

## Vertical column hydroclassification of metal-contaminated soils

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### Abstract

The purpose of this work was to reduce soil volumes requiring aggressive treatment. A second purpose was to determine differences in separation due to distinct forms of the metal contamination and soil texture. The objectives were to apply hydroclassification and find mass and metal-contaminant distribution of four soils contaminated with heavy metals from firing ranges, a small arms incinerator, and an electroplating operation. The soils were slurried in water, sieved, and exposed to upward flowing water to separate the soil particles into four nominal size ranges. The popping furnace soil exhibited substantial lead among all particle size fractions. The firing range soils exhibited bimodal distributions. The electroplating soil exhibited a strong concentration of metals toward the  $< 63 \mu\text{m}$  fraction. Attrition scrubbing moderately improved the enrichment of metals in several fractions. Extraction revealed the lead and chromium in the electroplating soil to be relatively immobile. These results suggest metal distributions are influenced by the different mechanisms of introduction into the soil. They also help to predict performance of processing options such as sieving hydroclassification and attrition scrubbing. © 1999 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

### 1.1. Problem statement

Numerous industrial, construction, and military practices have contaminated soil, and water with heavy metals and organic compounds. Examples include use of lead-based paints, firing ranges, electroplating, and nuclear materials manufacture [1]. Heavy metals frequently disrupt metabolic processes and produce toxic effects in the lungs, kidneys, and central nervous system. Organometallic forms such as dimethyl mercury and tributyl tin are ‘highly’ toxic. Heavy metal contamination threatens both industrial sites and heavily populated areas. Furthermore, the fact that metals do not degrade has historically limited the options for remediation to solidification/stabilization, ‘dig and haul,’ and to a lesser extent, soil flushing. The 1993 EPA Status Report on Innovative Treatment Technologies [2] stated that of 301 innovative treatment applications (as of June 1993) only 20 involved metals. Remediation costs on the order US\$500 per cubic meter, and more for radioactive materials, motivate research to minimize volumes requiring costly treatment and to improve the efficiency of those treatments.

The physical separation technology in this study used minerals processing technologies to deplete soil fractions of the contaminant. The depleted soil should require less aggressive follow-up treatment, improving cost effectiveness for additional treatment such as soil extraction. Research is needed to assess separations technologies and the impact of contaminant and soil properties on performance in partitioning contaminants among resulting soil fractions. This work focused on the separations achievable by hydraulic classification, ‘hydroclassification’ based on the relative size and density of soil and contaminant particles.

### 1.2. Objective and scope

The objectives of this project were: (1) perform vertical column hydroclassification of four metal-contaminated soils; (2) for resulting particle-size fractions, determine mass distribution, metal concentration, and metal distribution; (3) determine the effects of attrition scrubbing on these distributions; and (4) evaluate metal mobility from the leaching characteristics of the separated fractions.

## 2. Background

### 2.1. Physical separation

Each form of metal contamination exhibits different physical properties: particle-size, density, and surface charge depending upon the metallic particle, soil characteristics, and contaminant. As a result, the contamination will not occur uniformly in the soil, but distributed according to these physical properties. The major parameters affecting the association of a heavy metal with soil and sediment include grain size, surface area,

geochemical substrate (iron oxide, clay mineral, etc.), and metal affinity. In general, most adsorbed metals are associated with small soil particles [3]. In contrast, metal fragments may sometimes preferentially concentrate in larger particle size fractions. Physical separation exploits the distribution of metals in soil/sediment by physically separating a select, contaminant-rich fraction. Ideally, the ‘cleaned’ fraction will require no further treatment, and the ‘concentrated’ fraction can be more economically processed.

## *2.2. Overview of physical separation treatment trains*

The general approach in physical separations remediation is to use processes commonly applied in the minerals processing industry. The processes exploit differences in particle-size, density, surface, and other properties to effect a separation. A typical process chain might begin with a scrubbing trammel [4]. The soil flows into a rotating drum fitted with interior baffles and water spray. The rolling motion and the water condition, scrub, and break up clumps in the soil. The soil then moves to the outlet where smaller material falls through a cylindrical screen mounted around the mouth of the drum. The oversized material rides to the edges of the screen and falls into a chute.

First-stage products (oversized and tailings) go on to secondary separation. Tailings (generally smaller or less dense material) might go to a ‘cleaning’ or ‘concentrating’ stage to concentrate contaminants into an even smaller volume. This approach can be taken, if the contamination is preferentially associated with a distinct soil density or particle size fraction. A spiral concentrator may be appropriate for this stage. As a soil/water slurry spirals downward, the heavier soil fractions accumulate toward the inner radius and the less dense fraction moves toward the outer radius. The concentrate stream passes through the take-out ports.

By the end of this stage, the soil has passed through separations based first on size and then on density. Further separations based on density difference may employ centrifuges or shaking tables. Differences in particle surface hydrophobicity may be exploited with a flotation cell.

## *2.3. Hydroclassification*

Because many physical separation processes trains use gravity-based unit operations such as hydrocyclones, it has become important to predict performance. The method here used upward flowing water in a small column to elute a series of contaminated soil fractions, again to produce depletion and enrichment of metals among the fractions. We based the approach on work by the US EPA at its National Air and Radiation Environmental Laboratory (NAREL), Montgomery, AL. With its contractor, Sandy Cohen and Associates, they developed small elutriation column methods for separating small radioactive particles from the soil matrix [5]. Results provide a ‘best case’ separation for gravity-based methods, for example: shaking table, hydrocyclone, mineral jig, spiral concentrator, or hydroclassifier.

