Soil-washing technology and practice

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Abstract

Soil washing in the United States has been studied and evaluated with increasing thoroughness during the last 15 to 20 years. It is now entering a phase of actual use and acceptance as its applicability and economics become clearer. This paper reviews the principles behind soil washing, methods of predicting and measuring its performance, some typical soil-washing processes, and several recent field applications.

1. Introduction

Soil washing is a simple, straightforward technology with a misleading name. The early usage referred to water-based processes in which fine soil particles are scrubbed from larger soil particles, thus washing the larger particles. Reagents such as surfactants were often added to improve the washing. The process offered promise because bench-scale studies showed that contaminants sometimes preferentially adhered to the fine particles. Thus, if the fines were a modest percentage of the bulk soil, and if the fines could be washed from the coarse particles, a large percentage of clean, coarse soil could be produced.

Technology vendors, researchers, and others are increasingly beginning to distinguish between the physical separation methods that characterized early soil-washing methods and newer, related technologies that also try to separate the contaminants from the fines by solubilizing or suspending them in the wash water. Besides surfactants, these approaches use acids, bases, chelating agents, alcohols, or other additives.

This paper will consider soil washing in the broad sense, including both separation of contaminated fines from clean coarse fractions and 'solubilization' of contaminants.

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2. Background

2.1. Historical perspective

Soil washing as a volume reduction process is relatively new. Early related efforts concentrated on extraction using aqueous solutions and ignored the physical separation/volume reduction possibilities inherent in the equipment that was used. For example, Gumtz [1] examined methods for cleaning oil from beach sand, which led to the development of a mobile froth-flotation unit for cleaning sand, mainly using pine oil as an extractant. Aqueous extraction also received close attention in Europe. Rulkens and Assink [2] and Hoogendoorn [3] presented comprehensive accounts of efforts in the Netherlands, but neither used the term 'soil washing' nor discussed the volume-reduction potential of extraction apparatus and processes.

Recognition of the practical value of separating the highly contaminated fines from the cleaner coarse fractions grew during the mid-1980s. In the United States, this recognition was furthered by the Superfund Amendments and Reauthorization Act (SARA), which provided specific statutory justification for soil washing. SARA prescribes remedial actions that permanently and significantly reduce the volume, toxicity, or mobility of contaminated material. The law further prescribes that remedial actions shall be permanent solutions and that alternative treatment technologies or resource recovery technologies be used to the maximum extent practicable.

Processes and apparatus such as the EPA's Mobile Soil Washing System were developed to accomplish the combined goals of separating particles according to size and extracting contaminants from the particles [4] . Also, several fixed facilities were constructed in the Netherlands and the Federal Republic of Germany that employed particle sizing combined with extraction as key steps in soil cleaning processes [5].

2.2. Potential applicability

The EPA [6] has recently completed a review of the potential market for remediation technologies, including soil washing. This study concluded that:

"There is a need for increased use of new separation technologies (such as soil washing) that reduce the quantity of waste requiring solidification/stabilization, or allow the recycling of valuable metals."

The volumes of soil/sludge/sediment that potentially must be treated are enormous. Much of this material contains metals, which cannot be destroyed, and much contains volatile and semivolatile organics or both metals and organics. Many DOE sites contain 'mixed wastes': blends of organics, stable metals, and radioactive species.

The EPA estimates that over 20 million cubic yards of soil *at current NPL sites* are contaminated with metals. The total volume of contaminated NPL soil is estimated to be 26 million cubic yards. Sites will continue to be added to the NPL, so this volume will grow. DOE volume estimates range from 3.3 to 200 million yards. Sites with leaking underground storage tanks (UST) contribute an additional 56 million cubic yards. RCRA Corrective Action sites, DOD sites, and others continue to be assessed,

so the national total volume of contaminated soil, sediment, and sludge is sure to grow substantially.

How much of this contaminated material is amenable to soil washing is impossible to say. Remedies have not yet been selected for approximately 750 of the current NPL sites, and studies are still in progress for the various DOE, DOD, UST, and other sites.

Determining the applicability of soil washing for a specific site is covered under *predicting performance* below.

2.3. Current capacity

Reliable numbers on the collective capacity of the US soil-washing industry are not available. The best information is probably in the EPA's Vendor Information System for Innovative Treatment Technologies (VISITT) [7]. Unfortunately, even that source lacks data on several companies, and the data it does contain on numbers of soil-washing units and their process rates cannot simply be summed to obtain an estimate of the total national capability.

