.43	0.11
Pyrene	0.08	0.73	0.09	0.13	0.13	0.04	0.06	0.08	0.03		0.05	0.24		0.09	0.12	0.05	<0.03	0.06		0.05	0.05

<, Less than the method detection limit.

[†]Foundry identification number; refer to Table 1.

[‡]Average of four replicates.

Table 9. Concentration of phenolics in the Spent Foundry Sands from the Second Sampling Event (September 2005).

Compound	Concentration, mg kg ⁻¹																					
	1 [†]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
2-sec-Butyl-4,6-dinitrophenol	<0.21 [‡]	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21
4-Chloro-3-methylphenol	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	0.45	<0.18	<0.18
2-Chlorophenol	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11
2,4-Dichlorophenol	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
2,6-Dichlorophenol	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06
2,4-Dimethylphenol	<0.08	0.19	0.66	0.19	0.86	0.10	<0.08	0.23	<0.08	3.12	<0.08	2.10	1.48			0.78	0.13	<0.08	0.46	7.45	<0.08	0.09
2,4-Dinitrophenol	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24
2-Methylphenol	0.67	0.26	1.33	1.23	2.94	<0.21	<0.21	0.67	<0.21	5.30	<0.21	2.99	1.25			1.54	0.34	<0.21	1.15	5.52	<0.21	0.56
3- and 4-Methylphenol	0.20	0.21	0.43	0.46	0.73	0.14	0.09	0.34	<0.08	2.27	<0.08	1.34	0.36			0.65	0.30	0.08	0.42	1.71	<0.08	0.20
2-Methyl-4,6-dinitrophenol	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16
2-Nitrophenol	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
4-Nitrophenol	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44
Pentachlorophenol	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24
Phenol	2.28	0.41	0.85	4.75	50.0	0.74	0.63	1.73	<0.07	8.12	<0.07	4.78	0.47			4.57	0.44	0.37	2.75	4.95	<0.07	1.33
2,3,4,6-Tetrachlorophenol	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
2,4,6-Trichlorophenol	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
2,4,5-Trichlorophenol	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Compound	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	
2-sec-Butyl-4,6-dinitrophenol	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21		<0.21	<0.21	<0.21	<0.21	<0.21			<0.21	<0.21	<0.21	<0.21	
4-Chloro-3-methylphenol	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18		<0.18	<0.18	<0.18	<0.18	<0.18			<0.18	<0.18	<0.18	<0.18	
2-Chlorophenol	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11		<0.11	<0.11	<0.11	<0.11	<0.11			<0.11	<0.11	<0.11	<0.11	
2,4-Dichlorophenol	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12		<0.12	<0.12	<0.12	<0.12	<0.12			<0.12	<0.12	<0.12	<0.12	
2,6-Dichlorophenol	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06		<0.06	<0.06	<0.06	<0.06	<0.06			<0.06	<0.06	<0.06	<0.06	
2,4-Dimethylphenol	<0.08	0.52	<0.08	0.23	<0.08	<0.08	0.71	<0.08	<0.08		0.21	0.13	<0.08	0.33	2.74			3.34	0.27	0.63	<0.08	
2,4-Dinitrophenol	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24		<0.24	<0.24	<0.24	<0.24	<0.24			<0.24	<0.24	<0.24	<0.24	
2-Methylphenol	<0.21	0.68	0.27	0.46	0.21	<0.21	0.26	<0.21	<0.21		0.69	0.27	0.23	0.74	4.42			9.90	0.74	3.36	<0.21	
3- and 4-Methylphenol	<0.08	0.65	0.11	0.87	0.17	0.15	0.25	0.13	<0.08		0.19	0.12	0.96	0.32	3.21			3.98	0.09	0.78	0.09	
2-Methyl-4,6-dinitrophenol	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16		<0.16	<0.16	<0.16	<0.16	<0.16			<0.16	<0.16	<0.16	<0.16	
2-Nitrophenol	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09		<0.09	<0.09	<0.09	<0.09	<0.09			<0.09	<0.09	<0.09	<0.09	
4-Nitrophenol	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44		<0.44	<0.44	<0.44	<0.44	<0.44			<0.44	<0.44	<0.44	<0.44	
Pentachlorophenol	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24		<0.24	<0.24	<0.24	<0.24	<0.24			<0.24	<0.24	<0.24	<0.24	
Phenol	0.16	0.93	0.54	0.89	0.53	0.24	0.77	0.10	0.48		13.2	0.73	1.57	1.28	11.0			14.2	20.2	11.2	0.12	
2,3,4,6-Tetrachlorophenol	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09		<0.09	<0.09	<0.09	<0.09	<0.09			<0.09	<0.09	<0.09	<0.09	
2,4,6-Trichlorophenol	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12		<0.12	<0.12	<0.12	<0.12	<0.12			<0.12	<0.12	<0.12	<0.12	
2,4,5-Trichlorophenol	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14			<0.14	<0.14	<0.14	<0.14	

<, Less than the method detection limit.