### 3. Experimental design

#### 3.1. Concept

We chose a simple vertical column separation (hydraulic elution) tool to assess separation (enrichment and depletion) of soil fractions. The work assessed the distribution of contamination resulting from differences in soil type and contaminant source, (projectiles, incinerator residue, and plating solutions), as well as the effects of attrition scrubbing. Vertical column hydroclassification depends upon application of Stokes' Law. Up-flowing water separates the soil particles as a function of size and density. If the contaminant has a size or density distribution different from that of the bulk soil, the recovered soil fractions may be enriched or depleted. If metal particles are present, they may be separated due to their relatively high specific gravity, 11.35 for lead, vs. 2.65 for quartz. Thus soil particles will be carried up and out of the column leaving the metal particles of comparable size.

We used three upward terminal velocities to fractionate the soil into nominal particle-size fractions of < 63, 63–125, 125–250, and > 250  $\mu\text{m}$  (based on quartz particles of 2.65 specific gravity). We determined the mass (weight) distribution into the particle-size fractions, lead concentrations, and lead distribution. For two soils, we compared these results with those for wet sieving separation into (nominally) the same particle-size fractions. For two other soils, we investigated the effects of attrition scrubbing on subsequent hydroclassification. Finally, we performed leach tests on all four soils to assess the mobility of metals in the separated particle size fractions.

#### 3.2. Principle of operation

Stokes' Law indicates that at low Reynolds number, particles of uniform shape and density settle through water at a rate proportional to their density and the square of their diameter. Stokes' Law for spherical particles falling slowly through water appears in the following equations [6]:

$$u_t = g D_p^2 \rho (\rho_p - \rho) / 18 \mu. \quad (1)$$

A more general relationship allows for higher velocities beyond the Stoke's Law range (Reynolds Number > 1.0):

$$u_t = [4 g (\rho_p - \rho) D_p / 3 C_D \rho]^{1/2} \quad (2)$$

where,  $u_t$  = terminal or free settling velocity, m/s;  $g$  = acceleration due to gravity,  $\text{m/s}^2$ ;  $D_p$  = particle diameter, m;  $\rho_p$  = particle density,  $\text{kg/m}^3$ ;  $\rho$  = density of the surrounding fluid,  $\text{kg/m}^3$ ;  $\mu$  = viscosity,  $\text{kg/s} \cdot \text{m}$ ;  $C_D$  = the drag coefficient, dimensionless.

The velocity term is eliminated from the Reynolds number by substituting  $u_t$  from Eq. (1). For Stokes' Law range, the equation appears in the following form:

$$N_{\text{Re}, p} = D_p u_t \rho / \mu = D_p^3 g (\rho_p - \rho) \rho / 18 \mu^2 \quad (3)$$

where,  $N_{\text{Re}, p}$  = Reynolds Number.

By trial and error, a drag coefficient was found, then terminal velocity, and finally a comparison of old and new Reynold's numbers. This procedure allowed calculation of the needed terminal velocities and, thus, flowrates up the column.

An upward flow of water exceeding the terminal velocity of select particles will sweep them out the top of a column to a collection tank. Smaller or less dense particles will be preferentially removed. Larger, more dense particles will remain in the column until the flowrate is adjusted upward. Contaminant particles having a density different from the host soil will distribute differently from the soil.

## 4. Experimental methods and procedures

### 4.1. Apparatus and materials

The hydroclassifier shown in Fig. 1 consisted of: a vertically-mounted tube of clear PVC (inside diameter, 5 cm; height, 61 cm) and a slotted water distributor at the bottom covered with 16 cm of 3-mm diameter glass beads to distribute flow. At the top, all flow was directed into a 1.27 cm (1/2-in.) pipe fitting, and down through plastic tubing into 20-l buckets for collection of fractions. A vertical tube extended 15 cm above overflow height of the top outlet. This allowed us to introduce the slurry while flow was in progress using a funnel with attached tube extending into the column to just above the glass beads. Rotameters were calibrated to give flows of 0.68, 2.1, and 5.3 l/min. For the wet sieving, we used US Standard sieves (ASTM, E-11) with mesh sizes of 10, 30, 50, 100, and 200 corresponding to openings of 2000, 600, 250, 125, and 63  $\mu\text{m}$ , respectively. During sieving, the samples were sprayed with deionized water through a nozzle. Attrition scrubbing was performed with a Wemco<sup>®</sup> laboratory attrition scrubber. The extractions simulating the TCLP (Toxic Characteristics Leaching Procedure) were performed with an Eberbach linear shaker and a Dupont-Sorvall RT 6000 centrifuge with 50 ml plastic centrifuge tubes.

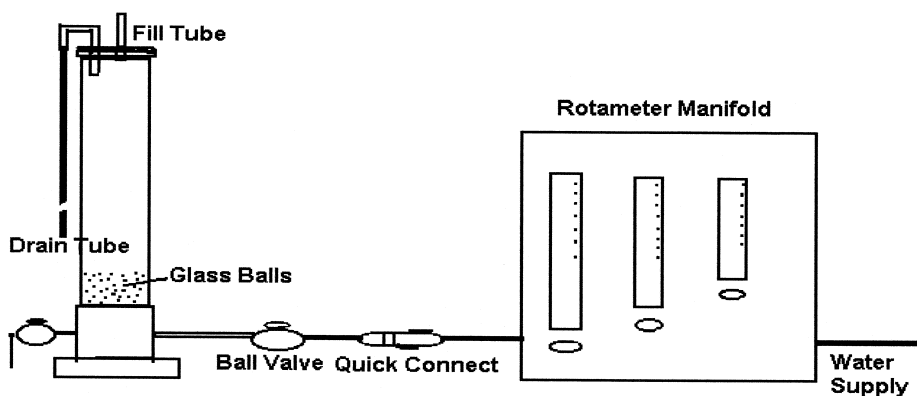


Fig. 1. Hydroclassification system with rotameters and 5 cm i.d. column of clear PVC.

