

APPENDIX I

LEACHING OF RADIONUCLIDES FROM SLAGS

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LEACHING OF RADIONUCLIDES FROM SLAGS

As described in Appendix E, a number of radionuclides are expected to partition strongly to the slag during the electric arc furnace (EAF) melting of contaminated carbon steel scrap. Typically, this slag is stored at the steel mill for as long as several months before disposal. During storage and use (or disposal), the slag will be subjected to weathering and certain components may leach from the slag and ultimately contaminate the local groundwater. This appendix presents the limited information uncovered in this study which can be used to model the leaching of radionuclides which partition to the slag.

I.1 STEEL SLAGS—BACKGROUND DATA

Steelmaking slags are typically composed of calcium silicates and aluminoferrites together with fused oxides of calcium, iron, manganese, and magnesium. Based on a 1991 survey of member companies, the National Slag Association (1994) quoted the average chemistry for steel slags as:

CaO	42.88%
SiO ₂	14.89%
MgO	8.14%
MnO	5%
FeO	25%
P ₂ O ₅	0.8%
S	0.078%
Al ₂ O ₃	5.00%
Moisture	3.60%

Ultimate disposal of steel slags generally involves their use in road fill and as an aggregate in building products. In 1992, 6.9 million metric tons of steel slag were sold or used in the U.S. for the following purposes (Solomon 1993):

- Asphaltic concrete aggregate 13%
- Fill 16%
- Road base 35%
- Railroad ballast 3%

- Soil conditioning, ice control, misc. . . 33%

According to the U.S. Geological Survey¹, there are currently 13 firms which process steel slags at 76 facilities in 28 states (USGS 1996). In 1995, 85% of all iron and steel slags were shipped by truck for an distance of 30 miles, 4% were shipped by water for an average distance of 250 miles, and 4% by rail for an average distance of 175 miles. The balance of the slag (7%) was used at the plant sites.

I.2 SLAG CEMENT LEACHING STUDIES

The American Nuclear Society has developed and formalized detailed procedures for measuring the leachability of solidified low-level radioactive wastes (American Nuclear Society 1986). This procedure involves testing of controlled geometry specimens in demineralized water at 17.5°C to 27.5°C to determine the release during individual time steps and cumulatively. Mass transport is assumed to be controlled by a diffusion process. When the fraction leached from a uniform sample is less than 20%, the behavior can be approximated by a semi-infinite medium where the "effective diffusivity" is given by the following equation:

$$D = \pi T \left(\frac{a_n V}{A_o \Delta_{nt} S} \right)^2 \quad (\text{I-1})$$

- D = effective diffusivity (cm²/s)
 V = specimen volume (cm³)
 S = geometric surface area (cm²)
 A_o = total activity of a given nuclide at $t = 0$
 a_n = activity of nuclide released during time interval n
 Δ_{nt} = $t_n - t_{n-1}$, duration of n th leaching interval
 T = mean time of the leaching interval
 $= \left(\frac{\sqrt{t} + \sqrt{t_{n-1}}}{2} \right)^2$

¹ This data collection and analysis function was handled by the Bureau of Mines prior to 1996.

When the cumulative fraction leached, $\sum_n \frac{a_n}{A_o}$, is greater than 20%, corrections must be made to Equation I-1 to account for specimen geometry.

Using a model and procedures similar to those described by the American Nuclear Society (1986), Japanese investigators have determined the fractional leaching of Sr-90, Co-60, Cs-137, and H-3 from cement/slag composites (Matsuzuru et al. 1977, 1979; Matsuzuru and Ito 1977) in deionized water and synthetic sea water. The duration of the leaching tests was about 100 days. The radionuclides were incorporated into the cement via a sodium sulfate solution. The composition of the slag cement was as follows:

SiO ₂	28.7 (wt %)
Al ₂ O ₃	11.5 (wt %)
Fe ₂ O ₃	2.3 (wt %)
CaO	50.9 (wt %)
MgO	3.2 (wt %)
Insoluble residue	0.8 (wt %)
Ignition loss	0.6 (wt %)

Leaching data were analyzed using a plane source diffusion model to derive the expression

$$f_i = \frac{2S}{V} \sqrt{\frac{D_i t}{\pi}} \quad (\text{I-2})$$

f_i = fraction of nuclide i leached in t days.

Equation I-2 can be rewritten as

$$f_i = \left[\frac{2S}{V} \sqrt{\frac{D_i}{\pi}} \right] t^{1/2} \quad (\text{I-3})$$

$$= m_i t^{1/2}$$

where the expression in the square brackets is represented by m_i , the slope of the line obtained by plotting f_i vs. $t^{1/2}$.