The numbers are most certainly small, however. The number of companies with even one full-scale apparatus is approximately 10. Most of the processing capacity lies in only five companies. A non-rigorous estimate of the total capacity, considering the numbers of units and their ranges of capacity as listed in VISITT, is only 750 tons per hour.

3. Current soil-washing practice

No single, universal soil-washing process exists. The processes employed by the various vendors and researchers vary in the selection of hardware, the sequence of the unit processes, and the chemical agents/additives used. However, most of the apparatus in common use has been borrowed from the minerals processing industry (mining and ore processing), so certain devices that have proven effectiveness and reliability appear in many vendors' systems.

To illustrate typical processes, the following sections will examine two soil-washing systems developed by the EPA and will examine alternative components representative of the variety of hardware available for soil washing/volume reduction.

3.1. The mobile soil-washing system

The MSWS was developed during the early 1980s. Scholz and Milanowski [4] described the system in detail. Fig. 1 shows the major unit processes in the system. (It does not show complete flow details.)

The drum washer and trommel are a combined unit in which soil is contacted with wash water, which may have chemical additives, and an initial particle-size separation is performed. The drum section contains water knives to promote breakup of soil lumps, and it provides time for the soil to soak in the wash water. The trommel separates particles larger than 2 mm from the rest of the mixture. Ideally, this +2 mm gravel/sand fraction is clean.
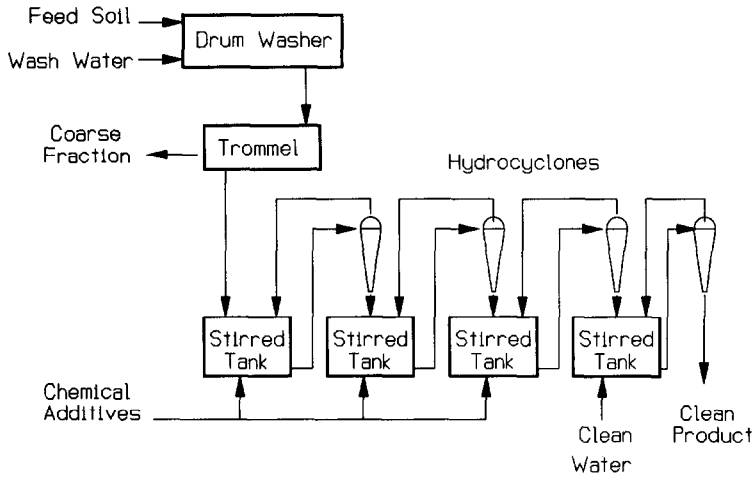
Fig. 1. The EPA mobile soil-washing system.

The −2 mm mixture is fed to a four-stage, counter-current extractor. The soil becomes progressively cleaner as it flows from left to right, and it contacts progressively cleaner water in each tank.

For most soils, this design obtains minimal benefit from volume reduction. It relies primarily on chemical extraction. Only the trommel is operated under conditions that effect particle-size separation. The hydrocyclones are operated primarily so as to perform separation of solids and water; they do not perform a particle-size separation.

3.2. The volume reduction unit

The VRU was developed during the late 1980s. Masters et al. [8] described the system in detail. Fig. 2 shows the major unit processes in the system. (It does not show complete flow details.) The VRU is a versatile design for performing experiments to learn more about soil washing.

The heated screw is a jacketed screw feeder capable of warming soil to approximately 200 °F for low-temperature desorption tests. The miniwasher is a small trough-bottom hopper fitted with a ribbon blender. Soil is blended with a small quantity of water and concentrated surfactant, caustic, or other washing additive. High attrition is achieved in this mixture.

A small feed screw on the axle of the ribbon blender pushes the washed mixture from the miniwasher into the adjacent trommel. Soil in the trommel is sprayed with additional wash water, and a particle-size cut is made at 2 mm. Coarse soil overflow from the trommel is usually collected in a drum. Ideally, this fraction is clean.

Underflow from the trommel falls to a series of two vibrating screens that have replaceable inserts. Typically, a particle size cut is made at 40 or 60 mesh (420–250 μm) in the first screen and 100 to 200 mesh (149–74 μm) in the second screen.