#### 4.2. Sample preparation

The four soils used were as follows: (a) a firing range soil, No. 1, (sandy loam by USDA soil texture classification); (b) a soil from near a small arms incinerator (Popping Furnace) (sandy soil); (c) a soil from near an electroplating operation (sandy soil); and (4) a second soil from a firing range, No. 2, (loamy sand). For each separation, approximately 200–250 g of well homogenized soil was mixed in a weight ratio 4:1, water:soil in a 4-l plastic container. This was agitated for 1 h on a linear shaker at 200 oscillations per minute. After this vigorous wash, we wet sieved the slurry through 10 and 30-mesh sieves. Material passing the 30-mesh sieve was hydroclassified.

#### 4.3. Procedure for hydroclassification

Glass beads were added to the column and water flow begun at a rate (0.68 l/min) to elute quartz particles nominally  $< 63 \mu\text{m}$  ( $< 200$  mesh) in size. The slurry feed funnel, with 3/8 in. diameter feed tube attached, was lowered into the standpipe on top of the column. The  $< 600 \mu\text{m}$  ( $< 30$  mesh) soil slurry was slowly poured into the feed funnel over about 10 min. As soon as feeding began, the plastic discharge tube was diverted from the sink to a 20-l receiving bucket to capture the eluted fraction. After collecting about 12 l, the water in the column had clarified. The water flowrate was increased to 2.1 l/min to elute quartz particles nominally  $< 125 \mu\text{m}$ . The discharge tube was diverted to another bucket and this fraction collected in a total volume of about 20 l. Finally, the water flowrate was increased to 5.3 l/min to elute quartz particles nominally  $< 250 \mu\text{m}$  in size in about 40 l of water. The soil fraction remaining in the column was recovered by disconnecting the column and pouring its contents through a 600- $\mu\text{m}$  opening screen to capture the glass balls and collect the nominally  $> 250 \mu\text{m}$  particles. The  $< 63 \mu\text{m}$  fraction was slurried in a bucket with an electric stirrer and impeller, and a 250 ml sample was collected. This sample was weighed and dried to determine the solids content of the  $< 63 \mu\text{m}$  fraction and to provide a sample for metals analysis. The other fractions were readily decanted to remove water. All samples were dried at 60°C for 16 to 24 h and reweighed to find mass yields. Material balances and metals distributions were calculated on this dry basis.

#### 4.4. Procedure for wet sieving

We added 100 to 150 g soil and 400–600 g tap water to a 4-l plastic container. This was mixed on a linear shaker for 1 h at 200 oscillations per minute. We sequentially wet sieved the resulting slurry through the screens with openings of 2000, 600, 250, 125, and 63  $\mu\text{m}$  into 20-l buckets. At each step, the sieve was agitated up and down in the water in the bucket and then rinsed with deionized water from a spray nozzle. The fractions were recovered and dried as for the hydroclassified samples.

#### 4.5. Procedure for attrition scrubbing

A bulk soil sample consisting of 1250 g dry solids was added to the attrition cell. Water was added to produce an 80% solids slurry. The sample was attrited at 1200 rpm

for 15 min. This material was slurried and sieved in the same manner as the other samples.

#### 4.6. Procedure for extraction

We extracted a sample of each size fraction produced by hydroclassification and wet sieving as well as the starting soil samples. We used a procedure analogous to the standard Toxic Characteristics Leaching Procedure (TCLP), except that we used much smaller sample sizes (1.5–2 g). We first mixed the soil with deionized water in the weight ratio of 1:19.3, respectively and measured pH. Finding that all fractions tested above pH 5, we used the appropriate extraction solution of 5.7 g glacial acetic acid per liter of solution. The soil and solution were mixed in the ratio of 1 g/20 ml, placed in a 50 ml plastic centrifuge container, and mixed for 18 h on a linear shaker at 200 oscillations per minute. The samples were then centrifuged for 20 min at 3000 rpm with a radius of 18.67 cm, producing an rcf of 1876.

#### 4.7. Analysis

All resulting metals-contaminated soil fractions were microwave digested and analyzed by atomic absorption spectroscopy in accordance with US EPA procedure 3051. The extracts were analyzed by the same method, excluding digestion.

### 5. Results

Results presented in the following sections, rely on Figs. 2–10 and provide observations of: (1) the distribution of weight and metal into particle-size fractions; (2) metal concentrations in the fractions; (3) the mobility (extraction) of metal; and (4) effects of attrition scrubbing and wet sieving on these distributions.

#### 5.1. Weight percent distribution into particle-size fractions

Hydroclassification produced material balances generally within 2 to 3% of closure. Variations of fraction yields were also within 2 to 3%, when coarser 600–2000  $\mu\text{m}$  material was excluded. The Furnace and Plating soils were sandy, as shown in Fig. 2, with less than 15 and 18%, respectively in the silt/clay range ( $< 63 \mu\text{m}$ ). In contrast, the two Firing range soils yielded 45 to 48%  $< 63 \mu\text{m}$  material (Fig. 2). Attrition scrubbing of the Plating and Firing Range 2 soils decreased the weight distribution to the 600–2000  $\mu\text{m}$  fraction by approximately 4%. Attrition scrubbing increased the weight distribution to the  $< 63 \mu\text{m}$  fraction for the Plating soil by 2%, and for the Firing Range 2 soil by 4%. Hydroclassification and wet sieving of the Furnace and Firing Range 1 soils produced distributions that generally tracked each other. For the Furnace soil, however, hydroclassification (relative to wet sieving) increased the 600–2000  $\mu\text{m}$  fraction from 24 to 35 wt.% and decreased the 250–600  $\mu\text{m}$  fraction from 39 to 20 wt.%. This indicated that dense material (perhaps rich in lead) screened into the 250–600  $\mu\text{m}$  fraction was retained with the larger material during hydroclassification.