Once m_i is determined, Equations I-3 can be solved for D_i

$$D_i = \pi \left(\frac{m_i V}{2 S} \right)^2 \quad (\text{I-4})$$

Since the actual leaching process involves an initial rapid leaching rate of a few days' duration (≈ 7 days for Sr-90, 2 days for Co-60), followed by a longer-term linear relationship between f and \sqrt{t} , the experimental data are fitted to an equation of the form

$$f_i = m_i t^{1/2} + \alpha_i \quad (\text{I-5})$$

Because of certain limitations and problems such as the initial leach rate, Matsuzuru et al. defined L , the leaching coefficient, with the same mathematical form as D in Equation I-4.

Adjustments to the fraction leached for various geometries can be made using the following expression:

$$f_{i2} = f_{i1} \left(\frac{S_2 V_1}{S_1 V_2} \right) \quad (\text{I-6})$$

where subscripts 1 and 2 refer to geometries 1 and 2, respectively.

I.2.1 Strontium-90

Matsuzuru and Ito (1977) reported values of L for Sr-90 leaching from slag cements that ranged from 1.2×10^{-7} to 1.7×10^{-7} cm²/day for both deionized water and synthetic sea water at 25°C. Using average values of L for samples cured seven days prior to testing in deionized water, a surface area of 94 cm² and a volume of 70 cm³, the following equation for the fractional leaching was developed for the present analysis:

$$f_{\text{Sr}} = 5.8 \times 10^{-4} \sqrt{t} + 4.97 \times 10^{-3} \quad (\text{I-7})$$

The leachability of Cs-137 was reported to be about ten times that of Sr-90.

I.2.2 Cobalt-60

Matsuzuru et al. (1977) reported values of L for Co-60 leaching from slag cements that ranged from 9.83×10^{-10} to 1.89×10^{-9} cm²/day for both deionized and synthetic sea water at 25°C.

Using the same principles as for Sr-90, above, the fractional leaching is

$$f_{\text{Co}} = 4.9 \times 10^{-5} \sqrt{t} + 4.33 \times 10^{-4} \quad (\text{I-8})$$

According to Equation I-8, 0.14% of cobalt would leach during the first year.

Matsuzuru et al. (1977) observed that the quantity of Co-60 leached during the initial 2-day period of accelerated leaching was comparable to that leached over the next 98 days, when the \sqrt{t} dependency was observed.

The leaching coefficient of Co-60 was found to be 10^3 to 10^5 lower than that of Cs-137.

I.2.3 Tritium

In their tritium studies, Matsuzuru et al. (1979) considered the initial period of accelerated leaching more rigorously than in previous studies, defining the initial rate by the equation

$$f_{i_0} = m_i t^{1/2} \quad (\text{I-9})$$

where the subscript *o* refers to the initial leach rate. Subsequent leaching was described by Equation I-5, above. Leaching coefficients (based on Equation I-5) in sea water and deionized water at 25°C for samples with seven days' curing ranged from 1.06×10^{-4} to 2.05×10^{-4} cm²/day. The fractional release equation is

$$f_{\text{H-3}} = 0.018 \sqrt{t} + 0.156 \quad (\text{I-10})$$

About 50% of the tritium in a sample 4.5 cm in diameter by 4.4 cm high would be released in one year.

I.3 SLAG LEACHING STUDIES

This section describes leaching studies done on pure slags rather than slag/cement composites.

Australian researchers at CSIRO incorporated the toxic elements As, Sb, Cd, Zn, and Cr into various types of slags by melting at 1300°C and subsequently leached the slags according to the EPA TCLP protocol (Jahanshahi et al. 1994). In the TCLP test, a sample of at least 100 g that has a minimum surface-to-mass ratio of 3.1 cm²/g or passes through a 9.5 mm sieve is treated with about 2,000 g of extractant for 18 ± 2 hours at 22 ± 3°C, using rotary agitation. The extractant has a pH of either 4.93 or 2.88, depending on the basicity of the sample (40 CFR 261, Appendix II, Method 1311). The pH is achieved by use of acetic acid which is buffered with sodium acetate for the higher pH level (55 FR 11798).