SOIL TREATMENT
SECTION
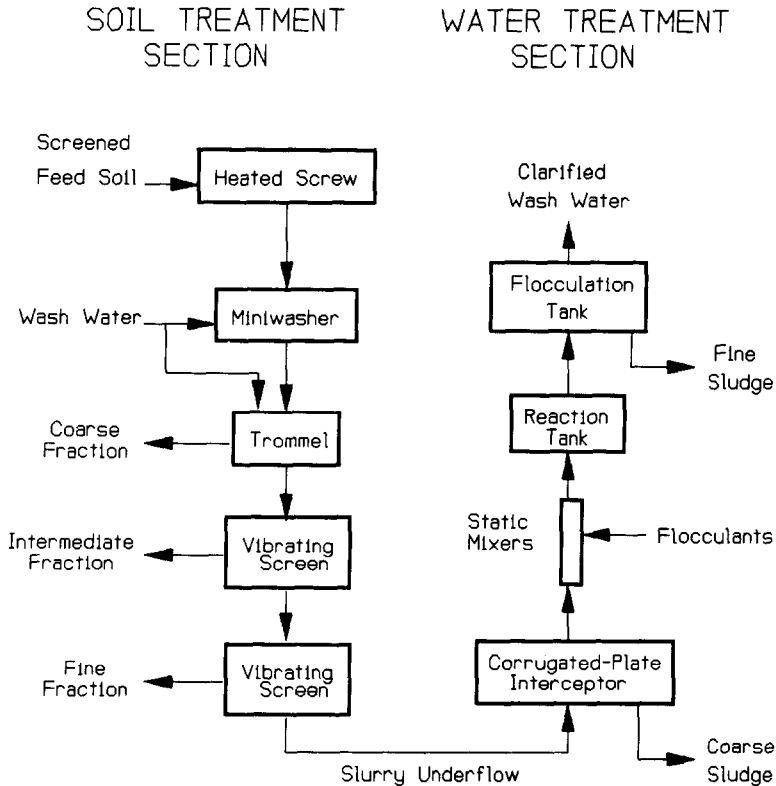
WATER TREATMENT
SECTION

Fig. 2. The EPA volume-reduction unit.

The overflows from these two screens are also collected in drums. Ideally, they are both clean.

Some of the remaining suspended fines are removed in a conventional lamella-type parallel-plate separator, which is also capable of removing any floatables that make it to this point. More thorough removal of fines is achieved by adding flocculation agents such as alum and a polyelectrolyte. The dosed wash water is passed through two static mixers and a small tank that allows time for the floccing reactions to begin. The growing floc is then allowed to precipitate in the larger floc-clarifier tank.

This design capitalizes heavily on volume reduction. The replaceable inserts in the vibrating screens allow for adjusting the particle-size cuts to optimize the volume reduction for a specific soil. Solubilizing the contaminants may occur, but this is not highly desirable, because additional wash water treatment would be needed.

3.3. Alternative apparatus

Numerous other material handling and mineral processing devices will perform the unit functions that comprise the MSWS and the VRU. Vendors of soil-washing

systems offer a wide range of hardware. Common references such as *Perry's Chemical Engineers' Handbook* [9] provide concise descriptions of mills, classifiers, filters, etc., and include data on ranges of flow rates, costs, etc.

Hydrocyclones can be effective substitutes for screens. In the MSWS, the hydrocyclones are used only to separate soil from wash water to maintain the countercurrent flows. Hydrocyclones can also perform particle-size classification. Under the right operating conditions, a hydrocyclone will pass water and small particles of a desired size out from the top (or the vortex finder) and will drop larger particles out from the bottom [10].

Spiral classifiers and elutriators (upflow classifiers) are also effective in volume reduction processes, particularly where the contaminants exhibit a significant density difference from the soil [11]. Froth flotation is frequently used for separating fines. Jigs and shaker tables, though they are effective devices for mineral processing, are not in wide use for soil washing [7].

Other mineral processing apparatus in common use for soil washing include devices for scrubbing (e.g., attrition mills) and high-performance dewatering devices (e.g., belt or plate-and-frame filter presses). Devices that do not accomplish soil washing but are needed for preparing the feed to the soil washer are covered in the next section.

3.4. Feedstock preparation

The feedstock preparation needed for most soil-washing processes is usually easily accomplished with readily available apparatus. The most common requirement is that the feed material be reduced to a particular maximum 'particle' size. This can be accomplished by prescreening to remove oversize material or by crushing, grinding, or shredding the oversize material. Numerous 'off-the-shelf' devices are available for these processes.

