ELECTRODE-ASSISTED SOIL WASHING

by

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ABSTRACT

Soil contamination has become a serious problem and has attracted much attention in the United States. In most cases the necessity to clean contaminated soil arises from a threat to our underground drinking water supply. There are many alternatives to solving this problem. One of the most viable alternatives for cleaning contaminated soil is Soil Washing. The state-of-the-art soil washing technologies are effective in cleaning large-grained soils (sands and coarse silts), but are ineffective with fine-grained soils (fine silts and flocculated clays). Usually, for successful soil washing, the soil should contain less than 25% of clays and silts.

An innovative soil washing technology has been experimentally demonstrated, at the Chemical Engineering Department of the Texas Tech University, to clean contaminated soils that contain a very high percentage of fines (silts and flocculated clays). This technology is called the Electrode Assisted Soil Washing (EASW) technology. The laboratory scale EASW device has proved successful in washing contaminated soils carrying a greater percentage of fine silts and clays.

The primary contaminants used to test the EASW device are a straight-run diesel fraction from the Fina refinery at Big Spring, Texas, and 26.2 API crude oil. The soil, these contaminants were tested on, is Lubbock top soil. To further strengthen the credibility of the EASW technology, authentic

contaminated soils from the "real world" were washed successfully. Soils from the Gulf Coast and from an old petroleum product loading terminal in New Jersey were washed to below 100 ppm of the contaminant on the soil.

A formal patent search has been made regarding the EASW process and no prior art was found. On this basis, a formal patent application has been filed and is pending, for the invention of the EASW process.

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CHAPTER I

INTRODUCTION

Soil contamination has become a serious problem and has attracted much attention in the United States. Hazardous wastes that were dumped in the landfills have leached through the soil into the groundwater (a major drinking water source). The number of contaminated sites requiring urgent attention in Canada and the United States is increasing which calls for efficient and cost effective treatment methods. Treatment of contaminated soil utilizing soil washing is used extensively in Europe and has become important in the United States only in the recent years.

1.1 Background

Effective treatment methods for the cleanup of contaminated sites are greatly facilitated by separation of inert and innocuous materials (such as soil) from the waste, prior to destruction or recovery of the hazardous or toxic material. These separations are frequently achieved by processes involving:

- (1) Soil Washing and
- (2) Solvent Extraction.

Soil washing is rather economical when compared with solvent extraction.

1.2. Soil washing

Soil washing is a water-based process for mechanically scrubbing soils ex-situ to remove undesirable contaminants. The process removes contaminants from soils in one of two ways: by dissolving or suspending the contaminants in the wash solution (which is later treated by conventional wastewater treatment methods) or by concentrating them into a smaller volume of soil through simple particle size separation techniques (similar to those used in sand and gravel operations). Soil washing systems incorporating both removal techniques offer the greatest promise for application to soils contaminated with a wide variety of heavy metal and organic contaminants.

1.2.1. Volume reduction in contaminated soil

The concept of reducing soil contamination through the use of particle size separation is based on the finding that most organic and inorganic contaminants tend to bind, either chemically or physically, to clay and silt soil particles. The silt and clay, in turn, are attached to sand and gravel particles by physical processes, primarily compaction and adhesion. Washing processes that separate the fine (small) clay and silt particles from the coarser sand and gravel soil particles effectively separate and concentrate the contaminants into a small volume of soil that can be further treated or disposed. The clean, larger fraction can be

returned to the site for continued use. This set of assumptions forms the basis for the volume reduction concept upon which most soil washing technologies are being developed.

Soil washing is a particularly effective and economical means of separating the inert material from the soil, since it does not require solvents which must be recovered efficiently, and which may be flammable and/or toxic. The soil washing process frequently employs hardware and technologies drawn from the mining and oil well drilling industries. State-of-the-art soil washing processes are effective for removing both heavy metals and organic materials from large grained soils (sands and coarse silts), but are ineffective in the treatment of fine-grained soils (fine silts and flocculated clays). One reference states that for successful soil washing, the soil should contain less than 25% of clays and silts.¹

1.3. Objective of research

The overall objective of this Electrode Assisted Soil Washing (EASW) research was to experimentally demonstrate an innovative soil washing procedure to remove contaminants from soils containing a higher percentage of fine silts and clays because the state-of-the-art technologies addressed the contamination problem in large-grained soils (sand & coarse silt) effectively, but failed considerably with fine-grained

soils that contained a very high percentage of fine silt and clays.