Slag samples were prepared by both slow cooling and quenching. Examination of the slag samples with an optical microscope showed that interconnected porosity was present in the slow-cooled and most of the quenched samples. Slow-cooled slag samples were crushed to either a "coarse" size (100% minus 10 mm)² or a "fine" size (100% minus 1 mm) for the leaching tests. In generalizing the results of the TCLP tests, the researchers observed that:

- As and Sb leached more readily than Cd, Cr, and Zn
- Fine particles generally leached more readily than coarse particles
- Slow-cooled samples showed similar behavior to quenched samples

In the present analysis, estimates of the fraction leached were based on the information presented by Jahanshahi et al. (1994) and on the following assumptions:

- Slag compositions from Table III (Jahanshahi et al. 1994)
- Sample size 100 g
- Extractant volume 2 L

The results are presented in Table I-1. For three of the slags (CaFe1, CaFeSi1, and FeSi1), the compositions are markedly dissimilar to those expected from EAF melting of carbon steel. The other three slags, while not identical to EAF slags, are useful for developing preliminary model parameters. Unfortunately, of the five elements studied, only chromium is expected to partition to the slag in any significant quantity. However, in the absence of element-specific leaching data, chromium can be considered a surrogate for the stable oxides expected in slags. If the fraction leached is proportional to \sqrt{t} , it can be expressed by the second line of Equation I-3, where the

² "100% minus 10 mm" means that 100% of the particles passed through a screen with a 10 mm mesh.

upper limit of m_i is about $7 \times 10^{-6}/\text{day}^{1/2}$ (based on chromium in the BF2 slags and an 18-hr leach test).

Table I-1. Fraction of Various Toxic Elements Leached from Slags Using EPA TCLP Protocol

Slag	Fraction Leached				
	As	Sb	Cd	Cr	Zn
CaFe1	3.48e-03	4.21e-05	3.10e-04	0.00e+00	3.00e-05
CaFeSi1	3.53e-03	2.68e-04	2.40e-04	0.00e+00	2.70e-05
CaFeSi2	5.09e-04	2.37e-04	6.80e-05	5.63e-07	2.30e-05
FeSi1	1.54e-04	1.10e-04	1.15e-04	4.82e-07	2.30E- 5
BF1	1.68e-04	1.03e-04	1.10e-04	0.00e+00	1.34e-04
BF2	9.80e-04	4.29e-04	1.20e-03	6.00e-06	1.23e-03

The U.S. Army Corps of Engineers has used slags extensively for fill and bank erosion protection in the upper Ohio River Valley drainage basin. Because of concerns about which chemical species might leach from the slags, the Corps of Engineers (1989) conducted a series of slag leaching experiments. Two types of experiments were conducted: one involving experimental weathering beds and the other involving laboratory elutions. In the weathering bed experiments, slag samples weighing 40 to 75 lb were placed in Nalgene containers and exposed to atmospheric weathering for 980 days. The leachate (i.e., rainwater and melted snow) passing through the slag beds was collected and analyzed at 11 different times to determine the quantities of various species leached from the slag. For the laboratory elution experiments, 1-kg samples of weathered slag were collected at the same times as the leachate samples and mixed with distilled water. These laboratory samples were then eluted for 109 to 198 hours with periodic stirring. The elutriate was analyzed for the same species as the leachate from the weathering tests. Elution tests were also conducted on unweathered samples.

Five types of slag were tested, including:

- Three air-cooled blast furnace slags Slags 1A, 1B, and 1C
- One mixed slag: ca. 50% BOF and 50% EAF Slag 2
- One slag mixture: BOF, EAF, blast furnace, foundry waste, and fire brick .. Slag 3

The discussion which follows focuses on the mixed BOF/EAF slag (Slag 2), since it is deemed to be most relevant to the expected leaching behavior of EAF slags. Slag 2 was in the form of gravel, with 99.9% being between 2.38 mm and 4.76 mm in diameter, and was two days old at the time of collection. The measurements are summarized in Table I-2.

Table I-2. Constituents Leached from Slag 2

Constituent	Concentration (µg/L)				
	Slag Elutriate (mean)		Weathering Bed Leachate		
	Unweathered	Weathered	initial	mean	final
P	17	12	<100	<10	<10
Ca	108,000	63,000	22,000	20,000	27,000
Mg	8,000	3,000	13,000	15,000	12,000
Na	2,000	1,000	44,000	8,000	1,000
K	2,000	2,000	14,000	4,000	<1,000
Ba	35	23	<10	68	<10
Be	12	1	<1	<1	<1
Cd	1	1	<1	2.3	<1
Cr	130	100	38	24	21
Cu	17	12	<5	10	8
Fe	18,286	4,038	<100	<100	<100
Mn	1,464	352	<10	<10	<10
Ni	114	40	39	9	<5
Pb	11	16	<2	2	<2
Zn	60	<50	<50	66	<50
Sb	<100	<100	<100	<100	<100
Al	7868	950	<50	99	70
pH	9.8	9.6	8.4	8.2	8.6