Grizzlies and trommels provide easy, effective prescreening of relatively dry soil, and they are in widespread use for feedstock preparation [7]. However, some problem soils may contain (or form during handling) excessive amounts of clay or silt lumps. These lumps may be highly contaminated, so they should not merely be screened out and left among the otherwise clean oversize material.

3.5. Wash water additives

Using additives in the wash water is generally undesirable. If sufficient volume reduction can be achieved with plain water, additives should be avoided entirely.

Additives complicate recycling or disposal of the water. Additional unit processes may be needed to remove the additives and to remove or degrade any contaminants that may have become dissolved or suspended in the water.

Additives often are contaminant-specific. Those most commonly used are acids, bases/caustics, surfactants, and chelating agents. Acids and chelating agents are applicable to metals, but the particular reagent needed can depend not only on the metal involved but also on the specific metal compound or species involved.

A compromise among reaction rates, the ultimate solubility of the metal salts, hazards to personnel, etc. must often be made.

Caustics can improve the extraction of organic acids; increasing the pH is a common strategy for removing pentachlorophenol. Many organics, especially those of low solubility or high viscosity, may require surfactants.

4. Predicting performance

The EPA [12] has recommended a progression of successively more detailed and definitive steps for predicting the performance of soil washing for a particular site. These steps are called preliminary screening, remedy screening testing, remedy selection testing, and remedy design testing.

4.1. Preliminary screening

Preliminary screening is an evaluation based on existing data. The evaluation begins with a search for relevant data from existing reports, from electronic databases, from expert consultants, etc. This review may identify sites that have similar contaminants and soils. If soil washing was evaluated for one of those sites, the results will be highly relevant to the current problem. Frequently, however, data specific to the new site must be obtained before engineering judgments can be made.

Knowing the distribution of the contaminants among the various particle-size fractions is key to predicting the effectiveness of volume reduction processes. Although it may generally be true that higher contaminant concentrations are often found in the finer fractions, it is not always true, and applying the generality to a specific instance may be a serious mistake.

Scholz and Milanowski [4] have shown that contaminant concentrations actually may be higher in the coarse fraction in some cases. More recent data obtained by Stinson et al. [13] showed a bimodal distribution, in which concentrations were high in both the coarse material (10% of the total) and the fines (7%) at a former wood-treating site. Stinson attributed the high concentrations in the coarse material to the large amount of 'woody residues', which were not separated out by the pre-screening for debris. Data collected by Serne et al. [14] at Hanford show many metals more concentrated in the fines but several almost uniformly distributed. Important contaminants that appeared primarily in the fines included chromium, lead, and uranium. In contrast, strontium, barium, and cesium were nearly uniformly distributed.

Lacking detailed measurements of the distribution of contaminants, educated guesses can still be made if enough is known about the properties of the contaminants and the soil. Key properties, some of which provide comparable or overlapping information, are the solubilities of the contaminants (including dependence on pH), the various partition/distribution coefficients (octanol/water, soil/water, organic carbon), the Freundlich or Langmuir isotherm constants, the cation exchange capacity (CEC) of the soil, and the amount of organic carbon in the soil. Numerous other

features of the soil/contaminant environment can affect the effectiveness of volume reduction or extraction. Dragun [15] presented an excellent review of the many physical, chemical, and biological phenomena in a series of three articles.

4.2. Remedy screening

Remedy screening involves bench-scale treatability tests to obtain more specific information about the ability of a type of technology to treat a specific waste. The procedures used by the EPA [16] for soil washing are generic jar tests that do not attempt to simulate any one vendor's full-scale process. They provide 'ballpark' information on the probable effectiveness of soil washing and are intended mainly to decide whether more expensive remedy selection testing is warranted. For soil washing, these tests may be frequently skipped [12], because preliminary screening often can produce enough information to make an equally sound decision.

4.3. Remedy selection

Remedy selection testing produces quantitative information on whether or not cleanup goals can be met. The results are sufficiently detailed to support analysis of alternatives and to indicate the optimal operating conditions. Pilot-scale testing may be needed to obtain this type of information. Good mass balances are desired. Toxicity tests may be performed on the cleaned soil [12].