1.3.1. Development of the EASW process

A novel soil washing process has been experimentally demonstrated by the author, a research associate, and his advisor, a professor in the Chemical Engineering Department at Texas Tech University, to remediate contaminated sites having a greater percentage of fines (silt and flocculated clays) in their soils. This new soil washing procedure has been called the Electrode Assisted Soil Washing (EASW) process. The new soil washing process can be utilized either as a stand-alone process or it can be applied to the "contaminated fines stream" produced by conventional soil washing processes. Presently, this "contaminated fines stream" from a conventional soil washing process must be placed in a permitted landfill, or further treated by an expensive process such as incineration.

The primary contaminant targeted in this research was organics (chiefly petrohydrocarbons). The soil used in most of the experimental runs was Lubbock top soil. Authentic contaminated soils from Gulf Coast, and an old petroleum product loading terminal in New Jersey have also been successfully washed. The contaminants present in these authentic soils were reported to be very difficult to biodegrade.

Toxic Environmental Control Systems (TECS), a regional firm, has funded this research over the past two and a half years.

CHAPTER II

FUNDAMENTALS OF SOIL WASHING

Soil washing is a physical/chemical separation technology in which excavated soil is screened to remove large objects and soil clods and then washed with fluids to remove contaminants. To be effective, soil washing must either transfer the contaminants to the wash fluids or concentrate the contaminants in a fraction of the original volume, using size separation techniques.² In either case, soil washing must be used in conjunction with other treatment technologies. Either the washing fluid or the fraction of soil containing most of the contaminant, or both, must be further treated or disposed of in an environmentally acceptable manner.

2.1. Description of a soil washing process²

A schematic diagram of a typical soil washing process is presented in Figure 2.1.² There are three major steps involved in any soil washing process and they are described briefly in the following subsections.

2.1.1. Soil preparation

The first stage in the soil washing process is preparation of the excavated soil. Soil preparation involves mechanical screening of the soil feedstock to remove debris such as rocks, roots, etc. The maximum size of particles

Figure 2.1. Schematic diagram of a typical aqueous soil washing process

allowed in the feedstock varies with the soil washing technology being used. For example, in the EASW device for soil washing, the maximum particle size desired is 1 mm, although it could function with somewhat larger particles.

2.1.2. Soil washing process

The second stage is the soil washing process. Typically, soil washing involves mixing, washing, rinsing, and size separation steps. During mixing, the wash fluid is introduced to the soil in measured proportions. Frequently, the wash fluid is largely water recycled from elsewhere in the process. At some installations, this is a separate step. Other installations combine mixing and washing into one step (as shown in Figure 2.1).

The intimate energetic mixing of the wash fluid with soil constitutes the "washing" step. Intensive contact between the soil grains and the wash fluid causes the soil contaminants to dissolve or become suspended into the water. Energy is introduced into the mixture by high-pressure water jets, vibration devices, and other means, depending upon the equipment.

After the appropriate contact time, treated soil is separated from the wash water. Coarse soil particles are separated with a trammel or vibrating screen device. Fine particles are separated in a sedimentation tank, sometimes with the addition of flocculating agents. Silt is removed in

a hydrocyclone or centrifuge device. The coarse soil fraction is rinsed with clean water to remove residual contaminants and fine soil particles which may still be adhering to coarse particles. The coarse fraction is recovered from the process as clean soil.

2.1.3. Wastewater treatment

The final step processes the blowdown or discharge water to meet regulatory requirements for heavy metal content, organics, total suspended solids, and other parameters. When possible, treated water should always be recycled to the soil washing process. Residual solids, such as spent ion exchange require post-treatment to ensure safe disposal or release.

Vapor treatment may be needed to control air emissions from excavation, feed preparation, and extraction; these emissions are collected and treated, normally by carbon adsorption or incineration, before being released to the atmosphere.

In the actual operation, there are more sidestreams and equipment involved than shown in Figure 2.1. This equipment typically includes feedstock and treated soil conveyors and earthmoving equipment for stockpiling soil. This equipment is, however, ancillary and not critical to understanding the basic soil washing process.

There are four main waste streams generated during soil washing: contaminated solids from the soil washing unit,

wastewater, wastewater treatment sludges and residuals, and air emissions. It is very important that these process residuals are taken care of in an environmentally sound manner.

2.2. Particle size distribution³

The particle size distribution of the soil is a standard physical characterization criteria used. Recent studies indicate that contamination in soils is often distributed as a function of soil particle size. As treatment efficiency is a function of particle size, it is important to study the particle size ranges of the soil that affect the effectiveness of soil washing technologies.