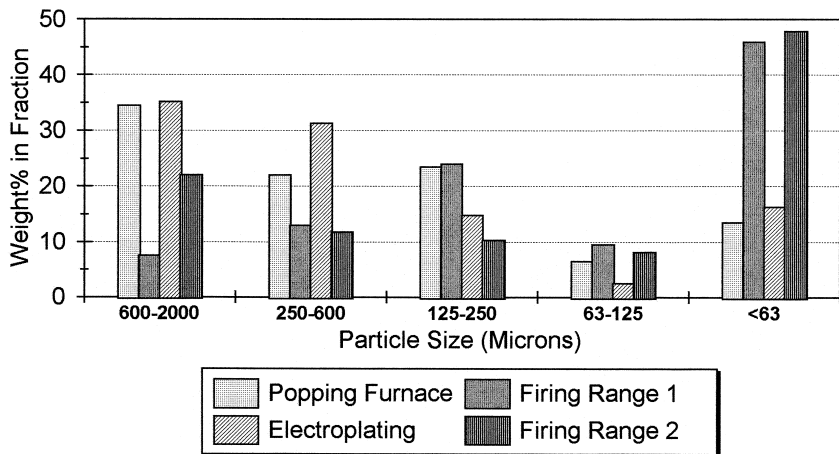


Fig. 2. Distribution of < 2000 μm soil into particle size fractions from hydroclassification.

### 5.2. Concentrations of predominant metals in the particle-size fractions

The Furnace and Firing Range 1 and 2 soils had lead as the predominant metal. The Furnace soil had a concentration of over 100 000 mg/kg in the 600–2000 μm fraction (Fig. 3) and 40 000 mg/kg or less in the other size fractions. Relative to wet sieving, hydroclassification enriched the lead content of the 250–600 μm fraction, while depleting lead in the < 250 μm fraction (Fig. 4). The Firing Range 1 soil had a more dramatic metal concentration profile, with over 550 000 mg/kg in the 600–2000 μm

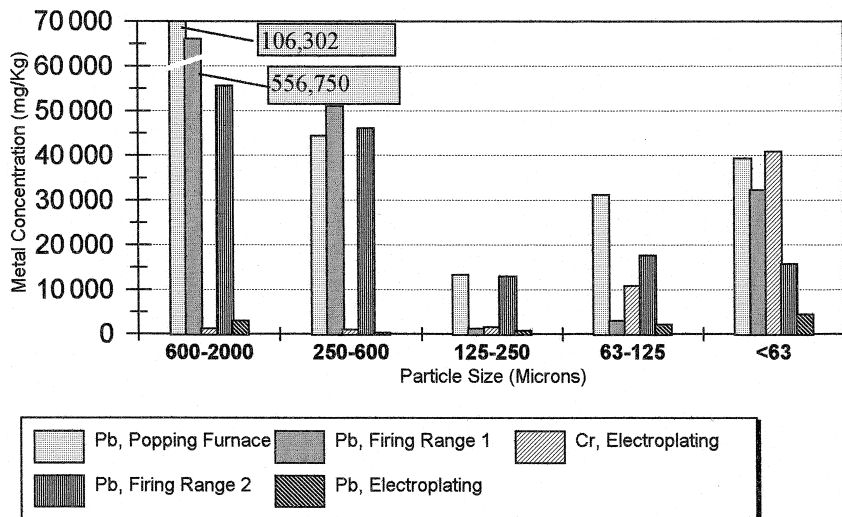


Fig. 3. Metal concentrations in particle size fractions from hydroclassification.



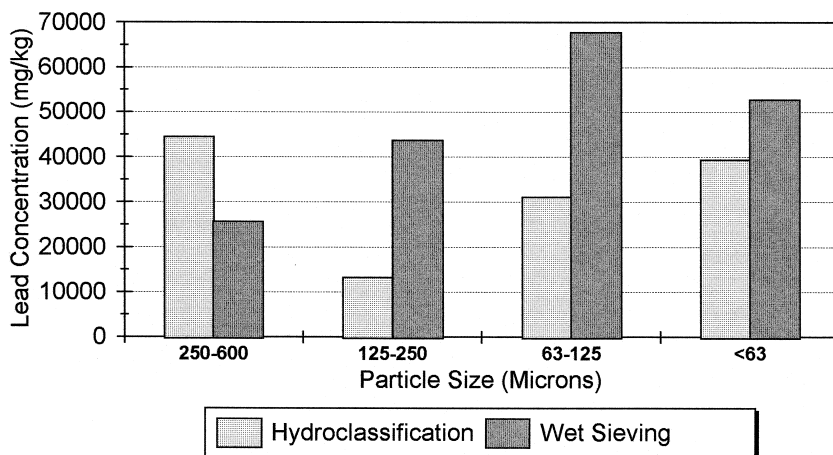


Fig. 4. Comparison of concentration of lead in particle size fractions from hydroclassification and wet sieving of Furnace soil.