Source: U.S. Army Corps of Engineers 1989

It can be seen from Table I-2 that, in a number of instances, the elutriate from the weathered slag contains significantly higher contaminant levels than does the weathered slag leachate. The Corps of Engineers observed that:

Standard and modified slag elutriate procedures provide some insights into worst case scenarios that might occur during and immediately following placement of disturbed slags and can provide some general ideas about slag reactivity and leachate composition. These procedures, however, can very grossly exaggerate the potential of stabilized slags

to leach metals and otherwise have serious limitations in providing a basis for predicting long term leachate quality.

The leaching process was temperature-dependent, with higher concentrations of contaminants detected in samples taken during the summer months. However, over the 980-day duration of the tests, the concentrations appeared to be independent of time with the exception of K, Na, and Ni. The temporal concentration dependence of Ba, Ca, Cr, K, and Mn is shown in Figures I-1 and I-2. Temporal variations for other sampled elements were not presented by the Corps of Engineers (1989).

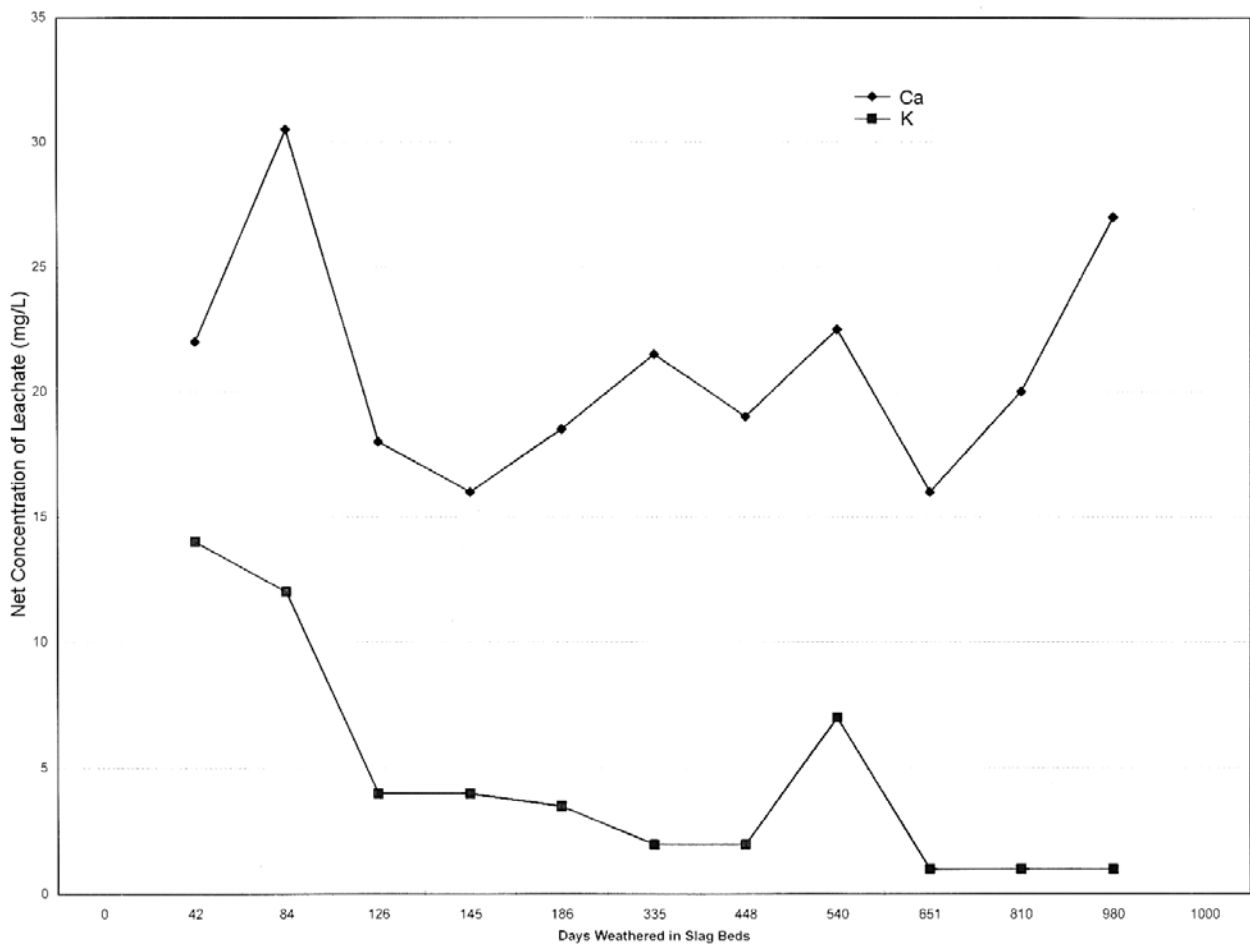


Figure I-1. Weathering of Slag 2: Ca and K

Emery (1980) also examined the leaching of toxic elements from slags. He noted that "[l]eachates from steel slags do not contain significant concentration of toxic constituents, but, in stagnant water conditions, deposits of calcite have been noted." He also observed that slags

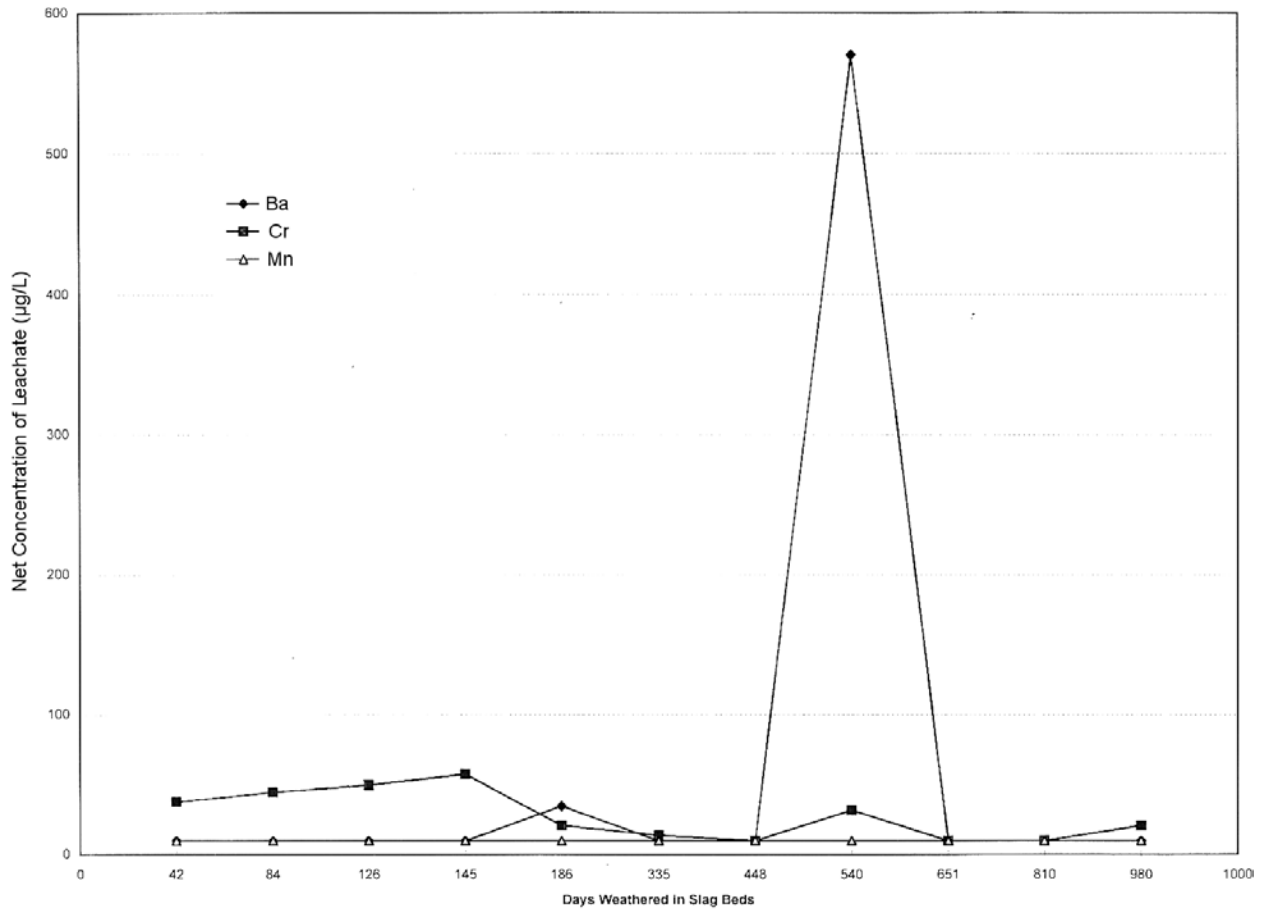


Figure I-2. Weathering of Slag 2: Ba, Cr, and Mn

could undergo a potential volume expansion of up to 10% due to hydration of free calcium and magnesium oxides.