Three particle size ranges have been frequently studied:

- (1) > 2 mm,
- (2) 0.25 mm to 2 mm, and
- (3) < 0.25 mm.

These fractions are obtained from U.S. Standard Sieve Series #10 and #60. Figure 2.2² shows the applicable particle size ranges (in terms of particle diameter in mm) plotted against the sieve throughput percent by weight.

2.2.1. Range I--Economic soil wash regime

Range I consists of coarse soils. Soils in Range I are economically washed with a simple particle size separation. This process is used to concentrate contaminants in the finer

Figure 2.2. Ranges of soil washing difficulty

particles of the soil. When fractionation does not occur, as is the case with lead, there is no improvement in the economics of separation expected from a Range I soil.

Soils in the area to the right of Range I are primarily stone and large gravel. Particle size separation is normally not needed for these materials. However, soluble contaminants may be removed from such soils in the wash water.

2.2.2. Range II--Soil wash with specific fluid

The types of contaminants present in the matrix will govern the composition of wash fluids and affect the overall process efficiency. Process efficiency is also affected by soil particle distribution patterns and the fractionation of contaminants in fine particles. Both particle size separation and contaminant solubilization can be important for cost-effective treatment of soils in Range II.

2.2.3. Range III--Difficult soil washing regime

Soils in Range III consist primarily of finer sand, silt and clay fractions. Soils with high humic content, tend to contain strongly adsorbed organics that generally do not respond favorably to systems that work by only dissolving or suspending contaminants in the wash solution. However, they may respond to soil washing systems that also incorporate a particle size separation step whereby contaminants can be concentrated into a smaller volume. The state-of-the-art

technologies, which usually work by only dissolving or suspending contaminants, find it difficult to clean Range III soils. This Range III soil regime is the prime target of the EASW research.

2.3. Soil contaminant interactions and chemistry⁴

Soil fractions are identified and categorized by classification schemes that loosely correlate particle size range and mineralogical type, class, and origin. There are seven such classification schemes used in the United States. They isolate from three to seven respective groups. However, for behavioral grouping four are sufficient: sand, silt, clay and humus.

2.3.1. Sand fraction

Sand is essentially composed of free silicon dioxide, and constitutes about 12 percent of the earth's crust. It can also contain other minerals such as feldspar, limestone, etc. Silicon dioxide occurs in three crystalline forms, quartz, tridymite, and cristobalite, each of which have a number of modifications. Quartz is the stable allotrope at room temperature. Silicon dioxide is highly stable and chemically unreactive as evidenced by its high heat of formation (200 kcal/kgmole) and low Cation Exchange Capacity (CEC) of 2 to 7 meq/100 grams. That compares to CECs in the range of 80 to 200 meq/100 grams for chemically active clays.

Bonding of hydrophobic organics to sand particles is essentially by Van der Waal's physical forces. The larger the organic molecule, the greater the propensity for Van der Waal adsorption. This is due to the multiplicity of their Van der Waal attachments with the substrate (because of their molecular size). The Van der Waal bonding forces are particularly amenable to rupture by surfactants.

2.3.2. Silt fraction

Silt is essentially composed of equidimensional quartz particles derived from weathering and disintegration of igneous rock minerals. In addition to quartz, this fraction contains significant quantities of oxides of aluminum, iron, magnesium, and calcium. These metal oxides/hydroxide constituents give this fraction the capacity for hydrogen bonding to organic molecules. Hydrogen bonding can be a significant attachment force when large organic molecules such as polymers are involved. This is due to the fact that as the number of hydrogen bonds between each functional group and the surface increases, the extent of adsorption of the large organic molecule also increases.

In summary, attachment of organic molecules to silt will be by:

1. Van der Waal forces to inert mineral surfaces; and
2. Hydrogen bonding to metal oxide/hydroxide surfaces

In the cleaning process, Van der Waal attachments are

rupted by surfactant action, and hydrogen bonding attachments are attenuated by adjusting the bath pH.

2.3.3. Clay fraction

The term "clay" refers to mineral sediments having individual particles with dimensions of 2 microns or less. However, these may be tenaciously aggregated into multimicron-size agglomerates depending on their history of environmental exposure to heat and drying.

Clay minerals are chiefly composed of magnesium and aluminum silicates with a layered crystalline structure. The layered silicate crystals are formed by stacking a number of composite layers. These are often interspersed with layers of hydrated metal cations that compensate for charge discrepancies caused by structural defects in the silicate layer. Due to differences in geological history, clay mineral structures can be either highly reactive or essentially inert.