fraction (Fig. 3). Lead fragments were clearly visible. Concentrations in the other fractions included 50 000 mg/kg in the 250–600 and over 30 000 mg/kg in the < 63  $\mu\text{m}$  fraction. Both hydroclassified and wet sieved Firing Range 1 soil showed similar bimodal patterns, with the highest concentrations at the size range extremes (Fig. 5). The Plating soil had chromium as the predominant metal (Fig. 3) with concentrations from about 1000 mg/kg to a high of 41 000 in the < 63  $\mu\text{m}$  fraction. There were also significant concentrations of lead (up to 4400 mg/kg) and cadmium (62.5 mg/kg to 9272 mg/kg). This high concentration of chromium and cadmium in the < 125  $\mu\text{m}$  (and more so in the < 63  $\mu\text{m}$ ) fraction is significant, because the < 63  $\mu\text{m}$  fraction

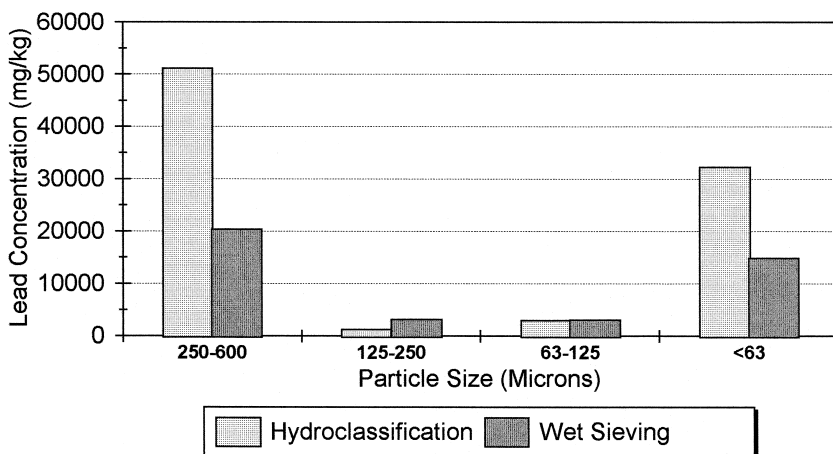


Fig. 5. Comparison of concentration of lead in particle size fractions from hydroclassification and wet sieving of Firing Range 1 soil.

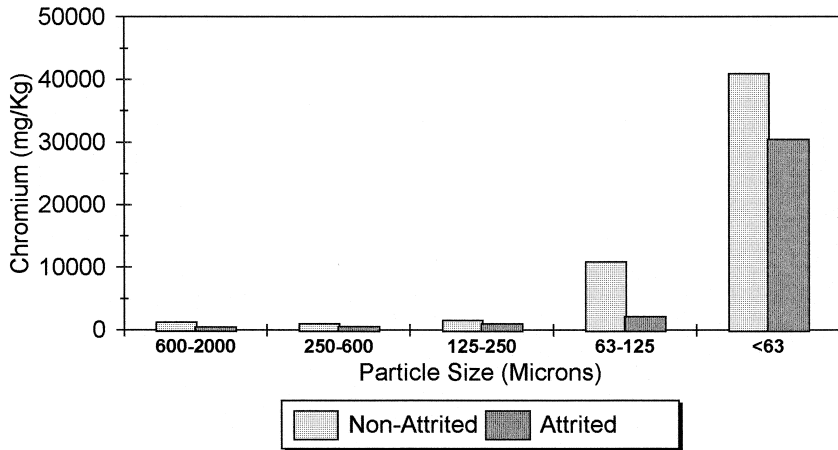


Fig. 6. Comparison of concentration of chromium in particle size fractions from hydroclassification of Plating soil, with and without attrition scrubbing pretreatment.

comprises less than 20 wt.% of the total soil weight. Attrition decreased the chromium concentration in all fractions, including a reduction from about 41 000 to 30 000 mg/kg for the < 63  $\mu\text{m}$  fraction (Fig. 6). For the Firing Range 2 soil, lead concentrations ranged from 12 969 mg/kg in the 125–250  $\mu\text{m}$  fraction to a high of 55 651 mg/kg in the 600–2000  $\mu\text{m}$  fraction (Fig. 3). The attrited 600–2000  $\mu\text{m}$  sample exhibited a lead concentration of approximately 27 000 mg/kg vs. 55 000 mg/kg for the unattrited sample. This may be attributed to heterogeneity, since analysis of other fractions showed no significant shift in lead to the smaller size-fractions.

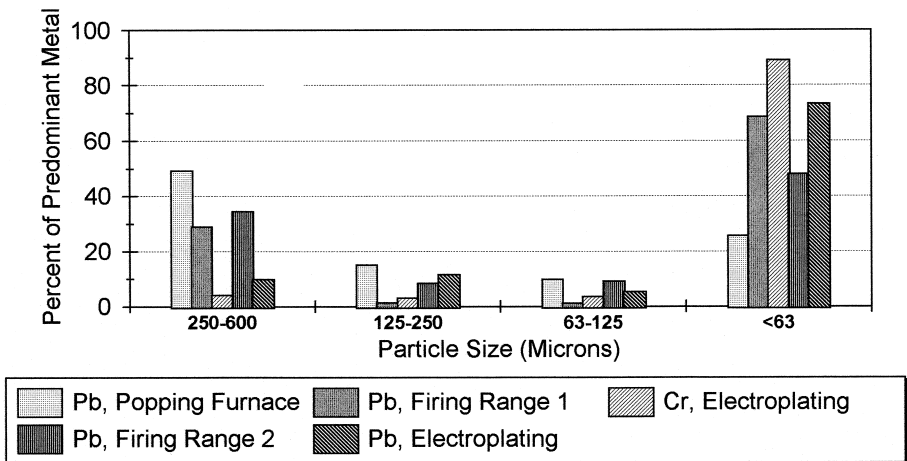


Fig. 7. Percent of total of each metal distributed into particle size fractions by hydroclassification.