[†]Foundry identification number; refer to Table 1.[‡]Average of four replicates.

Table 10. Concentration of Phenolics in the Spent Foundry Sands from the Third Sampling Event (July 2006).

Compound	Concentration, mg kg ⁻¹																					
	1 [†]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
2-sec-Butyl-4,6-dinitrophenol	<0.21 [‡]	<0.21	<0.21		<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21		<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21
4-Chloro-3-methylphenol	<0.18	<0.18	<0.18		<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18		<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18
2-Chlorophenol	<0.11	<0.11	<0.11		<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11		<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11
2,4-Dichlorophenol	<0.12	<0.12	<0.12		<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12		<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
2,6-Dichlorophenol	<0.06	<0.06	<0.06		<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06		<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06
2,4-Dimethylphenol	0.33	1.05	0.59		0.61	<0.08	0.28	<0.08	<0.08	4.38	<0.08	4.25	10.85		0.80	<0.08	0.32	0.62	6.42	<0.08	<0.08	<0.08
2,4-Dinitrophenol	<0.24	<0.24	<0.24		<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24		<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24
2-Methylphenol	1.00	2.63	0.69		0.17	<0.21	0.53	<0.21	<0.21	8.82	<0.21	5.44	8.74		1.56	<0.21	<0.21	2.27	10.5	<0.21	0.22	
3- and 4-Methylphenol	0.42	1.56	0.23		0.33	<0.08	0.20	<0.08	0.11	4.08	<0.08	2.62	2.74		0.64	<0.08	0.15	0.76	4.70	<0.08	0.27	
2-Methyl-4,6-dinitrophenol	<0.16	<0.16	<0.16		<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16		<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16
2-Nitrophenol	<0.09	<0.09	<0.09		<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09		<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
4-Nitrophenol	<0.44	<0.44	<0.44		<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44		<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44
Pentachlorophenol	<0.24	<0.24	<0.24		<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24		<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24
Phenol	1.05	4.47	0.38		28.5	<0.07	0.91	<0.07	0.47	23.4	<0.07	7.68	6.10		3.90	<0.07	0.10	4.52	23.7	<0.07	1.16	
2,3,4,6-Tetrachlorophenol	<0.09	<0.09	<0.09		<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09		<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
2,4,6-Trichlorophenol	<0.12	<0.12	<0.12		<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12		<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
2,4,5-Trichlorophenol	<0.14	<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14
Compound	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	
2-sec-Butyl-4,6-dinitrophenol	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21	<0.21		<0.21	<0.21		<0.21	<0.21	<0.21	<0.21	<0.21		<0.21	<0.21	
4-Chloro-3-methylphenol	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18		<0.18	<0.18		<0.18	<0.18	<0.18	<0.18	<0.18		<0.18	<0.18	
2-Chlorophenol	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11	<0.11		<0.11	<0.11		<0.11	<0.11	<0.11	<0.11	<0.11		<0.11	<0.11	
2,4-Dichlorophenol	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12		<0.12	<0.12		<0.12	<0.12	<0.12	<0.12	<0.12		<0.12	<0.12	
2,6-Dichlorophenol	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06		<0.06	<0.06		<0.06	<0.06	<0.06	<0.06	<0.06		<0.06	<0.06	
2,4-Dimethylphenol	0.26	0.78	<0.08	2.11	0.24	<0.08	0.44	0.09	<0.08		0.56	0.82		1.01	2.18	<0.08	<0.08	1.44		0.23	0.11	
2,4-Dinitrophenol	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24		<0.24	<0.24		<0.24	<0.24	<0.24	<0.24	<0.24		<0.24	<0.24	
2-Methylphenol	0.73	0.84	0.29	1.70	1.47	<0.21	<0.21	0.21	<0.21		1.85	3.81		2.91	3.86	<0.21	<0.21	4.00		1.13	<0.21	
3- and 4-Methylphenol	0.26	0.83	0.08	3.19	0.49	<0.08	0.13	0.20	<0.08		0.41	1.46		1.42	2.88	<0.08	<0.08	2.39		0.30	<0.08	
2-Methyl-4,6-dinitrophenol	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16		<0.16	<0.16		<0.16	<0.16	<0.16	<0.16	<0.16		<0.16	<0.16	
2-Nitrophenol	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09		<0.09	<0.09		<0.09	<0.09	<0.09	<0.09	<0.09		<0.09	<0.09	
4-Nitrophenol	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44	<0.44		<0.44	<0.44		<0.44	<0.44	<0.44	<0.44	<0.44		<0.44	<0.44	
Pentachlorophenol	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24		<0.24	<0.24		<0.24	<0.24	<0.24	<0.24	<0.24		<0.24	<0.24	
Phenol	1.45	1.45	1.64	3.15	2.44	0.29	1.05	0.65	0.46		20.0	11.5		10.0	7.10	<0.07	<0.07	6.10		2.71	0.10	
2,3,4,6-Tetrachlorophenol	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09		<0.09	<0.09		<0.09	<0.09	<0.09	<0.09	<0.09		<0.09	<0.09	
2,4,6-Trichlorophenol	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12		<0.12	<0.12		<0.12	<0.12	<0.12	<0.12	<0.12		<0.12	<0.12	
2,4,5-Trichlorophenol	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14		<0.14	<0.14		<0.14	<0.14	<0.14	<0.14	<0.14		<0.14	<0.14	