4.4. Remedy design

Remedy design testing provides comprehensive engineering data for operating and optimizing a process at a specific site. They usually consist of bringing a mobile unit onto the site, or constructing a pilot-scale unit on site [12].

5. Measuring performance

Measuring the performance of a process involves measuring all of the feeds (inputs) and the products or residuals (outputs). If extensive recycling is done within the process, measurements at intermediate steps where the process has no inputs or outputs may also be desirable. Intermediate measurements may also be desirable as diagnostics or for optimizing the process.

In general, full accounting of all the soil, water, contaminants, additives, etc., that enter and leave the system (obtaining 'mass balance') is desirable. It is not always possible, mainly because of analytical chemistry limitations, which are discussed below.

Day-to-day performance monitoring during an active remediation needs less comprehensive and less frequent sampling and measurement than evaluating a new process for future use. Many parameters may need to be monitored to assure smooth

operation of the apparatus, but relatively few need to be monitored to document the quality of the remediation.

Cleanup criteria are now well-defined, quantitative targets for the concentrations of contaminants in the cleaned soil. Although more-extensive measurements may be desirable, analyzing samples of the outputs may be all that is needed to document a remediation. If the process costs are under $100 per ton, unnecessarily processing a few tons of clean material may be less expensive than performing comprehensive sampling and analysis of the feed.

The analyses of output samples should address the following questions:
– How much contaminant remains in the coarse material that will be redeposited on site? Does the coarse material pass TCLP or other required tests?
– How much contaminant is in the fines/sludge/filter cake produced by the process? Does this material pass TCLP or other required tests?
– Where did the additives go? Are additives still in the coarse material or wash water? Did they concentrate in the fines? Are they biodegrading?
– What is the practical value of the material to be redeposited? Is it sterile? Will vegetation grow in it? Does it display enough integrity to build upon?

Measurements that address the following may be needed to optimize the process:
– What is the particle-size distribution within each fraction generated by the process? Is sufficiently complete separation being performed?
– How much water is in the processed solids?
– How much labor and power is each stage of the process consuming? How much downtime is being encountered for maintenance or repairs?

Measuring the performance of a soil-washing process faces an inherent limitation in the analytical methods that must be used to determine concentrations in samples. The conventional analytical methods begin with extraction of the contaminants from the soil. The laboratory extraction methods produce less than 100% recovery of the contaminants; in some cases, they produce very low percentage recovery. QA checks can verify the occurrence of poor recovery, but using those results to 'correct' the analyses of samples generated by the full-scale process is questionable.

Two phenomena aggravate the situation: (1) the volume-reduction process drives the contaminants to those components of the soil to which they bind most tightly and (2) soil washing is itself an extraction process that will remove the most readily extractable contaminants. From a regulatory viewpoint, this situation may be acceptable. But evaluators should understand that the results of the analyses may not truly indicate how well (or poorly) the process performed.

6. Recent experience

The EPA has completed pilot-scale soil-washing experiments using the VRU at four sites since July 1992. Complete results are available for three of those sites, and brief summaries are presented below. The soils at these sites spanned the range from highly favorable (5% fines) to marginal (31% fines). The contaminants included pentachlorophenol (PCP), creosote, pesticides, and diesel fuel.

6.1. Escambia

Tests were conducted at the Escambia Wood-treating Site in Pensacola, Florida, in July 1992 [17]. Approximately 250,000 cubic yards of sandy soil have been excavated at this site and stockpiled on tarps. The primary contaminants are PCP and creosote.

The soil was prescreened to remove gravel and wood chips larger than $\frac{1}{4}$ in. The surface soil contained many wood chips, but the subsurface was mostly sand. Table 1 shows the particle-size distribution after prescreening.

Thirteen creosote components were tracked in the sample analyses, including five that are classified as carcinogenic. The feed concentrations were approximately 150 mg/kg (ppm) of PCP, 1200 ppm total creosote, and 71 ppm carcinogenic creosotes. The target concentrations were less than 30 ppm of PCP, less than 100 ppm total creosote, and less than 50 ppm carcinogenic creosotes.

Twenty runs were completed. More than 90% of the soil was separated as clean coarse product. Most of the fines remained suspended in the wash water. The wash water was not treated using the CPI and floc-clarifier; it was saved in tanks for later use in biodegradation and other treatment studies.