Organic compounds react with clay minerals in a descending order of propensity:

1. Positively charged organic radicals - displace exchangeable cation in clay.
2. Uncharged polar organics - replace water of hydration in clay structure.
3. Uncharged nonpolar organics - form only external surface Van der Waal attachments.
4. Negatively charged organic radicals - repelled and

minimally sorbed (particularly at edges of clay plates which are positively charged).

The first two categories include most organic compounds on the EPA Priority Pollutants and Acutely Hazardous Substances list. The aliphatics comprise the third category. Aliphatics are found to form only physical Van der Waal attachments to external surfaces and consequently can be removed by surfactant action. The first two categories, which form chemically bound clay-contaminant complexes, are immune to surfactant action. Consequently they cannot be removed by this means.

2.3.4. Humus fraction

Biological degradation and transformation of vegetable matter is the origin of humic substances present in soil. Humus is generally synonymous with "soil organic matter." Soils vary greatly in organic matter content. A typical prairie grassland soil may contain 5 to 6% organic matter in the top 15 cm; a sandy soil less than 1%. Certain specific properties which can be used to identify humus are:

- (1) Humus possesses a dark brown to black color.
- (2) Humus is practically insoluble in water, although a part of it may go into colloidal solution in pure water. Humus dissolves to a large extent in dilute alkali solutions, especially on boiling, giving a dark colored extract; a large part of this extract

precipitates when the alkali solution is neutralized by mineral acids.

- (3) The carbon content of humus is usually about 55 to 56% and frequently reaches 58%.
- (4) Humus contains nitrogen, usually about 3 to 6%.
- (5) Humus also contains the elements carbon and nitrogen in proportions which are close to 10:1.

Humic substances may be described as polymers with molecular weights between 300 and 30,000. While humus is called a soil fraction, it is actually a colloid of organic origin and occurs in soil as a coating or mixture with clay and silt. As for its sorption of organic chemicals, recent research has shown that a number of organic chemicals such as Poly Chlorinated Biphenyls (PCBs), Polynuclear Aromatic Hydrocarbons (PAHs), toluene, cholesterol, and many pesticides bind onto the humic macromolecules, and this makes cleaning the humus fraction very difficult. Usually the humus fraction will be separated with the clay fraction.

2.4. Remediation techniques⁵

Remediation of contaminated soils generally is accomplished by using one or more of 3 types of systems. These systems are:

- (1) In-situ,
- (2) Prepared bed, and
- (3) In-tank reactor.

2.4.1. In-situ systems

An in-situ treatment system consists of treating contaminated soil in place, where the contamination is located, i.e., the contaminated soil is not moved from the ground. Soil flushing, soil vacuum extraction (SVE), neutralization, oxidation, reduction, ion exchange, vitrification, etc., are some examples of in-situ treatment systems.

2.4.2. Prepared bed systems

In a prepared bed system, the contaminated soil may be either:

- (1) physically moved from its original site to a newly prepared area, which has been designed to enhance treatment and/or to prevent transport of contaminants from the site; or
- (2) removed from the site to a storage area while the original location is prepared for use, then returned to the bed, where treatment is accomplished.

Aerobic bioremediation, anaerobic bioremediation, biological seeding, enzyme addition, composting, precipitation, Soil Vacuum Extraction (SVE), etc., are some examples of prepared bed treatment systems currently used in the industry.

2.4.3. In-tank systems

In-tank treatment systems are used for treatment of contaminated soil, where the soil is physically removed and placed in an enclosed reactor based upon batch, complete mix, or plug flow systems commonly used in chemical and environmental engineering systems; the soil may be in an unsaturated or a saturated physical form. Common tank treatment systems include composting, slurry-phase treatment, and solid-phase treatment. Fluidized bed, incineration, solvent extraction, etc., are examples of in-tank systems.

2.5. Fate of hazardous contaminants in soil

The hazardous contaminants in soil can:

- a. migrate upward (volatilization),
- b. migrate downward (leaching),
- c. migrate laterally (aqueous plume and pure product),
- d. biodegrade, and
- e. remain at the site as persistent chemicals.

