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Application of remedy studies to the development of a soil washing pilot plant that uses mineral processing technology: a practical experience

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Abstract

Soil washing employing mineral processing technology to treat radionuclide-contaminated soils has been examined as a remedy alternative to the exclusive excavation, transportation, and disposal of the soil. Successful application depends on a thorough remedy study, employing a systematic tiered approach that is efficient, self-limiting, and cost effective. The study includes: (1) site and soil characterization to determine the basic mineral and physical properties of both the soil and contaminants and to identify their relative associations; (2) treatment studies to evaluate the performance of process units for contaminant separation; (3) conceptual process design to develop a treatment pilot plant; and (4) engineering design to construct, test, and optimize the actual full-scale plant. A pilot plant using soil washing technology for the treatment of radium-contaminated soil was developed, tested, and demonstrated. The plant used particle-size separation to produced a remediated product that represented approximately 50% of the contaminated soil. Subsequently, it was modified for more effective performance and application to soil with alternate characteristics; it awaits further testing. The economic analysis of soil washing using the pilot plant as a model indicates that a remedy plan based on mineral processing technology is very competitive with the traditional alternative employing excavation, transportation, and disposal exclusively, even when disposal costs are modest or when recovery of remediated soil during

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treatment is low. This paper reviews the tiered approach as it applies to mineral processing technology to treat radionuclide-contaminated soils and a pilot plant developed to test the soil washing process.

Keywords: Radionuclide; Mineral processing; Mineral technology; Soil washing; Physical separation; Treatment technology; Pilot plant; Economic analysis; Radium; Review

1. Introduction

The term soil washing has been used to describe several wet processes that remove contaminants from toxic soils. Soil washing has been employed more extensively in Europe than in the United States as an integral part of full-scale remediation plans to separate organic compounds by volatilization, thermal desorption, steam distillation, extraction, and particle-size classification. Less commonly, metals have been removed by leaching, desorption at acid pH, and size classification. Particularly, the experience in this country with the application of soil washing to radionuclide-contaminated soils has been primarily restricted to bench-scale and pilot-plant studies. Several of these studies have been conducted in the last 10 years to evaluate the technology as a method to remediate radionuclide-contaminated soils, but to date, few radioactive sites have actually been remediated using this method. The goal of each study has been to develop a treatment scheme that would separate the radionuclides from the soil, leaving concentrations in a portion of the soil that will not pose a threat to the environment or health of the community. The studies have also examined methods for collecting or concentrating the contaminants in a significantly reduced volume for disposal. Soil washing offers an alternative to disposal of the total soil volume, thus lowering remediation costs by reducing the expenditures for transportation and disposal at an approved site. An added benefit would be the reduction of the amount of material buried at a waste site, material that might require additional handling or treatment in the future.

Most soil washing studies to date have been inconclusive, primarily, because of their limited scope. Some efforts have also been characterized by an incomplete commitment to a systematic study approach that might lead to a definitive solution and by a concomitant lack of funding to develop the most effective and reliable approach to remediation by soil washing. Although the principles of soil washing as they apply to radionuclide removal from whole soil have been partly misunderstood, and the application of separation technology provided by the mineral processing industry has been fragmentary, much has been learned in the last 10 years. During that time, we have been involved in remedy studies and their application to the design, construction, and testing of a soil washing pilot plant to reduce the volume of radium-contaminated soil. During the studies and plant development, we gained considerable experience in applying mineral processing technology to the treatment of whole soil. At the same time, we combined the experience of our respective disciplines to contribute to the development of an approach to remedy studies that provides a very effective evaluation and application of soil washing to the treatment of radionuclide-contaminated soils. The tiered protocol described in Section 2 was developed out of this experience with soil-washing studies and plant development and testing. Indeed, the protocol and plant design evolved side-by-side in a practical effort to try to produce the most effective soil washing plant based on the characteristics of the contaminated soil requiring treatment. Simultaneous development of protocol and process was not the ideal way to proceed for site remediation, but it evolved in this manner during ground-breaking studies before much was known about the application of soil washing technology to the treatment of radionuclide-contaminated whole soils. In this paper, we review a systematic tiered approach that is efficient, self-limiting, and cost effective [1]. Development and testing of the pilot plant are also reviewed [2,3] along with an economic evaluation of soil washing, particularly as it compares to exclusive disposal of all the contaminated soil from a site.

Ultimately, the properties of the host soil and radionuclide contaminants as well as their association mechanisms will govern the treatment technology that will be appropriate for site remediation [1]. Some radionuclide contaminants that are free and uniquely distinguishable will be relatively easy to separate by a single process such as particle-size classification. Others that are intimately associated with the soil matrix through tight bonding mechanisms or whose physical properties are virtually identical to the host soil will require additional liberating or, possibly, almost complete solubilization of the soil matrix. Metallic radionuclides in their ionic form are specifically associated with host soil materials by absorption, ion exchange, precipitation, coprecipitation, ligand and chelate exchange, and occlusion [4,5]. Soil minerals bound to contaminants by these processes include clay minerals, hydrous metal oxides, carbonates, and humic substances [6]. Together, these association mechanisms and soil mineral categories produce a wide spectrum of soil-contaminant interactions, some strong and intractable and others significantly weaker and easier to overcome. The potential for separation and isolation of the contaminants is, therefore, tied to the physical and chemical nature of the contaminants and their location in the soil matrix. Large metallic particles with a distinctive particle-size range can be removed by simple size classification. Contaminants located in a specific soil particle-size fraction can similarly be separated by the process, while surface minerals are often isolated by attrition before removal by size classification. Alternatively, radiominerals with significant magnetic properties might be removed by magnetic techniques. Overall, the level of complexity of the technology required for remediation depends on three factors: (1) the type and mineral nature of radioactive contaminants present and their host-soil association characteristics, (2) the type and complexity of the host soil matrix itself, and (3) the processes necessary for separation and collection of the radionuclide contaminants.