Emery (1980) quoted solubility data based on an early EPA procedure of mixing two parts distilled water and one part slag and gently agitating for 72 hours. The following leachate concentrations were cited for an EAF slag:

- Cr 0.27 mg/L
- Cu <0.03 mg/L
- F 1.5 mg/L
- Mn <0.01 mg/L Pb 0.44 mg/L
- Zn <0.01 mg/L

pH 12.4

Emery (1980) also obtained data on filtrates from blast furnace slag sampled every 24 hours for five days. His results are presented in Table I-3. The slags were crushed to -13mm/+300 μm and vigorously agitated at 3 Hz (60 g slag per 3 L of water)³. Tests were run on freshly-produced slag and slag which had been stored in a small pile for two years. Unlike the EAF slag leachates described above, the pH of the blast furnace slag leachates varied from 7.6 to 7.9. With the exception of Fe and Mn, Emery's results agree within an order of magnitude with those of the Corps of Engineers (1989) (see unweathered slag elutriate in Table I-2).

According to West (1996), all slags which his company—International Mill Services, a major slag dealer—handles meet the TCLP test limits by at least an order of magnitude. Regulatory levels for the test are:

As 5 mg/L
Ba 100 mg/L
Cd 1 mg/L
Cr 5 mg/L
Pb 5 mg/L
Hg 0.2 mg/L
Se 1 mg/L
Ag 5 mg/L

Pillai and Pandey (1989) considered the use of slag for the removal of undesirable ions in water treatment plants. In support of this activity, they determined the extent to which minor elements were leached from the slag. Chemical analyses of minor elements in slag leachates were performed after holding 5-g slag samples in 50 mL distilled water overnight and sampling the filtrate. Cu, Co, Ni, Pb, Zn, Bi, Cd, Cr, Sb, Be, Mo, V, Li, and Rb were found in both blast furnace and open hearth furnace slags at ppm levels, but *none* found were in slag leachates. The water soluble fraction of open hearth and blast furnace slags was 0.83% and 0.80%, respectively. The water soluble components are mainly alkali and alkaline earth metals.

³ “- 13 mm” means that the particles passed through a screen with a 13-mm mesh, “+300 μm ” means that the particles were retained by a screen with a 300 μm mesh.

Table I-3. Blast Furnace Slag Solubility Data

Slag	Analysis of Filtrate (mg/L) ^a					
	Ca	Cu	Fe	Mg	Ni	Pb
F-1 ^b	13.5	0.02	0.02	0.60	<0.01	<0.01
F-3	7.2	<0.01	0.04	0.84	<0.01	0.02
F-5	6.6	<0.01	0.02	1.08	0.03	<0.01
A-1 ^c	15.9	0.05	0.03	0.60	<0.01	<0.01
A-3	7.5	<0.01	0.07	0.76	<0.01	<0.01
A-5	8.0	0.04	0.05	0.87	<0.01	<0.01

Source: Emery 1980

^a Cr, Mn, and Zn less than 0.01 mg/L in all cases

^b F: freshly produced slags; F-1: sample from first 24-hour period, F-3 from third 24-hour period, etc.

^c A: slag which had been stored in a small pile for two years; A-1: sample from first 24-hour period, etc.

In its report to Congress on mineral processing wastes, the U.S. EPA (1990) described analyses of BOF slags leached by the EP or SPLP tests⁴. These results are presented in Table I-4.

U.S. EPA (1990) made the following observations about exposure potential from slags:

In theory, constituents of potential concern in blast furnace and steel furnace slag could enter surface waters by migration of slag leachate through ground water that discharges to surface water or direct overland (storm-water) run-off of dissolved or suspended slag materials. The constituent concentrations and pH levels detected in blast furnace and steel furnace slag leachate confirm that the potential exists for slag contaminants to migrate into surface water in a leached form. The potential for overland release of slag particles to surface waters is limited considerably by the generally large size of the slag fragments. A small fraction of the slag particles that are 0.1 mm or less in size tend to be appreciably erodible,⁵ and only a very small fraction of the blast furnace and steel furnace slag solids are expected to be in this size range.

Based on environmental settings of the facilities and the presence of storm-water run-on/run-off controls at slag management units, the potential for contaminants from blast furnace and steel furnace slag to migrate into surface water at the eleven facilities appears to range from relatively low to relatively high. The potential for significant exposure to these contaminants, however, appears moderate at most.