Table 2 shows the results from six runs selected to illustrate the effects of additives. A plain-water wash using no reagents accomplished substantial cleaning of the coarse fraction, but the target concentration for total creosote was not reached. Increasing the pH had little effect, but adding surfactant brought the creosote figures well below the target. Adding one additional rinse with plain water (W and R) produced excellent results.

Mass balances were poor for these tests. The measured contaminant concentrations were low in the coarse material, the fines, and the wash water. The low values for the coarse material and wash water were supported by the QA checks, but the laboratory extraction of the fines produced poor recoveries. The contaminants were probably in the fines, but this could not be proved due to analytical difficulties.

6.2. Sand Creek

Tests were conducted at the Sand Creek Superfund Site in Commerce City, Colorado, in September 1992 [18]. The soil contains much more fines than the

Table 1
Escambia particle-size distribution

Sieve no.	Particle size (mm)	Weight (%)
5–3	4–6	0
10–5	2–4	1
18–10	1–2	10
35–18	0.5–1	60
60–35	0.25–0.5	23
120–60	0.125–0.25	5
Pan	< 0.125	1

Table 2
Results from the Escambia tests

Test conditions				Residuals (mg/kg)		
Comment	Surfactant (%)	Temperature (°F)	pH	Creosote PCP	Total	Carcinogenic
Wash	0.0	85	7	2.4	110	3.7
Wash	0.0	85	10	2.5	130	6.0
Wash	0.2	85	10	2.0	69	3.5
Wash	0.2	120	10	3.8	80	3.4
Wash	0.2	120	10	1.6	66	2.4
W & R[a]	0.2	120	10	nd	1.6	nd

[a]W & R = Wash and rinse.

Table 3
Sand Creek feed soil

Depth (ft)	Dieldrin (mg/kg)	Heptachlor (mg/kg)	Particle sizes	
			(μm)	(%)
0–1	25	260	+ 2000	5
			425–2000	15
			75–425	49
			− 75	31
1–3	13	180	+ 2000	3
			425–2000	17
			75–425	49
			− 75	31

Pensacola site. The primary contaminants are chlorinated pesticides, mainly dieldrin and heptachlor.

Soils from several different depths were used to obtain different feed concentrations. The soil was prescreened to remove gravel larger than $\frac{1}{4}$ in. Table 3 shows the particle size and the contaminant distributions after prescreening.

The target concentrations were 0.155 ppm for dieldrin and 0.553 ppm for heptachlor. These targets equate to 99.4% removal for dieldrin and 99.8% removal for heptachlor, results not normally achievable by soil washing.

Twenty runs were completed using three different surfactants. Approximately 80% of the soil was separated as clean coarse product. The amount of fines in the washed soil proved to be different from that shown in Table 3 (acquired by laboratory sieving). The contractor for EPA Region 8 who performed the analyses speculated that the fines swelled during washing, thus altering the particle-size distribution.

Table 4
Results from the Sand Creek tests

Test conditions				Residuals (mg/kg)	
Comment	Surfactant[a] (%)	Temperature (°F)	pH	Heptachlor	Dieldrin
Wash	None	Ambient	7	50	4.6
Wash	1.0 A	130	10	25	2.9
W & R	1.0 A	130	10	7.9	1.3
Wash	1.0 S	130	10	36	4.4
Wash	0.4 T	130	10	27	5.0
Wash	1.5 T	130	10	16	3.2
Wash	1.5 T	130	10	20	2.0
Wash	1.0 M	130	10	22	3.8

[a]A = Mixture: 50% Adsee 799, 50% Witconol NP-100. S = Sodium dodecyl sulfate (SDS). T = Tergitol 15-S-9. M = Mixture: 60% SDS, 40% Tergitol.

Table 4 shows the results from eight runs selected to illustrate the effects of the various surfactants tested. Substantial removals were achieved by all runs, including the plain-water wash, but the target concentrations could not be achieved by any of the test conditions. One reason for this shortcoming was apparently carryover of too much fines in the overflow from each screen. This incomplete separation of contaminated fines from cleaner coarse material left too much contamination in the coarse overflow material. As found at Escambia, adding one additional rinse to the existing VRU process improved the removals considerably with no additional reagents.