Application of soil washing technology to radionuclide-contaminated soil must ultimately exploit the differences between contaminant and host soil particles to provide a method(s) for release, separation, concentration, and collection of contaminants [1]. Ideally, application of mineral processing technology can provide a processes for separating virtually any soil contaminant provided it can be dissociated from the bulk of the host soil. In practice, however, successful application to site remediation depends on development of a treatment scheme that provides a solution acceptable to stakeholders and regulators. It must also be economically competitive with alternative remediation methods, including the most supported method to date, total excavation and disposal, and must provide overwhelmingly advantageous cost savings. Development of the scheme, in turn, requires a comprehensive understanding of the physical, mineralogical, and chemical properties of the soil constituents and contaminants and their association mechanisms. Obtaining this information is followed by selection of processes and process units that have been optimized to provide the most effective isolation of the contaminants and, finally, combined into a full-scale treatment operation.

2. Approach to remedy studies [1]

A reasonable, cost-effective remedy-study plan for application of soil washing studies to site remediation should employ a tiered approach. A step-wise protocol attempts to confine the study to those tests necessary to develop a treatment plant or to conclude the study if tests reveal that soil treatment is not competitive. These objectives are realized by evaluating the test data as they are generated and using the results to guide the development of additional tests. The protocol evolves with the study to help guide its development and to limit the tests to those that accomplish its goals. The tiered approach also enables the investigator to follow promising results but avoids bypassing or attenuating tests needed to obtain the information required to make the best decisions about its conduct. It also avoids preconceived assumptions such as presuming that a more complex technology or a combination of technologies will not be successful solely because a simpler method has been rejected earlier in the study.

It should be noted that the tiered approach is not unique to mineral processing technology but is used by the chemical industry for the conceptual design of process plants [7] and can be aided by computer-based automation of conceptual designs [8]. From our experience in developing and testing a soil washing pilot plant, we cannot overemphasize the importance of performing a complete, integrated, and reliable study. Remedy decisions are greatly affected by both the success of the separation processes and their ability to compete with alternate remediation technologies. Unless complete reliable data are available to make these decisions, treatment processes might be prematurely eliminated from consideration or, alternately, given too much emphasis as a promising remedy. Both errors are very costly in time and money and negative to the development of soil washing technologies, which otherwise might be important to remediation efforts at other sites.

There are four tiers in remedy studies used to evaluate the potential for applying mineral processing technology to soil washing: characterization, treatability, conceptual process design, and engineering design. The tiers have a pyramidal relationship with characterization as the base and engineering design at the apex. Each step is essential to the study process, follows in order, and, accordingly, cannot be omitted. In fact, the tiers are complementary to each other and integrated in their application, using an efficient overlapping protocol that judiciously relies on each tier to enhance the other. No tier study is absolutely closed until the remedy study is completed, allowing succeeding tier studies to revisit alternate technologies of former tiers, if needed, and beginning the next tier only when sufficient results are available from a preceding tier to warrant its initiation.

2.1. Characterization studies

Characterization studies determine the basic mineral and physical characteristics of the contaminants and host soil particles and their interaction mechanisms. They are used to propose a plausible remediation scheme using an ideal mineral separator. The proposed scheme will exploit differences in the intrinsic properties of host-soil and contaminant particles to achieve a separation. Intrinsic properties primarily exploited for separation include particle size, density, magnetic susceptibility, hardness, surface (flotation) properties, and solubility; they depend only on the inherent properties of the soil constituents and are independent of any process that might eventually be used to achieve separation. Generally, the greater the property difference between contaminant and host soil, the easier the separation. Complete separation is never possible to achieve, however, because real separation processes, although fully optimized, are never ideal. Characterization data are collected, therefore, to suggest a plausible remedy plan and to estimate the remediation potential that can be expected for the proposed separation processes under ideal conditions.

Before a soil and contaminant characterization study begins, it is essential that the site itself be characterized and cleanup criteria be established. The natures of host soil and contaminants are usually different for each site, and even within a site. Results from previous studies of similar sites are not necessarily reliable when applied to other soils. As our understanding of soil contamination and radionuclide associations evolves and as the application of mineral processing principles to treatment of whole soil is developed, it might be possible to project behavior of soil from one site to that of another, but some degree of characterization will always be required. In any event, it is also critical to remedy studies that representative samples be used and that sufficient quantities be collected for all tiers of the study. Complete characterization studies performed on samples that adequately represent the material to be treated provide a realistic estimate of the magnitude and extent of contamination and suggest approaches to soil removal and treatment. Incomplete or inaccurate information during characterization or absence of well-defined cleanup criteria will be detrimental to the entire remedy study and lead to very costly errors in evaluation, planning, and remediation attempts.

Based on the cleanup criteria, site characterization, and subsequent remedy studies, soil from the site might be divided, ultimately, into three categories: (1) soil that meets the cleanup criteria as they exist and that could remain on site, (2) soil that cannot be cleaned up by any treatment method and will require disposal, and (3) soil that can be treated by a separation technology to meet the criteria. The relative amounts of soil in each of these categories will greatly influence the options and costs of site remediation by any remedy ultimately selected.

Characterization studies begin with a particle-size and contaminant distribution profile determined by wet sieving [2,9]. The profile affects the choice and effectiveness of treatment technology. If the contaminants are in a specific size fraction, for example, isolation of that fraction from noncontaminated material can provide a relatively simple treatment solution. Size distribution within the bulk soil material also influences the type of treatment process that might be applicable. For example, soils with large amounts of small clay-sized material can be difficult to treat by some mineral processing units. Soils with contaminants in larger-sized sand fractions, alternatively, are usually easier to process, providing the contaminants are not occluded in uncontaminated particles. Size classification is also indicative of certain mineral compositions that adsorb radionuclides. Clay particles, for example, carry a negative charge on their surface that strongly adsorbs cations.

Determination of the mineral content of the soil and nature of contaminant associations follows the size tests. Data are collected by scanning electron microscopy (SEM) and energy-dispersive X-ray analysis (EDX) on particle-size fractions produced by the sieving study; the examination is often complemented by traditional petrographic examination by polarized-light microscopy. These studies provide a means of determining if the undesired components in the contaminated soil are sufficiently unassociated to be separated by physical soil washing processes. In each mineral analysis, radionuclide content from radioanalysis is correlated with mineral type and concentration to aid in identifying the contaminant soil material. In addition to these tests, other mineral characterization tests might be necessary to fully delineate the radioactive components present. X-ray fluorescence (XRF) measurements and X-ray diffraction (XRD) are often used to aid in the mineralogical identification.