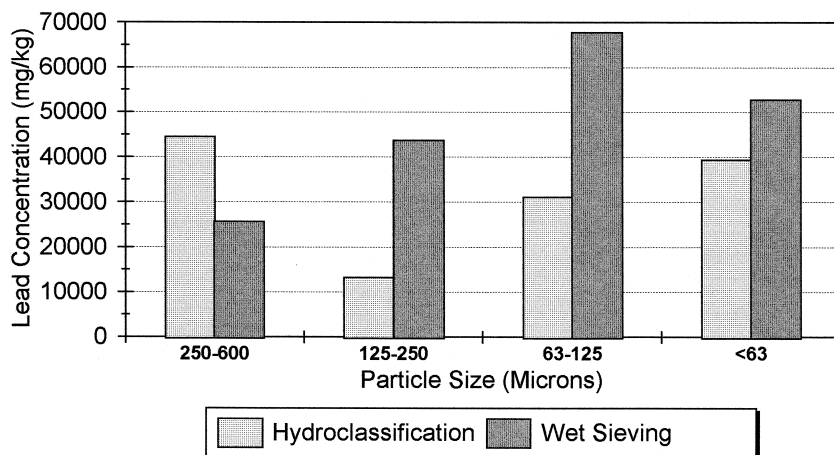


Fig. 8. Comparison of distribution of lead in particle size fractions from hydroclassification and wet sieving of Furnace soil.

### 5.3. Distribution of predominant metals in the particle-size fractions

The metal distribution data are presented in Fig. 7 for the  $< 600 \mu\text{m}$  fraction. The discussion excludes the  $> 600 \mu\text{m}$  material for three reasons. The  $> 600 \mu\text{m}$  material was prescreened out before hydroclassification. Metal concentrations were extremely high ( $> 10\%$ ) for three of the soils, and from replicate trials, were also highly variable. Examining the  $< 600 \mu\text{m}$  material should better reflect the distribution from hydroclassification, and reduce variability.

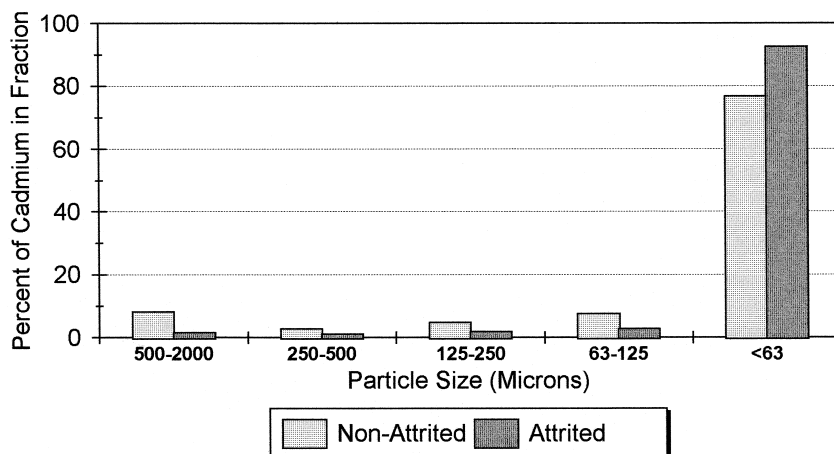


Fig. 9. Comparison of distribution of chromium in particle size fractions from hydroclassification of Plating soil, with and without attrition scrubbing pretreatment.

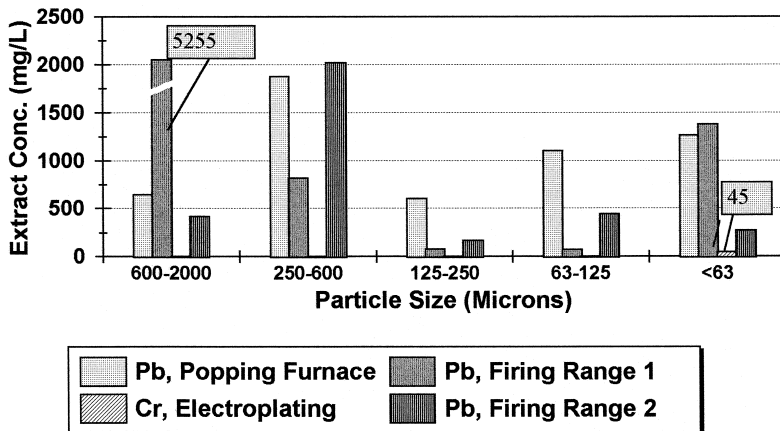


Fig. 10. Concentration of metal in extracts of particle size fractions from hydroclassification.

For the Furnace soil, lead comprised about 90 wt.% of the heavy metals analyzed for (Cd, Cr, Cu, Pb, and Zn) in the as-received sample. There was a significant distribution of lead to all fractions of  $< 600 \mu\text{m}$  soil (Fig. 7), with the 250–600  $\mu\text{m}$  fraction containing approximately 50 wt.% of the total heavy metal in the  $< 600 \mu\text{m}$  fraction. Relative to wet sieving, hydroclassification of the Furnace soil produced a shift of lead to the 250–600  $\mu\text{m}$  fraction (Fig. 8).

For the Firing Range 1 soil, lead comprised about 93% of heavy metal contaminants in the  $< 2000 \mu\text{m}$  sample. The 600–2000  $\mu\text{m}$  fraction screened from the firing range soil had about three fourths of the lead mass in it. This fraction was rich in clearly visible lead fragments which could be readily separated by an alternate unit operation. The lead distribution for the  $< 600 \mu\text{m}$  material exhibited a bimodal distribution (Fig. 7) with approximately 30 wt.% in the 250–600  $\mu\text{m}$ , and 65 wt.% in the  $< 63 \mu\text{m}$  fractions, respectively. Relative to wet sieving, hydroclassification produced no significant differences in lead distribution.