2.6. Literature pertaining to the EASW process⁶

Literature regarding existing processes for soil washing is relatively abundant. An EPA bulletin² on the subject lists 5 domestic soil washing processes and 14 international processes, some of which have been operated on a commercial scale. This publication, among others, stresses the difficulty in washing soils having a large portion of fine

particles--silts and clays. This problem is the soil washing limitation addressed by the EASW process described later in this thesis. Ronald C. Sims⁵ has published a lengthy critical review of all methods for soil remediation at uncontrolled hazardous waste sites. These publications provide over 150 references concerning remediation of contaminated soil. An EPA supported investigation has compared several soil remediation processes for treatment of a contaminated synthetic soil, and gave soil washing a rather favorable review as follows:

Soil washing was the best metals reduction technique across all the soils, averaging 93 percent. Soils washing was also very effective in reducing the semivolatile compounds (averaging about 87 percent) and the volatiles (99 percent).⁷

One recent paper⁴ has found ultrasonic washing effective for removal of organic contaminants from soil. Their beaker-scale studies showed that ultrasonic cavitation excitation could eliminate or minimize the need for surfactants in soil washing. The EASW process is another method for high energy scrubbing of soil particles.

One of the important factors contributing to the success of the EASW process is the volume boiling phenomenon. Volume boiling must be distinguished from bulk boiling, a regime of boiling for fluids flowing in a externally heated tube, for which there is considerable literature. Information regarding the volume boiling phenomenon has been difficult to locate.

In a similar manner, heterogenous nucleation of steam bubbles on soil particles must be distinguished from homogenous nucleation of bubbles in an uncontaminated fluid.⁸ When these two distinctions were made in searching the literature, no directly useful information on the volume boiling process was found in the recent literature. Some older documents pertain to generation of steam by flow of electricity through water.^{9,10} These documents focused on avoiding a critical current density, above which AC electrolysis of water would occur, resulting in dangerous accumulations of hydrogen. They found that catalytically active metals allowed higher critical current densities, and noted that ordinary carbon steel was unsatisfactory for this purpose. In these older studies, there was no need to distinguish between steam generated on the surface of the electrodes, and steam generated in the volume of the water. This generation of steam in the volume of the water, not on the electrode surface, is an essential feature of the present EASW process.

A formal patent search has been made regarding the EASW process and no prior art was found.¹¹ On this basis, a patent application has been filed and is pending, for the invention of the EASW process.

CHAPTER III

EXPERIMENTAL SETUP

The experimental setup used in the EASW research is described in full detail in the following subsections. This description also includes devices, initially tried in the EASW research, but no longer used in the EASW facility.

3.1 Description of apparatus

The basic device used comprises a container, a pair of electrodes, a temperature probe (an RTD) and a variable-voltage power supply which includes a step-up transformer. Figures 3.1. and 3.2. are photographs of the EASW batch facility used in this research. Detailed drawings of the various components used in the EASW device are shown in Appendix A. These include drawings of the electrodes and electrode support, and the condenser unit. The primary objective in designing the apparatus is to achieve volume boiling (i.e., boiling between the electrodes within the volume of the soil slurry). Several beaker-scale devices were built and tested. The models that were tried have been briefly described.

3.1.1 Model #1

This model utilizes a 1000 ml tall form pyrex beaker to hold the soil slurry to be treated. The electrode pair is

ELECTRODES

RTD

CONDENSER UNIT

MIXER

SOIL SLURRY CONTAINER

Figure 3.1. Photograph of the EASW batch facility.

POWER SWITCH

TEMPERATURE DISPLAY (RTD)

Figure 3.2. Photograph of the variable voltage power supply.

made of brass and is designed as shown in Figure 3.3.⁶ The clearance between the tip of the electrodes is about a quarter of an inch. This design facilitates boiling between the electrodes only to a certain extent. The maximum power that can be supplied, before boiling on the surface of the electrodes dominates over volume boiling, is 1 Kilowatt. At higher power levels arcing is observed to occur on the surface of the electrodes. The reason for this observation is explained in chapter IV, Principle of the VBfSW process.

3.1.2 Model #2

To improve volume boiling between the electrodes, a minor change was made to model #1. The brass electrodes were replaced by a pair of nickel electrodes. These Ni electrodes were expected to be more electrochemically active than the copper electrodes. Except for the material of construction of the electrodes, model #2 is the same as model #1. In this case the maximum power input possible between the electrodes without boiling on the surface of the electrodes was 1.5 Kilowatts.

3.1.3 Model #3--Orifice-type cell

The orifice-type cell (Figure 3.4¹³) has a 1000 ml tall form pyrex beaker which has been divided in half by a vertical partition. At the bottom of the partition is a slot. This slot allows the stirbar to stir the soil slurry, as well as

Cross Section at Level of Electrodes

Figure 3.3. Model #1

Figure 3.4. Model #3--Orifice-type cell

provides a constriction which causes the current to be concentrated in a rather small volume. Much of the electric power supplied to the solution will be released in the vicinity of the hole, because the local power release is proportional to the current density squared and the resistance, and both the factors will be at a maximum near the hole in the partition.