Sequential leaching by select chemical reagents can also be used to help identify the association mechanisms of contaminants to the host soil matrix [4]. Reagents are chosen to selectively destroy specific binding minerals in the matrix. They are applied sequentially, using increasingly aggressive chemicals until the matrix is completely solubilized. At each step, radionuclide analysis reveals which contaminant is released as the matrix is attacked, in turn, indicating which host-soil component is binding the contaminant.

In addition to sieving, other classification procedures are often important to characterization studies in order to identify the distribution of radionuclides with regard to other mineral properties. One of the most distinguishing characteristics of common radioactive minerals is that their specific gravities are all substantially higher than most host materials found in the soil [10]. Therefore, some radiominerals might be isolated by density separations. The magnetic susceptibility of several radiominerals also provides another physical separation option for volume reduction by contaminant removal [11].

2.2. Treatability studies

If differences in intrinsic particle properties are discovered that can be reasonably exploited to achieve separation, a treatability study is performed to select the most effective mineral processes and processing units for treatment and to design a treatment train that will accomplish the separation and meet the cleanup requirements. With these properties, process strategies, drafted as flowsheet designs, are proposed using treatment units in combinations that can exploit material differences to produce a separation. Chemical treatment might also be used to solubilize select contaminants and collect them by precipitation, coprecipitation or flocculation, and/or ion exchange.

In the past, considerable confusion has existed over the difference between characterization studies and treatability studies, partly because of misunderstandings of the protocol of each study and partly because of the inherent overlapping and integrated nature of remedy studies. Generally, characterization studies are focused on the properties of the soil components and contaminants and their association mechanisms, while treatability studies are directed at the identification of processes for separating the contaminant from the host soil. As such, the characterization data are independent of the process used to achieve the separation, whereas treatability data are not. For example, information obtained from laboratory sieving tests is appropriately termed characterization data since it depends only on the physical properties of the soil. Related treatability data can be obtained using a variety of particle-size separators such as mechanical screens or hydroclassifiers. The treatability data are different for each separator because their efficiency varies with the mechanical design and operating principle of each sizing device. In some instances, characterization studies, incomplete endeavors by themselves, have been mislabeled treatability studies. Independently, characterization studies, for example, might indicate that soil washing is not a promising remediation alternative for a site, but they will not, alone, provide sufficient information to determine if soil washing could be a competitive component of a remedy plan. Treatability studies are the next step in the tiered approach leading to that decision.

The treatability study is an iterative process applied to develop the most effective and economical remediation design and to optimize its performance. The preferred design developed during the study must be cost-effective, meet or exceed the stated cleanup criteria, and maximize the overall volume reduction of contaminated soil. The iterative study makes use of both computer simulation analysis and bench-scale testing of probable units and unit combinations [3,12]. Computer simulations are used to the extent possible to eliminate unnecessary and costly tests in a complementary relationship to save time, money, and materials by reducing the need for labor-intensive and costly laboratory and bench-scale testing. Flowsheet development also employs standard partition-curve data to convert characterization results into actual performance data that may be expected for a given separator, ensuring that the design flowsheet reflects real-world values for selecting and evaluating process units.

Treatability studies begin by an evaluation of reasonable technology options. Those that meet the selection criteria are assembled in an initial flowsheet design. To maximize the usefulness of the characterization data, a computer simulation program is used based on existing mathematical models to predict the performance of the conceptual flow diagram. From the input of characterization data and unit partition data, the computer simulation predicts the separation of each unit operation and overall separation efficiency (volume reduction of soil and total activity) for the flowsheet design. Optimization of that flow diagram leads to a preferred process flowsheet. Once the probable combinations of selected technologies are evaluated in the flowsheet, a final or preferred flowsheet design is selected. The preferred flowsheet might actually be several flowsheet designs that produce comparable volume reductions. Each will then have to be evaluated to determine which is the most economical and feasible design for the site. If no plausible scheme can be identified, it might be necessary to conduct additional characterization tests to identify one or more additional basic properties that might be exploited.

After the final flowsheet designs are selected, bench-scale tests are used to verify the computer simulations and to allow fine-tuning of the operating parameters of each unit in the flowsheet and to demonstrate their reproducibility. Because of cost considerations, these tests are typically performed at a small scale (< 500 lb/h) using continuous or semi-continuous pilot-plant separators. Additional process simulations are often performed in conjunction with the bench-scale tests in the iterative design and testing process. Although bench-scale tests are often labor-intensive and costly, the test work can be minimized through use of these computer simulations. The laboratory bench-scale testing will determine the operating parameters for each selected separation unit and will demonstrate the ability to consistently reproduce the results. Reproducibility of bench-scale test results is an important consideration in treatability studies, because it affects the reliability of the overall process design.

After the bench-scale tests are completed, the results are applied to the flowsheet design. This fine-tuned flowsheet constitutes the final flowsheet design. Like the final design from the computer simulations, it might consist of several designs that produce equivalent volume reductions. Each one will require an economic evaluation to determine which is the preferred conceptual process design.

2.3. Conceptual process design

If the treatability study provides a competitive soil washing strategy, the remedy study continues with a conceptual process design study. This step provides a final conceptual engineering design for the treatment plant that will meet or exceed treatment goals and be approved for on-site operations. To achieve these goals, comprehensive engineering analysis and a feasibility study are conducted to identify the preferred process design that can be readily implemented.

Conceptual design studies begin with the development of process flow diagrams that are based on the preferred process flowsheet. Computer simulation techniques are again used to evaluate each processing alternative selected. Bench-scale tests are performed to resolve uncertainties associated with the configuration and behavior of the proposed circuitry and to refine the performance of the process units. The conceptual design is then reevaluated, with emphasis on both technical and economic factors. Based on these evaluations, new processing alternatives will be introduced if necessary, and the engineering analysis procedures and technical/economic evaluations repeated. This iterative process eventually leads to development of a preferred processing strategy that will serve as the basis for the final conceptual design.

Sizing the process equipment for each flowsheet design is next in the protocol. Site characterization data are used to define the volume and location of the contaminated soil. The volume of contaminated soil and overall remediation schedule are important to sizing the process equipment, since they are key factors in determining the capacity or throughput of the conceptual process design. The constraints of the process site are another important consideration in sizing process equipment. With these criteria in mind, the principle of ‘economy-of-scale’ must be considered. In many cases, small-scale production equipment is more costly (on a per-ton basis) than large-scale units. Therefore, most mineral processing plants are constructed to process high tonnages so that the unit cost-per-ton can be kept low.