For the Electroplating soil, chromium was the predominant heavy metal. Hydroclassification produced a consistent distribution of metals to the  $< 63 \mu\text{m}$  fraction (Fig. 7). Approximately 85 wt.% of the chromium and 66 wt.% of the lead were distributed to the  $< 63 \mu\text{m}$  fraction. Attrition produced only modest shifts in distribution (about 8 to 13%) for the chromium, and for the cadmium, as shown in Fig. 9.

For the Firing Range 2 soil, lead was the predominant heavy metal. After hydroclassification, the soil fractions exhibited a bimodal distribution of lead similar to that of the Firing Range 1 soil, with approximately 34 wt.% in the 250–600  $\mu\text{m}$  and 46 wt.% in the  $< 63 \mu\text{m}$  fractions, respectively (Fig. 7).

#### 5.4. Comparison of weight and lead distribution

For each of the four soils investigated, Table 1a and b give the weight and heavy metal distributions into the  $< 600 \mu\text{m}$  fractions resulting from hydroclassification and

Table 1

a. Metal distribution for Popping Furnace and Firing Range 1 soils—hydroclassified and wet sieved

Particle size mesh	Particle size ( $\mu\text{m}$ )	Hydroclassification		Wet sieving	
		Percent of mass	Percent of lead	Percent of mass	Percent of lead
<i>Popping Furnace (lead)</i>					
30–50	250–600	34.4	49.3	51.3	35.3
50–100	125–250	35.3	15.1	27.0	31.6
100–200	63–125	9.9	9.9	5.9	10.8
< 200	< 63	20.3	25.8	15.8	22.4
<i>Firing Range 1 (lead)</i>					
30–50	250–600	13.6	28.9	19.3	33.3
50–100	125–250	25.5	1.3	28.9	7.7
100–200	63–125	9.7	1.2	6.4	1.7
< 200	< 63	51.2	68.7	45.5	57.2

b. Metal distribution for Electroplating and Firing Range 2 soils—attrited and non-attrited

Particle size mesh	Particle size ( $\mu\text{m}$ )	Non-attrited		Attrited	
		Percent of mass	Percent of lead	Percent of mass	Percent of lead
<i>Electroplating (lead)</i>					
30–50	250–600	48.3	9.9	47.1	7.1
50–100	125–250	22.8	11.5	22.2	3.9
100–200	63–125	3.8	5.3	4.1	1.5
< 200	< 63	25.1	73.3	26.7	87.5
<i>Firing Range 2 (lead)</i>					
30–50	250–600	15.1	34.5	13.8	31.4
50–100	125–250	13.2	8.5	13.3	5.9
100–200	63–125	10.4	9.1	9.7	8.4
< 200	< 63	61.4	48.0	63.1	54.3
<i>Electroplating (chromium)</i>					
30–50	250–600	48.3	4.2	47.1	3.1
50–100	125–250	22.8	3.1	22.2	2.6
100–200	63–125	3.8	3.6	4.1	1.0
< 200	< 63	25.1	89.1	26.7	93.2

wet sieving, with and without attrition scrubbing. As noted above, Figs. 2 and 7 show the weight and heavy metal distributions from hydroclassification. For the Furnace soil, hydroclassification marginally enriched the 250–600  $\mu\text{m}$  fraction and depleted the 125–250  $\mu\text{m}$  fractions, respectively (Table 1a). For the Firing Range 1 soil, hydroclassification and wet sieving both enriched the larger and smaller size fractions, 250–600  $\mu\text{m}$  and < 63  $\mu\text{m}$ , respectively (Table 1a). More importantly, the mid-size range

fractions, 63–250  $\mu\text{m}$  fractions, were significantly depleted of lead. For example, hydroclassification yielded a percent of mass to percent of lead ratio of 25.5% to 1.3% for the 125–250  $\mu\text{m}$  fraction. Thus the mid-size fractions contained about 35 wt.% of the mass, but only about 2.5 wt.% of the lead, with hydroclassification producing the sharper separation of mass and lead. For the Electroplating soil, hydroclassification depleted the larger (250–600  $\mu\text{m}$ ) fraction and enriched the smaller ( $< 63 \mu\text{m}$ ) fraction (Table 1b). Attrition scrubbing improved the sharpness of the hydroclassification separation for lead, giving a percent of mass to percent of lead ratio in the  $< 63 \mu\text{m}$  fraction of 26.7 wt.% to 87.5 wt.% vs. 25.1 wt.% to 73.3 wt.% without attrition. Attrition had little effect on chromium enrichment. For chromium, the larger 250–600  $\mu\text{m}$  fraction was strongly depleted with a percent of mass to percent of chromium ratio of 48.3 wt.% to 4.2 wt.%. The smallest ( $< 63 \mu\text{m}$ ) fraction was enriched with a mass to metal ratio of 25.1 wt.% to 89.1 wt.%. For the Firing Range 2 soil, hydroclassification enriched the 250–600 and  $< 63 \mu\text{m}$  fractions. Attrition scrubbing had a very small enriching effect on the  $< 63$  material (Table 1b).