<, Less than the method detection limit.

[†]Foundry identification number; refer to Table 1.[‡]Average of four replicates.

tions above the MDLs during all three sampling events (i.e. benz[a]anthracene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[ghi]perylene, benzo[a]pyrene, chrysene, dibenz[a,h]anthracene, fluoranthene, and indeno[1,2,3-cd]pyrene). The respective MDLs were 0.10, 0.12, 0.13, 0.14, 0.20, 0.08, 0.16, 0.06, and 0.14 mg kg⁻¹.

Tables 9 and 10 show the concentrations of 17 U.S. EPA-priority phenolics in the SFSs collected in September 2005 and July 2006, respectively. Phenolics were targeted since many of the core binders are phenol-based resins. Their thermal degradation results in the production of 2-methylphenol, 3-methylphenol, 4-methylphenol, and 2,4-dimethylphenol [6], all of which are on the U.S. EPA's priority list. Along with phenol, these phenolic compounds were quantitatively detected above the MDL in the majority of the SFSs. The sands with higher concentrations of phenol, also generally contained higher concentrations of 2,4-dimethylphenol, 2-methylphenol, and 3- and 4-methylphenol. During the first sampling event, the phenol concentration was the highest in sand 6 at 186 mg kg⁻¹ [5]. In the second set of samples, the phenol concentration ranged from < 0.07 to as high as 50 mg kg⁻¹ in sand 6. By the third sampling event, the phenol concentration in sand 6 was 29 mg kg⁻¹, which was the highest concentration compared to all other sands. In comparison, the remaining phenolic compounds (i.e. 2-sec-butyl-4,6-dinitrophenol, 4-chloro-3-methylphenol, 2-chlorophenol, 2,4-dichlorophenol, 2,6-dichlorophenol, 2,4-dinitrophenol, 2-methyl-4,6-dinitrophenol, 2-nitrophenol, 4-nitrophenol, pentachlorophenol, 2,3,4,6-tetrachlorophenol, 2,4,6-trichlorophenol, and 2,4,5-trichlorophenol) were not found to be above the MDLs in the majority of the SFSs during all three sampling events.

In conclusion, this one-year study to characterize trace metals, PAHs, and phenolics in SFSs has revealed that the concentrations of these constituents remain relatively consistent. When metal fluctuations did occur, it was usually limited to Fe in the ferrous molding sands or Cu, Pb, and Zn in the brass molding sands. By and large, however, the trace metal concentrations in the SFSs were found to be within ranges normally found in surface soils. While the PAHs and phenolics were detected at relatively low concentrations, with most below our MDLs, a few sands contained higher than usual concentrations of these organic compounds. This was not limited to any particular molding sand type and metal poured, but the sands with the highest PAH and

phenolic concentrations were generally chemically-bonded molding sands. Since the most abundant compounds in the sands are naphthalene, phenanthrene, anthracene, phenol, 2,4-dimethylphenol, 2-methylphenol, and 3- and 4-methylphenol, which are semi-volatile in nature, methods to enhance their dissipation before beneficial use may be required. The soil blending process itself might be sufficient by stimulating volatilization, along with the enhanced chemical and biological degradation from the organic byproducts that are added to manufactured soils.

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