Since the conceptual process design might produce more than one flowsheet with different combinations of separation technologies, an overall economic evaluation of each flowsheet (cost-per-cubic-yard of remediated soil) is performed to determine the final conceptual design for the site. After the economic factors are established, any conceptual process design that is technically feasible, achieves maximum volume reduction, and meets the site cleanup criteria is subjected to an overall economic evaluation. Several combinations of separation technologies might achieve cleanup goals, however, only one will be the preferred process design. This design is selected by performing a thorough comparative economic evaluation including each technically feasible design.

The most important factor in an economic evaluation is the net savings realized from using the treatment process to remediate the site compared to an alternate remediation proposal, including complete removal, transportation, and disposal in an approved landfill (see Section 4, Economic Evaluation). The total cost of the remediation is calculated from three factors: (1) savings from percentage of volume reduction, (2) total operating cost, and (3) and initial capital investment. By comparing the total cost of the remediation using the treatment process with the cost of complete disposal, for example, the cost effectiveness of the treatment process is determined. If net savings are significant, then the conceptual process design should represent a viable option. It is important to recognize that a reasonable savings does not ensure that treatment should be undertaken. For example, even a good sampling program might provide only a 95% confidence that the samples are actually representative of the site material to be processed. Therefore, the potential savings must always be compared to the potential risk for failure. Since the risk is very difficult to estimate, the final decision to apply a treatment process should be left to very experienced personnel.

2.4. Engineering design

The last step in the remedy study is engineering design, the construction, testing, and optimization of the full-scale pilot (semiworks) plant followed by construction of the final operational plant to be used in the overall remediation plan for site cleanup. Both are capable of meeting the desired cleanup criteria, maximizing the volume reduction, while remaining economically feasible for the site.

The preliminary flowsheet is formulated solely on the basis of the available technical data, focusing on the design of processing circuits that offer the best overall performance in terms of separation efficiency. In the second stage, a revised flowsheet is again developed that addresses economic factors. Finally, the revised flowsheet design is reevaluated in light of secondary considerations important to the successful implementation of the proposed soil treatment facility: maintenance, operation, control, long-term performance, and public acceptance of each of the selected processing circuits. In addition, the conceptual flowsheets incorporate features and/or provisions that meet or exceed all applicable Federal, state, and local regulations to ensure operational safety and minimize potential hazards to the environment. This iterative process is a combination of characterization studies, treatability studies, and process design. Designs considered to be economically viable are subjected to flowsheet simulation to evaluate the technical performance of proposed conceptual designs. The simulation input values include (1) specification of the characteristics of the feed soil in terms of particle size, particle density and contaminant distribution and (2) specification of the relevant design parameters or operating conditions for each unit operation, known as the partition data, (3) detailed information related to the separation performance of each unit operation, and (4) the characteristics of each flow stream. The output values include a summary of clean and contaminated products leaving the soil treatment plant.

Next, the semiworks plant is constructed, tested, and optimized. By definition, the semiworks plant represents the first full-scale production facility for the proposed remediation scheme. The semiworks plant might be slightly different from future copies of the full-scale plant since there will be additional lessons learned during construction. The semiworks plant might not have all the refinements that will eventually be incorporated into a final treatment facility. However, the semiworks plant should be capable of achieving the target cleanup levels at the rated throughput capacity.

The last step in the development process is construction of the final treatment plant. Since the semiworks plant represents the first full-scale production model for the remediation site, it is possible that, with modifications and adjustments to provide the design changes developed from study of the semiworks plant, the semiworks plant could be converted into the final treatment plant. With this step a successful remediation study is complete and cleanup can begin.

3. Pilot plant

3.1. Background

Over 300 000 cubic yards of soil contaminated with radionuclides were located at a large Superfund site in New Jersey [13,14]. Radium-226 was the most significant contaminant, although thorium-230 was also present. More than 1600 people were affected in varying degrees by elevated levels of gamma radiation and radon-222, the gaseous decay product of radium-226. The initial cost estimate for excavation, transportation, and disposal at a waste site ranged from US$150 000 000 to US$300 000 000. Besides the high cost of this remediation option, legislation had made the consideration of alternate remediation technologies necessary, since the Superfund Amendments and Reauthorization Act (SARA) of 1986 had mandated, where practical, the use of technologies that would reduce the volume or toxicity of wastes. Treatment over disposal was also preferred in the legislation. As a result, a decision was made to study the contaminated soil and pursue a physical and/or chemical treatment plan if it proved to be viable. Ultimately, a pilot plant was designed, constructed, and tested with soil samples from the original Superfund site. The design was further refined and awaits thorough testing with contaminated soil samples from a FUSRAP (Formerly Utilized Site Remedial Action Program) site.

3.2. Characterization and treatability studies

Mineral studies indicated that the contaminants in the soil from the Superfund site were present as insoluble radiobarite [$Ba(Ra)SO_4$], radium and thorium bearing amorphous silica coated on sand, silt, and clay particles, incompletely processed uranium ore, and other radiominerals associated with the native soil and ferruginous slag [15]. Representative soil samples from the site were further characterized according to particle-size and radionuclide distribution. Water-insoluble forms of radium-226 were distributed primarily in the small-sized soil fractions, suggesting that the soil might be physically separated into: (1) a larger-sized particle fraction below the clean-up criteria of 15 pCi/g, representing approximately half the volume of contaminated soil, and (2) a smaller-sized particle fraction with a radionuclide concentration that exceeded the clean-up criteria [2]. A 5/15 pCi/g above background radium-226 concentration criterion, with specific distribution requirements for treated soil around buildings and at given soil depths, was adopted in the Record of Decision (ROD) for the site. Bench-scale treatment studies revealed that these fractions could be separated and collected using a series of soil pretreatment [9], hydroclassification [16], screening [9,16], and clarification and filtration methods employed by the mining industry [17,18]. Soil pretreatment with vigorous wash conditions proved to be successful in liberating small surface particles from larger ones and breaking up aggregates of particles without generating excessive fines [9]. Particle separation could be achieved by either screening or hydroclassification [16]. A recycling process would regenerate the process water for reuse in the washing process, since the contaminants were essentially insoluble in water [16,17]. Flocculating agents were selected that would rapidly aggregate suspended fine soil particles, permitting their removal by sedimentation and filtration [2,16,17]. The water met disposal criteria at the end of the treatment process and could be disposed in a sanitary sewer.