### 5.5. Extraction of metals by small-scale TCLP method

The Toxic Characteristics Leaching Procedure (TCLP) has a limit of 5 mg/l for lead and for chromium. For the Furnace soil, extract concentrations ranged from 601 to 1874 mg/l (Fig. 10). Extraction of fractions from wet sieving produced higher lead concentrations than did hydroclassification in all but the 250–600  $\mu\text{m}$  fraction. Hydroclassification resulted in 1102 mg/kg lead in the 63–125  $\mu\text{m}$  fraction, while wet sieving yielded 3029 mg/kg. For the Firing Range 1 soil, the extract concentrations ranged from 73 to 5255 mg/l. Significantly, the hydroclassified Firing Range 1 soil (63–250  $\mu\text{m}$  fractions) had extract concentrations in the mid 70's mg/l, an order of magnitude less than for the other fractions. This was consistent with the significant depletion of lead in these fractions. In comparison, the Electroplating soil exhibited extract concentrations of  $< 1.0$  mg/l for the  $< 250 \mu\text{m}$  material, and 20 mg/l for the  $> 250 \mu\text{m}$  material. These results indicate that the lead, particularly the 4000 to 4400 mg/kg in the  $< 63 \mu\text{m}$  fractions, is relatively immobile. Attrition of the Electroplating soil reduced the extractable lead for the 250–500  $\mu\text{m}$  fraction, but increased it for the 63–250  $\mu\text{m}$  material. For the Firing Range 2 soil, extract concentrations of lead ranged from approximately 300 to 2000 mg/l (Fig. 10). Attrition reduced the extractable lead for the 250–600  $\mu\text{m}$  fraction from approximately 2000 to 900 mg/l. Little effect was seen for the other size range material.

## 6. Summary of findings

The Furnace and Plating soils were sandy with only 15–18 wt.% in the  $< 63 \mu\text{m}$  fraction, while the Firing Range soils were finer, with 45–48 wt.% in the  $< 63 \mu\text{m}$  (silt/clay) fraction. Material balances were within 2–3 wt.% with comparable precision for the fractions, when  $> 600 \mu\text{m}$  material was excluded. Attrition scrubbing produced only small changes in mass distribution, 2–4 wt.%, among the fractions. Hydroclassification and wet sieving generally produced mass distributions that tracked each other

closely. However, for the Furnace soil, hydroclassification shifted more material (relative to wet sieving) from the 250–600  $\mu\text{m}$  to the 600–2000  $\mu\text{m}$  fraction. This indicates that dense material, potentially rich in lead, which would pass the 600  $\mu\text{m}$  screen, was retained with larger material during hydroclassification.

Lead dominated heavy metal contamination in both Firing range soils and the Furnace soil. Lead comprised about 93 wt.% of total heavy metal in the Firing Range 1 sample and about 90% in the Furnace sample. The Plating soil had predominantly chromium with significant amounts of cadmium and lead. The Firing Range 1 soil exhibited a bimodal pattern of lead concentration, while the Plating soil exhibited a sharply higher chromium concentrations in the  $< 63 \mu\text{m}$  material.

Regarding distribution of heavy metal, the Firing Range soils exhibited two characteristics that should be significant for separations. First, a substantial fraction of the lead mass concentrates in the coarse,  $> 600 \mu\text{m}$  material, about 75 wt.% of the lead for the Firing Range 1 soil. Further, the  $< 600 \mu\text{m}$  material exhibits a bimodal pattern, with substantially less lead distribution to the 63–250  $\mu\text{m}$  fractions. Also significant was that the Plating soil exhibits a strong distribution of both chromium (up to 93.2 wt.%) and lead (up to 87.5 wt.%) to the  $< 63 \mu\text{m}$  fraction, which comprises 25.1 wt.% of the mass. Again, this enrichment could be exploited to facilitate separation and thus remediation. Attrition scrubbing produced moderate depletion of metal in the 63–600  $\mu\text{m}$  fractions and enriched the  $< 63 \mu\text{m}$  fraction. While, not dramatic, this effect is significant for separation schemes.

In brief, the Popping Furnace, Firing Range soil (particularly No. 1), and the Plating soil exhibited clearly different heavy metal distributions. This occurred despite the similarities in soil type of the Plating and Furnace soils. In the Firing Range 1 and Furnace soils, substantial lead mass was available for further separation from the 600–2000  $\mu\text{m}$  size fraction. (About 75% in the Firing Range 1 soil and about 65% in the Furnace soil). Likewise, both chromium (up to 93.2 wt.%) and lead (up to 87.5 wt.%) were enriched in the  $< 63 \mu\text{m}$  fraction of the Plating soil.

Extraction results indicated that lead was generally mobile in all size fractions of the Furnace soil. Significantly, extraction of hydroclassified, mid-range, 63–250  $\mu\text{m}$  fractions of Firing Range 1 soil yielded extracts an order of magnitude lower in concentration. This is consistent with the sharp depletion of lead for this material. Chromium and lead were relatively immobile in the  $> 63 \mu\text{m}$  Plating soil.

Attrition scrubbing had some moderate beneficial effects on mass and metals distribution for these soils, for instance increasing the lead distribution of the Plating soil in the  $< 63$  fraction from 73.3 to 87.5 wt.%, while producing small depletions of the larger size fractions.

## 7. Conclusions

Based on the tests performed in this work, we reached the following conclusions:

1. In general, the hydroclassification system and methods appeared efficient and reproducible at characterizing gravity-based separation achievable for a particular soil/contaminant combination.

2. Regarding metal distribution, hydroclassification showed depletion and enrichment behavior for the Electroplating and Firing Range soils that may be exploited by gravity-based separations.
3. Hydroclassification readily reveals the strikingly different distributions of metal, probably due to the mechanism of introduction of the contaminants into the soil: incineration vs. impact of ordnance, and discharge of aqueous solutions.
4. In some cases hydroclassification can cause a shift of more dense contaminated material to the larger nominal size fraction (defined by Stokes settling of quartz particles).
5. Attrition scrubbing can improve depletion/enrichment of the target contaminant, and is thus significant for separation schemes.

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