⁴ This study considered only blast furnace and BOF slags; EAF slags were not addressed.

⁵ "As indicated by the soil erodibility factor of the USDA's Universal Soil Loss Equation."

Table I-4. Constituents of Concern in Steel Furnace Slag Leachates

Constituent	# Detections ÷ # Analyses ^a	Screening Criteria (µg/L)	#Analyses >Criteria ÷ # Analyses
Mn	3/6	500	3/6
F	1/1	21,000	1/1
		40,000	1/1
As	3/8	2 ^b	3/8
		500	1/8
Pb	4/14	210	3/14
		50	4/14
		320	3/14
Ag	2/14	12	2/14
Fe	3/6	3,000	1/6
Mo	2/8	100	1/8
Ba	7/14	18,000	1/14
		10,000	1/14

^a Based on EP leach test except As, which is based on SPLP test

^b Based on 1×10^{-5} lifetime cancer risk

de Villiers (1995) studied the leaching of arsenic-doped slags at Monash University in Clayton, Australia for his doctoral dissertation. While the primary focus was on arsenic leaching, he also developed some quantitative data on Fe, Mn, and Pb, and qualitative information on other elements. The studies involved four commercial slags from lead-zinc smelters and two synthetic slags. To obtain the desired arsenic levels, the commercial slags were remelted with appropriate arsenic additions at 1,300 to 1,400°C in an electric muffle furnace. Slags 1-4 were produced from commercial slags A-D with a nominal arsenic content of 0.66%, slags 5-8 were produced from commercial slags A-D with a nominal arsenic content of 2.66%, and slags 9 and 10 were prepared in the laboratory by blending and melting the requisite raw materials. Nominal compositions for the six base slags are listed in Table I-5.

Slags were leached for up to 40 weeks using either the EPA TCLP or SPLP⁶ leaching procedures. Temporal variation in the concentration of elements in the SPLP leach solutions from Slags 1 and 3 is presented in Table I-6.

Table I-5. Nominal Compositions (wt%) of Slag Mixtures Studied by de Villiers (1995)

Component	Slag A	Slag B	Slag C	Slag D	Slag 9	Slag 10
"FeO"	41.0	27.9	37.2	30.3	32.2	33.4
SiO ₂	19.5	21.7	25.8	23.9	22.4	23.2
CaO	19.0	15.1	19.1	17.9	28.7	29.8
ZnO	7.5	22.2	3.5	16.7		
Al ₂ O ₃	7.0	5.6	9.1	4.7	7.9	8.2
Pb	0.5	2.0	0.023	2.35		
S	2.0	2.1	1.4	0.93		
MnO		3.4	4.8		5.2	5.4
MgO	2.0	1.3	1.5	1.5		
Cu	0.4	0.18	0.68	0.16		

Table I-6.

Variation in the Concentration of Elements Leached from Slags 1 and 3 in SPLP Solutions

Observed Behavior	Slag 1	Slag 3
Increase with time	Ca, Mn, Sr, Ba, Ti	Ca, Mn, Sr, Ba, Ti
Decrease with time	Fe, Cu, Zn, As, Pb	Fe, Cu, Zn, As, Pb, Al
Similar concentration	Al, Sb	Sb
pH (18 hr)/pH (40 weeks)	7.9/8.6	8.7/7.5

Source: de Villiers 1995

In contrast to the Corps of Engineers (1990) data presented earlier, where the concentration of Ca, Ba, and Mn in the leachate was independent of time, de Villiers found these concentrations increased with time. A comparison of Corps of Engineers leaching data with those of de Villiers for a roughly comparable time period is shown in Table I-7.

⁶ The SPLP procedure uses a very dilute solution of sulfuric acid and nitric acid in water as the extractant to simulate acid rain. Since the solution is not buffered, the pH is subject to change during the leaching process.

The results on Fe and Pb leaching from the two studies indicate similar concentrations. The higher Mn levels observed by de Villiers may be related to the pH of the extractant. His studies indicated that when the pH of the extractant for Slag 6 (same source as Slag 2) was 10.2, the Mn concentration was 20 ppb.