Since characterization studies had revealed the presence of ferromagnetic minerals with elevated radionuclide concentration, magnetic separation was examined as a potential volume reduction technology. Radioactivity of the soil was not significantly reduced with the removal of magnetically susceptible particles [17].

Density separation processes were found to be of insignificant benefit, primarily because heavy radiominerals were less than 0.5% of any size fraction [15,17]. In addition, the very small particle size of the predominant heavy (dense) radiomineral, radiobarite, did not cause it to interfere with separation from larger, less radioactive particles by hydroclassification processes, which depend primarily on particle size differences for separation [16].

3.3. Plant design and testing

The pilot plant design was based on the physical properties determined from the characterization and treatability studies. A representative soil sample containing low levels of radium-226 (10 pCi/g) for test purposes was loaded into a hopper/grizzly and transferred by a belt conveyer for pretreatment into a trommel screen that provided vigorous washing [19]. Additional scrubbing was accomplished on various process streams by attrition mills. The trommel screen, two spiral classifiers, and two hydrocyclones provided particle sizing. Process water was recycled by mixing with a flocculant and settling the aggregated fines in a plate clarifier for collection by a filter press.

The pilot plant significantly reduced the volume of contaminated soil, producing four product streams. One gravel and two sand products had a combined concentration of radium-226 of 5 pCi/g above background [19]. The remediated products represented

35% of the representative whole soil. However, several flow imbalances and operational problems indicated that modifications would be necessary for continuous optimal operation over long periods of time. The required modifications were made to the plant before the next round of testing [2]. The belt conveyer was replaced by a screw conveyer, a vibrating screen was added to make a 200-mesh cut to one process stream, a feed sump was added to one cyclone system to provide water balance to the overall process, a refined polymer injection system was installed for improved control over flocculating agent injection, and the plant process water system was modified to provide more balanced and precise operation of the system. The plant flow diagram is illustrated in Fig. 1 [2,18].

Soil was placed in the hopper/grizzly that separates rocks larger than 2 in. (+2 in.) that are washed with a stream of water. The soil fraction with particles less than 2 in. (−2 in.) was conveyed up the scrubber/trommel where the soil was washed with tumbling and water from high-pressure nozzles. The +1/4 in. particles were collected at the front of the trommel on a 1/4 in. screen and washed again with a spray of water; the −1/4 in. particles passed through the screen into the primary screw classifier where a preliminary 60-mesh (250 μ) cut was made. The +60 material was passed to an attrition mill for additional scrubbing and then to the secondary screw classifier for a 140-mesh (105 μ) cut. Both the −60-mesh overflow material from the primary screw classifier and the −140-mesh overflow material from the secondary classifier were transferred to the cyclone feed sump. The slurry in the feed sump was fed to the

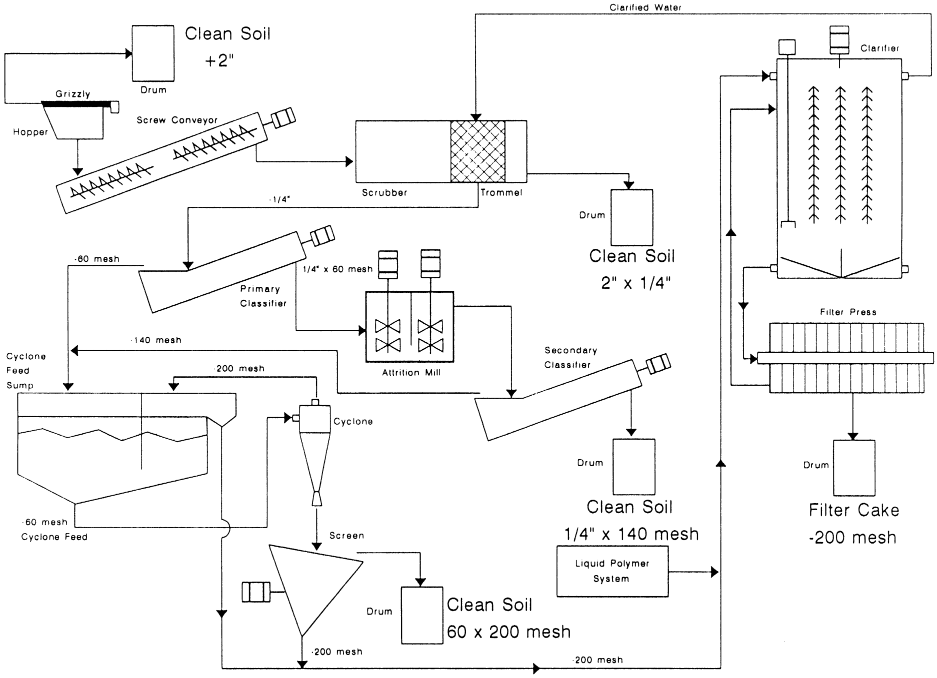

Fig. 1. Modified pilot plant flow diagram. Reproduced with permission from Ref. [18] Copyright © 1993 John Wiley & Sons, Inc.

hydrocyclone, which made a 200-mesh (74 μ) cut. The +200-mesh material fed to the vibrating screen for a sharper cut at 200 mesh, while the −200-mesh particles were recycled to the feed sump. The +200-mesh material from the screen was collected, and the −200-mesh material was mixed with flocculating agent and pumped to the clarifier where the fines settled from the water. The settled fines were removed by a pressure filter, while the wash water was recycled into the primary water feed tank.

The modified pilot plant was tested, first with representative ‘clean’ soil from the area of the Superfund site, and then with 10 and 40 pCi/g soils from the site. The plant was run at 800 pounds/h. The five product streams from the test with 40 pCi/g soil are presented in Table 1 [2,18].