Electrodes having increased surface area, and increased catalytic activity on their surfaces would directly permit higher current densities before polarization resulted in surface boiling. Hence the nickel electrodes of the previous model were replaced with large electrodes (60 by 90 mm) made of Nichrome wire mesh were provided. The slot in the partition was approximately 55 by 15 mm. This resulted in the current density near the slot being 6.5 times of that on the electrodes.

As a result of this improved design power levels of up to 2 kilowatt could be achieved without boiling on the surface of the electrodes.

3.1.4 Model #4

This cell is a slightly modified version of the orifice-type cell. This model was designed chiefly to control the stirring of the soil slurry in the container. This is done by embedding a donut shaped piece, made of polypropylene, on the floor of the beaker to keep the stir bar in place and ensure

effective stirring of the soil slurry. With this design the stable maximum speed of the stir bar achieved is 1300 rpm as against 800 rpm for the orifice-type cell.

3.1.5 Model #5

A 1000 ml beaker was taken and an electrically insulating partition was inserted into the beaker without a slot at the bottom as in the previous models, instead two plastic tubes were inserted in the partition. This model was designed to avoid the use of a stirbar and provide inherent stirring. Boiling was observed to be vigorous inside the plastic tubes but the larger soil particles settled to the bottom and so the stirring provided by this design was considered ineffective.

3.1.6 Model #6

Model #6 is a duplicate of model #4. The only difference is that the glass beaker of model #4 was replaced by a polypropylene beaker to avoid frequent breakage of the beakers.

3.1.7 Model #7

A 1000 ml tall form pyrex beaker is the container for the soil slurry. The electrodes were replaced by a one-sixteenth inch stainless steel tube resistance heater. Figure 3.5 clearly illustrates this design. The aim of this model was to illustrate that volume boiling is the key factor in the EASW

Figure 3.5. Model #7--Stainless steel resistance heater

process. The stainless steel resistance heater used will just provide boiling on the surface of the electrodes, not volume boiling.

3.1.8 Model #8

In this design a pair of titanium electrodes are used with a 1000 ml tall form pyrex beaker to hold the soil slurry. The titanium electrodes were coated with iridium and other precious metal oxides on their surface. The electrodes used in this model are catalytically active. These electrodes are commercially used in several electrochemical processes.

3.1.9 Model #9

Model #9 is the most successful of all the models tried in the EASW research. In all of the previous designs one major problem was the settling of the soil particles at the bottom along the walls of the beaker. To overcome this, the cell of model #9 was designed to have a sloping bottom. Figure 3.6¹³ represents the cell built for this purpose. Unlike the earlier models the container for the soil slurry is made of a 4" thick commercial glass pipe to avoid cracking of the containers. The electrodes are large (60 mm by 90 mm) and made of Nichrome (nickel and chromium in the ratio of 80:20). The electrode used in this model is the same as that used in model #3, and is catalytically more active than the titanium electrodes of model #8. The orifice is designed to be at the

Figure 3.6. Model #9--EASW device

bottom of the container. Soil particles which settle out slide along the tapered bottom of the cell into the rapidly boiling zone, located at the bottom of the container, to be mixed into the slurry. The volume boiling achieved in this model facilitates energetic mixing of the soil slurry which is essential for the intense scrubbing of the contaminated soil particles.

3.2. Description of experimental procedure

The experimental procedure used to wash the contaminated soil involves many steps and a schematic of this soil washing procedure is shown in Figure 3.7. The major steps involved are:

- (1) Preparation of contaminated soil,
- (2) Soil Slurry Preparation,
- (3) Treatment of the Soil Slurry,
- (4) Centrifuging and Washing, and
- (5) Total Petroleum Hydrocarbon (TPH) analysis of the washed soil.

The first step, i.e., the preparation of contaminated soil, does not apply to experimental runs made with authentic soils. The TPH analysis step is used to evaluate the effectiveness of the EASW soil washing technique in removing hydrocarbons from soil. All the major steps involved in the EASW process are explained in full detail in the following subsections.

Figure 3.7. Schematic diagram of the EASW soil washing process

3.2.1. Preparation of contaminated soil

Dry soil (Lubbock top soil) is screened to -0.2 mm using the U.S. Standard Sieves. This soil is selected to have a large fraction of clay and silt. The sieved soil is then mixed with approximately 50,000 ppm of the contaminant. The contaminants used are a straight-run diesel fuel fraction from the Fina refinery at Big Spring, Texas, and a 26.2 API crude oil. An analysis of the diesel fraction used is shown in Table 3.1. The soil and contaminant are thoroughly mixed to form a homogenous mixture. The homogenous mixture is then allowed to stand for about two to three weeks. This is done to simulate an authentic contaminated soil very closely.