Table I-7. Comparison of Corps of Engineers (1989) and de Villiers (1995) Leaching Data

Source	Slag	Leachate	pH	Fe (ppb)	Mn (ppb)	Pb (ppb)
de Villiers 1995	1	SPLP sol'n	7.1	≈0	73	≈0
de Villiers 1995	2	SPLP sol'n	6.9	≈0	214	≈0
de Villiers 1995	3	SPLP sol'n	7.4	≈ 0	150	≈0
de Villiers 1995	4	SPLP sol'n	6.9	≈ 0	16	≈0
USACE 89	2	Nat'l precip.	8.4	<100	<10	≈ <2

Note: de Villiers 1995: 4 weeks' leaching; Corps of Engineers 1989: 42 days' leaching

Dehmel et al. (1992) conducted radium leaching tests on finely ground slags in deionized water, 6N HCl, and 4N HNO₃. In each test, one gram of slag was mixed with 500 mL of solution and stirred for 24 hours. In these aggressive tests, all the radium was solubilized in the acid solutions and 8% of the radium was solubilized in the deionized water.

I.4 POSSIBLE MODELING APPROACH

Unfortunately, it is difficult to use the limited data described above for modeling the leaching of radionuclides from slag piles. Given this caveat, the following recommendations are made:

Constant source term approach. Use mean values for weathering bed leachates in Table I-2 for Ba, Ca, Cr, Fe, K, Mn, Se (use P data for Se), and Sr (use Ba data for Sr). Use Cr data for other strong oxide formers (e.g., Ac, Am, Ce, Cm, Eu, Nb, Np, Pa, Pm, Pu, Ra, Sm, Th, U, Y, and Zr).

Time-varying source term approach. Use Equation I-6 for Sr, Ca and Ba. Assume Cs leaches 10 times as fast as Sr. Use Equation I-7 for Co, Fe, Mn, and Ni. Use Equation I-2, with $m_i = 7 \times 10^{-6}/\text{day}^{1/2}$, for Cr and other oxide formers (e.g., Ac, Am, Ce, Cm, Eu, Nb, Np, Pa, Pm, Pu, Ra, Sm, Th, U, Y, and Zr).

Use of the data obtained from slag cement leaching studies is believed to be conservative since the radionuclides in the cement composites are not dissolved in the slag and therefore not expected to be as tightly bound in the solid matrix.

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APPENDIX I-1

RESULTS OF LEACH RATE STUDY

performed by

BROOKHAVEN NATIONAL LABORATORY

Brookhaven National Laboratory

MEMORANDUM

Date: February 3, 1997
To: Carey Johnston, EPA
From: M. Fuhrmann
Subject: Leach Rates of Slags

We have determined that releases of Sr generally can be described by diffusion. For the AS-3 column experiment, Incremental fraction releases vs Time follows the equation $IFR = 0.0075t^{-1/2}$ which indicates diffusion control. Examining the ALT data we find that diffusion coefficients for the AS and E series monolithic samples are:

AS-1 = $1.4 \times 10^{-11} \text{ cm}^2/\text{S}$	E-1 = 8.5×10^{-11}
AS-2 = 2.5×10^{-11}	E-2 = Linear release at $8.3 \times 10^{-4} / \text{day}$
AS-3 = 6.2×10^{-12}	E-3 = 5.5×10^{-11}

Assuming a cylinder of 1 cm height and 1 cm diameter, we have calculated the cumulative fractional release (CFR) for Sr at various times, with a diffusion coefficient of 2.5×10^{-11} .

Results are:

1 year	CFR = 0.178
10 years	CFR = 0.495
20 years	CFR = 0.642
100 years	CFR = 0.958

From the AS-3 column data we have determined that releases of Si are not diffusion controlled and speculate that releases are related to solubility in the alkaline leachate. This requires an induction period during which Si concentrations in the leachate increase. After about 20 days they become more linear but with a lot of scatter. The average rate is 3.85×10^{-5} fraction/day. Based on this linear rate about 1.4 % of the original Si would be released in one year.

Al in the column effluent and in the leachate from the monolithic samples appears to be diffusion controlled. Diffusion coefficients from the ALT experiments are:

$$\begin{array}{ll} \text{AS-1} = 3.4 \times 10^{-15} \text{ cm}^2/\text{S} & \text{E-1} = 3.7 \times 10^{-10} \\ \text{AS-2} = 2.8 \times 10^{-10} \text{ cm}^2/\text{S} & \text{E-2} = 3.1 \times 10^{-11} \\ \text{AS-3} = 8.5 \times 10^{-11} \text{ cm}^2/\text{S} & \text{E-3} = 7.2 \times 10^{-13} \end{array}$$

Using the diffusion coefficient from ALT sample AS-3, we estimate releases of a 1 cm × 1 cm cylinder as:

$$\begin{array}{ll} 1 \text{ year} & \text{CFL} = 0.314 \\ 10 \text{ years} & \text{CFL} = 0.762 \\ 55 \text{ years} & \text{CFL} = 0.999 \end{array}$$