The results presented in Table 1 demonstrate that the pilot plant produced four product streams that in combination had a radium-226 concentration of less than 15 pCi/g, based on dry weight, and that these products represented over half the soil material produced by the plant. The remediated products were not dry after collection; however, they would not have been dry had they been returned to the natural environment of the site. If one assumes that the average percent solids of the products in their natural state would be 90%, then the process represents recovery of 50% of the product stream as remediated material:

$$\text{Avg.\,\%\,Solids of Dry Remediated Soil} = \text{Dry\%Remediated}/\text{Wet\,\%\,Remediated} \times 100\%$$

or

$$45\%/57\% \times 100\% = 79\%$$

$$\text{Percent Recovery @ 90\% Solids} = \text{Wet Wgt.\% of Remediated Product} \times (\text{\%Solids of Dry Material}/\text{\%Solids@90\%})$$

or

$$57\% \times 79\%/90\% = 50\%$$

The radium-226 concentration of the treated material would not be 15 pCi/gdry, but about 12 pCi/gwet, where ‘wet’ means 90% solids:

$$(45\%\,\text{gdry} \times 13\,\text{pCi/gdry})/50\%\,\text{gwet} = 12\,\text{pCi/gwet}$$

The −200-mesh product is the material that would require disposal, according to the 5/15 pCi/g clean-up criterion, and it consists of half or less of the treated soil. If

Table 1
Results of testing the modified pilot plant

Product stream	Wet wt.%	% Solids	Dry wt.%	Normalized dry wt.%	Ra-226 (pCi/gdry)
+2 in.	11	99	11	15	6
2×1/4 in.	17	69	12	16	18
1/4 in.×140 mesh	18	80	14	19	9
60×200 mesh	*11*	74	*8*	*11*	*17*
Total	57		45	61	13[a]
−200 mesh	*43*	69	*30*	*40*	45[b]
Total	100		75	101	

[a] Average specific activity of the above product streams combined.
[b] Activity is low since some 10 pCi/g test soil was in the feed system at the start of the test.

treatment is performed at a cost that is significantly lower than that of transportation and disposal, then treatment represents considerable saving for the remediation project. In addition, a large part of the water could be removed from the -200-mesh product, reducing the weight and volume of material that would require transportation and disposal. Drying the product to 90% solids would reduce its weight by 23%, almost a quarter of the original weight:

$$[\text{Wet Wgt\%} - (\text{Wet wgt\%} \times \text{\%Solids Wet}/\text{Solids@90\%})]/\text{Wet Wgt\%} \times 100\%$$

or

$$[43\% - (43\% \times 69\%/90\%)]/43\% \times 100\% = 23\%$$

Additional modifications of the pilot plant were initiated when the project was expanded to include contaminated soils from additional Superfund sites and from FUSRAP sites [3]. The modifications were designed to improve overall performance of the process as they applied not only to the previously-tested New Jersey soils, but to the characteristics of the FUSRAP soils as well. The modifications were also made after evaluation of the tests on the New Jersey soils to overcome deficiencies in the plant feed and materials conveyance systems and the vigorous washing system, and to increase the feed input rate to the plant.

The major operational problem with the pilot plant was feeding the whole soil into the plant. The physical properties of whole soil can vary widely during operation, and large rocks and other material can interfere with steady and balanced input of material through blockages and bindings. To address the problem, the screw conveyor was replaced with a drag-conveyor unit.

The trommel screen was modified to provide additional washing to remove the small amount of fine particles found still clinging to the $+1/4$-in. product stream. These small particles add a surprising amount of radioactivity to the final product. A tapered discharge was added to the end of the trommel screen to restrict the flow of material discharging from the unit, resulting in additional wash time for the material. The taper was also fitted with screw-type lifter bars to remove coarse particles from the end of the mill. Finally, a variable speed drive was added to the trommel to allow adjustment of the rotational speed for optimal washing, providing a cascading action instead of a tumbling action. Flow inconsistencies and sanding problems at several locations in the plant were also addressed by providing screw conveyors and a lauder system in place of pumping systems.

Finally, a series of computer simulations [3] of the operation of the screw classifiers and the hydrocyclones based on data from the previous pilot plant tests indicated that both units were short-circuiting a significant quantity of fine feed material to the oversize product. The fine material represented significant product contamination, since most of the radionuclide activity of the FUSRAP soils was in the fine material. To improve separation and ensure a higher quality of clean product, a hydraulic classifier, designed to provide a sharp particle-size cut, was added after the hydrocyclone, providing a more select feed into the secondary classifier and the vibrating screen.

This model of the pilot plant is presently in the FUSRAP testing program. All tests performed to date indicate that the process shows promise as a treatment alternative to disposal alone, but data on large soil volumes are not available to assess its performance [20].

4. Economic evaluation

Economic considerations play a crucial role in determining the applicability of soil washing to site remediation (see Section 2.3, Conceptual process design). Regardless of the ability of a process or plant to reduce the volume of contaminated soil and meet the cleanup criteria, the operation must be competitive with alternate remedies, including complete excavation and disposal, the most common proposed remedy to date. To provide insight into how soil washing competes with excavation and disposal, a conservative economic analysis was performed on a proposed plant with operating parameters similar to those of the pilot plant tested and described above. Several aspects of the analysis were then examined that revealed the competitive nature of successful soil washing.

The economic analysis included an evaluation of: (1) the treatability study, (2) the capital expenditure; (3) production rate, project duration, and operating cost; (4) direct and indirect costs; and (5) overhead for treating 300 000 cubic yards of contaminated soil at 50 tph to reduce the volume requiring disposal by 50%. The treatability study was conservatively estimated to cost US$500 000, and the capital investment was US$1 500 000, including engineering fee and installation.

Production was estimated to be two 8-h shifts/day, 5 days/week, and 4 weeks/month for a total of 320 h/month. The project duration was based on 70% availability to allow for start-up and shutdown time, maintenance, and repair. Using a soil density of 106 lbs/ft^3, 300 000 cubic yards of soil has a weight of 429,300 tons (1.43 ton/yd^3), which would require 38 months to treat. Note that running a more typical industrial production schedule of 3 shifts/day and 7 days/week would reduce the treatment time considerably to 17 months. Operating cost included:

Direct costs (labor, utilities, supplies, expendables)	US$97 880/month
Indirect costs (security, maintenance, additional expendables)	US$38 500/month
Overhead (administration, field office, clerical, lab analyses)	US$27 500/month
Total	US$163 880/month

or US$6 227 440 for the treatment period of 38 months. The actual treatment cost would be US$20.76/yd^3.