6.3. Montana Post and Pole

Tests were conducted at this site in Butte, Montana, in June 1993. Except for one hot spot under a building, the soil had been excavated and stored in bags in several 'barns' erected on the site. The soil contains a moderate amount of fines. The primary contaminants at the site are PCP and diesel fuel. Although diesel fuel is being recovered in quantity from a pump-and-treat system on the site, no excavated and bagged soil could be found with sufficient concentration to justify tracking it through the soil-washing tests.

The soil was prescreened to remove gravel larger than $\frac{1}{4}$ in. Table 5 shows the particle-size distribution after prescreening.

Table 6 shows the results from selected runs. Rather than analyzing a composite of the entire coarse material, the two fractions shown were examined separately. The finer fraction consistently shows slightly higher concentration than the coarser. The target concentration for PCP, 32 ppm, was attained only after an additional rinse.

Table 5
Montana Post and Pole particle-size distribution

Sieve no.	Particle size (μm)	Weight (%)
+ 10	+ 2000	27
20–10	850–2000	25
50–20	300–850	18
200–50	75–300	14
Pan	− 75	16

Table 6
Results from the Montana Post and Pole tests

Test conditions					Residuals PCP (mg/kg)	
Comment	Surfactant (%)	Temperature (°F)	pH	Feed (ppm)	+ 250 μm	+ 100 μm
Wash	0.0	60	7	800	130	160
Wash	0.1	60	7	600	100	160
Wash	0.1	60	10	640	48	91
Wash	0.0	60	10	500	60	81
Wash	0.1	140	10	530	80	110
W & R	0.2	120	10	530	31	31

6.4. Private sector

Use of commercially available processes is growing after many years of discussion and evaluation but no real application. Two important recent applications are the soil-washing/volume reduction process by Alternative Remedial Technologies (ART) at the 'King of Prussia' (KOP) site in New Jersey [10] and the soil-washing/acid leaching process by BESCORP/COGNIS at the Twin Cities Army Ammunition Plant (TCAAP) in Minnesota [19] .

The ART apparatus is a modular system that employs screens, hydrocyclones, froth flotation cells, a floc clarifier, and a belt filter press. The feedstock is prepared using a large grizzly and a trommel, mainly to remove woody debris. The soil at the KOP site is contaminated with several metals and organics, but chromium is the main contaminant of concern. Extensive pilot-scale tests were performed while designing the process, and a thorough full-scale test was performed on-site during the summer of 1993 before beginning regular operations.

ART's preliminary results show effective volume reduction [10]. Approximately 85% of the feed is cleaned to below target levels, and 15% is produced as highly contaminated filter cake.

The BESCORP/COGNIS apparatus is a combination of particle sizing, gravity separation, and acid leaching apparatus designed primarily for removing metals from

soil. The TCAAP's Site F contains approximately 8000 tons of soil contaminated mainly with lead [19]. On-site cleanup began in September 1993.

The target concentration for lead cleanup is 300 ppm. The preliminary results show lead levels being reduced from as high as 86,000 ppm to approximately 100 ppm.

7. Summary comments

The number of sites and the volume of soil for which soil washing or volume reduction is potentially applicable apparently far exceeds the current capacity of the soil-washing units in the United States.

Many of the current soil-washer designs make extensive use of apparatus from the mineral processing industry. The more compact, easily modularized devices are favored. This approach may facilitate rapidly increasing the number of units and total capacity if demand continues to rise.

More attention needs to be paid to interfacing and integrating soil-washing processes with other technologies. Complete treatment trains in which highly contaminated residuals are destroyed or immobilized have rarely been studied or tested.

Effective volume reduction can sometimes be done without reagents. Exploratory studies such as bench-scale tests should always explore this possibility so that wastes and residuals can be minimized.

The focus of soil washing, volume reduction, acid leaching, and other related processes is producing clean soil as a product. An alternative focus that may produce the same result is that of the minerals processing industry: attempting to produce a salable product (lead, chromium, diesel fuel, etc.) from the ore called 'contaminated soil'. Combining this focus with the up-front objective of using only 'environmentally attractive' chemistry may lead to more-cost-effective processes.

Soil washing is potentially a good choice for wood-treating sites contaminated with pentachlorophenol. Soil washing can be reasonably effective for pesticides but is not likely to achieve the sub-ppm cleanup levels called for by some risk analyses.

The analytical tools available for determining the concentrations of contaminants in samples may be inadequate for evaluating technologies. Their limitations appear to stem from the fact that the analytical methods themselves generally begin with an extraction process, and these are known to be incomplete in many cases.

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