Table 3.1. Analysis of the diesel fraction from Fina refinery

Vol % distilled	Temperature F	
I.B	460	API Gravity
10	500	32.8
30	542	
50	560	Weight % S
70	576	1.105
90	596	
E.P	614	

3.2.2. Soil slurry preparation

A known amount of the contaminated soil is weighed and transferred to a one quart mason jar. A fixed amount of a salt (usually 2.0 gms of sodium carbonate) is then added to the contaminated soil. Distilled water (usually 600 ml) is finally added to the 1 quart mason jar containing the contaminated soil and the salt. If a solvent such as toluene is used, then the solvent is mixed with the soil prior to mixing the soil with water. The salt is added for three reasons: to raise the pH, to increase the conductivity of the soil slurry, and to minimize hydration of clays. The soil is dispersed by 30 seconds of stirring in a high-speed mixer. The mixer is an "osterizer"-type used for food preparation. The osterized soil mixture is transferred to the EASW cell for treatment. Initially, mixing was continued by means of a stirbar in the cell at a maximum stable speed of 600 to 1300 rpm. Subsequently, it was found that stirring was not necessary in a properly designed cell. Before treatment pH and conductivity of the soil slurry are usually measured.

3.2.3. Treatment of the soil slurry

After the soil slurry is transferred to the treatment cell a constant power input of 1 kilowatt is usually maintained. Each run typically lasts for about 5 minutes. The soil slurry in the cell is allowed to reach boiling (usually takes about 3 mins). As soon as the soil slurry

reaches boiling, the power input is lowered and usually maintained at 0.5 Kilowatts for about 1 to 2 minutes. This is done to avoid splashing of the soil slurry above the walls of the container, after boiling starts. The treated soil is then transferred to the mason jar and allowed to settle.

3.2.4. Centrifuging and washing

After settling, the water carrying the contaminants is decanted off and the remaining portion of the soil slurry is centrifuged in 50 ml polypropylene centrifuge tubes. This centrifuged soil slurry is then washed with a salt solution of the same concentration that was used before treatment in the preparation of the soil slurry. Usually during centrifuging, about 2 ml of the salt solution is used per 1 gm of the dry soil being washed.

3.2.5. TPH Analysis of the washed soil

The treated soil is analyzed using an EPA Method for Total Petroleum Hydrocarbons Recoverable. In this method 150 ml of freon-113 (1,1,2-trichloro-1,2,2-trifluoroethane) is used to extract any contaminants that are left over in the treated soil. This extraction is carried out in a Soxhlet Extraction Apparatus. The freon-113 extract carrying the contaminants is then analyzed for Total Petroleum Hydrocarbons (TPH) by means of Method 418.1. Beckman Spectrophotometer is used to do the TPH analysis of the extract. Information regarding the method

is furnished in Appendix B. From the peak heights of the standards run on the spectrophotometer, the amount of contaminants leftover, in parts per million (ppm), in the treated soil can be found. For information regarding the standards used please refer to Appendix B.

CHAPTER IV

PRINCIPLE OF THE VBfSW PROCESS

The acronym, VBfSW stands for "Volume Boiling for Soil Washing." Volume boiling of a soil slurry in the vicinity of a small orifice is the essence of the EASW process to wash contaminants from difficult to wash soils. The concept of volume boiling involved in the EASW process is described below.

4.1 Volume boiling

To comprehend the concept of volume boiling, it is imperative to first understand the phenomenon of boiling and the different types of boiling that are known to traditionally exist.

4.1.1. Boiling

Boiling is defined as the process of vaporization in the bulk of a liquid. Boiling begins when the liquid bulk temperature exceeds its saturation temperature (or boiling point) at a given pressure. Two types of boiling phenomena have been observed to exist: nucleate boiling and film boiling. Depending on the heat flux transferred to the liquid by the heated surface, either individual vapor bubbles or a continuous vapor film will form on that surface. The former process is called nucleate boiling; the latter, film boiling.

In nucleate boiling, the liquid is in direct contact with the heated surface, and its boundary layer is intensely disturbed by the forming vapor bubbles. Moreover, the bubbles detaching from the surface drag a mass of superheated liquid from the layer adjacent to the wall into the core of the stream, creating an intensive macroscopic transport of heat from the heated surface into the bulk of the boiling liquid.