Excavation, backfill, transportation, and disposal costs were:

Excavation	US$15/ton	US$21/yd^3
Backfill	9/ton	13/yd^3
Transportation	120/ton	172/yd^3
Disposal	156/ton	223/yd^3
	US$300/ton	US$429/yd^3

The cost per yard^3 was calculated from the cost per ton [12] by multiplying the cost per ton by 1.43 tons/yd^3.

The net savings using soil washing as compared to the cost of complete excavation and disposal was calculated from the total cost of soil washing at a 50% recovery of soil in this example (resulting in a concomitant 50% disposal requirement). The disposal option was based on expenditures for excavation, backfill, transportation, and disposal of 100% of the contaminated soil at 429/yd^3:

Disposal (100%)	300 000 yard^3 × US\$429/yd^3	US\$128 700 000
The treatment option includes:		
Treatability Study		US\$500 000
Capital Expenditure		US\$1 500 000
Operating Cost for 38 Months		US\$6 227 440
50% Excavation Only	150 000 yd^3 × US\$21/yd^3	US\$3 150 000
50% Disposal	150 000 yd^3 × US\$429/yd^3	US\$64 350 000
Total		US\$75 727 440
Net savings with treatment:		
Disposal		US\$128 700 000
Less Treatment		US\$75 727 440
Net Savings		US\$52 972 560

Treatment costs are 58.8% of the cost of disposal only. The actual treatment is US\$252/yd^3 compared to disposal with backfill cost of US\$429/yd^3, or US\$177/yd^3 less than the cost of the disposal option.

It is instructive to examine three calculations to illustrate the economic value of successful soil washing. In one calculation the cost of the disposal option is calculated under the conditions where the treatment option and the disposal option are equal in cost, that is, they break even and there is no net savings because the excavation, transportation, and disposal cost is low enough to equal the cost of treatment. Letting x equal the cost of the disposal option per yard^3 in an example where there is a 50% recovery of remediated soil in the treatment option (50% for disposal), the calculation is:

$$\text{Cost of Disposal Option} = \text{Cost of Treatment Option}$$

$$\begin{aligned}\text{Disposal} = {} & \text{Treatability Study} + \text{Capital Expenditure} + \text{Operating Cost}\\ & + \text{ExcavationOnly} + \text{Disposal}\end{aligned}$$

$$\begin{aligned}\left(300\,000\,\text{yd}^3\right)x = {} & +\text{US\$}500\,000 + \text{US\$}1\,500\,000 + \text{US\$}6\,227\,440\\ & + \text{US\$}3\,150\,000 + \left[0.50\left(300\,000\,\text{yd}^3\right)x\right]\end{aligned}$$

$$x = \text{US\$}76/\text{yd}^3$$

The disposal option would have to be very low (US\$76/yd^3) to break even, lower than any disposal option to date.

The calculation can be repeated in an example where the cost of the disposal option is equal to a treatment option in which the percent recovery of remediated soil is only 30% (70% must be disposed), a less advantageous recovery for the plant operation.

The equation is:

$$\begin{aligned}(300\,000\,\mathrm{yd}^3)\,x = {} & \mathrm{US\$500\,000} + \mathrm{US\$1\,500\,000} + \mathrm{US\$6\,227\,440} + 3\,150\,000 \\ & + \left[0.70(300\,000\,\mathrm{yd}^3)\,x\right]\end{aligned}$$

$$x = US\$126/\mathrm{yd}^3$$

The cost of the disposal option in this break-even comparison is more if recovery of remediated soil during treatment is less, but the treatment option is still very competitive unless the disposal option cost is near this low amount.

In the last calculation, the minimum percent recovery is calculated assuming a break-even point between the treatment option and disposal option using a disposal cost of US\$429/yd^3. Let x equal the fraction recovery of remediated soil, then $1-x$ represents the smallest fraction of soil that will require disposal. Multiplying the fraction by 100% will produce the percent value. The equation is:

$$\begin{aligned}(300\,000\,\mathrm{yd}^3)(\mathrm{US\$429/yd}^3) = {} & \mathrm{US\$500\,000} + \mathrm{US\$1\,500\,000} + \mathrm{US\$6\,227\,440} \\ & + \mathrm{US\$3\,150\,000} + \left[(1-x)(300\,000\,\mathrm{yd}^3)\right. \\ & \left.\times(\mathrm{US\$429/yd}^3)\right]\end{aligned}$$

$$x = 0.088$$
$$x = 0.088 \times 100\%$$
$$x = 8.8\%$$

Therefore, only 8.8% of the contaminated soil is the percentage of remediated soil that must be recovered in order for the treatment process to be economically competitive with the disposal option. These examples illustrate how economically competitive successful treatment can be. It also illustrates that, even in the event that disposal cost decreases or treatment cost increases, treatment is an option that should be considered from an economic point of view in any remedy investigation. Considering the high cost of disposal and the potential savings that could accrue from a successful treatment option, the cost of a thorough remedy study is comparatively very small, suggesting that the study should be performed under virtually any site conditions. Naturally, as we learn more about the behavior of contaminated soil fractions under mineral processing conditions, the effort and cost of the studies are expected to decline. Until then the cost of a treatment study, approximately US\$500 000, is only a small fraction of the total cost of the final remedy option selected, less than one-half percent in the case of the disposal option and slightly less than three-quarters percent in the case of soil washing as the remedy option.

5. Conclusions

Soil washing using mineral processing technology can be the most competitive, cost effective option for soil remediation at certain sites contaminated by radionuclides.

Before soil washing or any remedy option can be selected, a study is necessary to determine the characteristics of the contaminants and soil matrix and their relationship to volume reduction. The savings that might be realized from successful soil washing in lieu of alternate remediation schemes and the relative small investment for a remedy study compared to the overall cost of remediation strongly indicate that a study should be part of any site remediation program. The study should use a tiered approach to reveal the properties of the soil that can be exploited to reduce the volume of contaminated material. It includes site and soil characterization to determine the basic mineral properties of the soil and contaminants and their relationship, treatment studies to evaluate the performance of process units for contaminant separation, conceptual process design studies to provide a plan for a treatment plant and, if called for, engineering design to construct, test, and optimize the actual treatment plant. A pilot plant was designed, constructed, and tested with soil volumes containing radium-226. The plant produced a final remediated product that represented approximately 50% of the contaminated soil. Additional modifications were made to improve the overall performance of the process and to permit use of the plant on contaminated soil from an alternate site. All tests to date indicate that the process shows promise as a treatment alternative to disposal alone, but data on large soil volumes are not available to assess its performance completely.

An economic evaluation of successful soil washing reveals that it is very competitive for site remediation, potentially saving almost half the cost of exclusive excavation, transportation, and disposal. Even with a very low cost for disposal or, alternatively, a low recovery of remediated product, the technology is very competitive with disposal. This characteristic of soil washing demonstrates that it should be given serious consideration as a treatment option and that a thorough remedy study should be performed to asses its application.

References

[1] W.S. Richardson, C.R. Phillips, G.H. Luttrell, C. Cox, The Design and Conduct of Meaningful Soil Characterization and Treatability Studies Based on a Knowledge of Mineral Processing Technology, WM ’97 Conference Proceedings, CD-ROM Article 46-02, WM Symposia, Tucson, AZ, 1997.

[2] W.S. Richardson, C.R. Phillips, C. Cox, M.C. Eagle, A Pilot Plant for the Remediation of Radioactively Contaminated Soils Using Particle-Size Separation Technology, Proceedings of the ER ’93 Conference, Vol. I, Office of Environmental Restoration, U.S. Department of Energy, Washington, DC, 1994, pp. 133–136.

[3] R.T. Burchett, C.R. Phillips, W.S. Richardson, III, G. Luttrell, M. Mankosa, C. Cox, V.D. Lloyd, Conceptual Retrofit Design for a Pilot Plant to Treat Radionuclide Contaminated Soils, WM ’95 Conference Proceedings, CD-ROM Article 27-12, WM Symposia, Tucson, AZ, 1995.

[4] D. Gombert, J.B. Bosley, Soil Washing and Radioactive Contamination, presented at: Spectrum ’92 Nuclear and Hazardous Waste Management International Topical Meeting, Boise, ID, 1992.

[5] D. Gombert, Evaluation of Soil Washing for Radiologically Contaminated Soils, Report No. WINCO-1211, Westinghouse Idaho Nuclear, Idaho Falls, ID, 1994, pp. 7–11.

[6] D.L. Sparks, in: H.E. Allen, C.P. Huang, G.W. Bailey, A.R. Bowers (Eds.), Metal Speciation and Contamination of Soil, Lewis Publishers of CRC Press, Boca Raton, FL, 1995, pp. 36–37.

[7] J.M. Douglas, Conceptual Design of Chemical Processes, McGraw-Hill, New York, 1988.

[8] J.M. Douglas, G. Stephanopoulos, Hierarchical Approaches in Conceptual Process Design: Framework and Computer Aided Implementation, Fourth International Conference on Foundations of Computer-Aided Process Design, AIChE Symposium Series, No. 304, 1995, pp. 183–197.
[9] W.S. Richardson, T.B. Hudson, J.G. Woods, C.R. Phillips, Characterization and Washing Studies on Radionuclide Contaminated Soils, Superfund ’89: Proceedings of the 10th National Conference, the Hazardous Materials Control Institute, Silver Springs, MD, 1989, pp. 198–201.
[10] B.A. Wills, Mineral Processing Technology, 4th edn., Pergamon, Oxford, 1988, pp. 715–719.
[11] S. Rosenblum, Magnetic Susceptibilities of Mineral in the Franzz Isodynamic Magnetic Separator, American Mineralogist, 43, 1958.
[12] C.R. Phillips, G.H. Luttrell, R.T. Burchett, J. Stinson, W.S. Richardson, Characterization and Treatability Studies of Subsurface Soil Samples from the Maywood FUSRAP Site, S. Cohen and Associates, McLean, VA, for Science Applications International (SAIC), Oak Ridge, TN, April 18, 1997.
[13] Remedial Investigation Study for the Montclair/West Orange and Glen Ridge, New Jersey Radium Sites, Vol. I, Camp Dresser and McKee, Roy F. Weston, Clement Associates, ICF, U.S. Environmental Protection Agency Contract No. 68-01-6939, New York, September, 1985.
[14] Appendices for Remedial Investigation Study for the Montclair/West Orange and Glen Ridge, New Jersey radium Sites, Vol. II, Camp Dresser and McKee, Roy F. Weston, Clement Associates, ICF, U.S. Environmental Protection Agency Contract No. 68-01-6939, New York, September, 1985.
[15] J. Neiheisel, Characterization of Contaminated Soil from the Montclair/Glen Ridge, New Jersey Superfund Sites, EPA/520/1-89-012, Office of Radiation Programs, U.S. Environmental Protection Agency, Washington, DC, September, 1989.
[16] S. Hay, C. Cox, W. Richardson, J. Stinson, C. DuBose, Comparison of Wet Sieving to Vertical Column Hydroclassification for Soil Particle Sizing, U.S. Public Health Professional Association Annual Meeting, Atlanta, GA, May 27, 1991.
[17] W.S. Richardson, T.B. Hudson, D.A. Chambless, S.S. Hay, R.A. Liebermann, Superfund VORCE (Volume Reduction/Chemical Extraction) Technology Enhancement Study, S. Cohen and Associates, McLean, VA and Versar, EPA Contract No. 68-W9-0068, U.S. Environmental Protection Agency, Washington, DC, December, 1990.
[18] M.C. Eagle, W.S. Richardson, S.S. Hay, C. Cox, Remediation, Summer, 1993, p. 327.
[19] W.S. Richardson (Ed.), VORCE Pilot Plant I Test, S. Cohen and Associates, McLean, VA, EPA Contract No. 68-D9-0170, U.S. Environmental Protection Agency, Washington, DC, February, 1992.
[20] R. Anderson, M. Ryan, J. Hart, Pilot Plant Scale Testing of Soil Washing on Low Level Radioactively Contaminated Soils, WM ’96 Conference Proceedings, CD-ROM Article 44-5, WM Symposia, Tucson, AZ, 1996.