In film boiling, the liquid is separated from the heated surface by a continuous layer of vapor. Large bubbles are intermittently formed and become detached from the unheated side of the film.

4.1.2. Concept of volume boiling

The type of boiling involved in the EASW research is different from the traditional types of boiling described above. This new type of boiling is called "volume boiling." Volume boiling is boiling which occurs within the liquid, not on a heat transfer surface in contact with the boiling liquid. It is caused by supplying energy directly to the liquid without use of a heat transfer surface. Volume boiling can be achieved by several means--microwaves, nuclear fusion, dielectric losses, and radiant energy being adsorbed by the liquid.¹² An easily controlled method of causing volume boiling is passage of an electric current through the liquid, which then heats it to boiling, due to the electrical resistance of the liquid. It is similar to nucleate boiling

except that the vapor bubbles originate from within the fluid instead of from the surface of the heating material (i.e., the electrode in the treatment cell). The vapor bubbles originate from the soil particles (dirt) present in the soil slurry and rise to the liquid surface in the treatment cell or condense in the adjacent cool liquid.

4.2 Principle of Volume Boiling for Soil Washing (VBfSW)¹³

Commercial soil washing processes find it difficult to wash away contaminants from silts and clays due to the strong bonding between the contaminants and the fine soil particles. The EASW process developed at Texas Tech employs volume boiling of the soil-water slurry to energize washing of contaminants such as hydrocarbons, PCBs, and heavy metals from the soil.

Volume boiling achieves an intense scrubbing of soil particles within the volume being boiled. This intense scrubbing of soil particles allows effective washing of soils, which cannot be satisfactorily washed by state-of-the-art technologies.

Volume boiling is achieved by causing an AC electric current to flow through the soil-water slurry. This electric current results in boiling occurring within the volume of soil-water slurry between the electrodes due to resistive heating, not boiling on an externally heated surface.

4.2.1. Control of surface boiling

The problem of boiling on the surface of the electrodes occurs usually at higher power levels. This appears to be due to activation polarization, resulting in a high voltage drop at the electrode surface, and hence power release at the surface of the electrode. This activation polarization at high power levels may also relate to the AC-electrolysis phenomenon discussed in some patents and papers⁹ found in the literature survey. A subsequent result of boiling on the electrode surface was steam covering the electrode surface. The steam insulated much of the electrode surface, and so forced the current flow to the electrode edges. Under these conditions, arcing could be heard and seen at the edges of the experimental electrodes. At least four approaches may be taken to cope with the problem of boiling on the electrode surface. These approaches have been discussed in the subsections below.

4.2.1.1. Higher AC power frequencies. One way to cope with the problem of boiling on the electrode surface is to use AC power at frequencies higher than 60 Hertz, for example 200 to 5000 Hertz. By switching the polarity of the electrode more frequently, fewer reaction products would accumulate on the surface of the electrode to result in polarization. To employ higher frequencies, a converter would be required to convert 60 Hertz commercial power to higher frequencies. Converters to 400 Hertz may be available, since that frequency

is used on aircraft. This option was not exercised in this investigation, as other solutions to the surface boiling phenomenon were found.

4.2.1.2. Electrode cooling. Another approach would be to cool the electrodes. This approach, however, has only limited effectiveness in preventing surface boiling. Electrode cooling would be difficult to implement effectively.

4.2.1.3. Catalytically active electrodes. Electrodes having increased surface area, and increased catalytic activity on their surfaces would directly permit higher current densities before polarization resulted in surface boiling. This concept was demonstrated by replacing the brass electrodes with nickel electrodes. In one trial, it appeared that power levels of up to 2 kW could be achieved without boiling on the electrode surface, as a result of using nickel electrodes. Several soil samples were washed using the nickel electrodes, but their analysis was not complete. The electrodes were smooth nickel, not porous nickel which would have provided an even greater surface area. This improvement achieved with nickel electrodes was the impetus to seek electrodes with even greater catalytic activity. This approach has actually been implemented in the EASW apparatus to control surface boiling and enhance volume boiling in the soil slurry. The Titanium electrodes of model #8 and the Nichrome mesh electrode used in model #9 are some examples highly catalytically active electrodes.

4.2.1.4. Employment of large electrodes. Another way to cope with the problem of surface boiling is to employ rather large electrodes, which are separated from each other by an electrically insulating partition having a relatively small hole through it. All of the current flowing between the electrodes must flow through this hole. Much of the electric power applied to the solution will be released in the vicinity of the hole, because local power release is proportional to the current squared and the resistance, and both factors will be at a maximum near the hole in the partition.

4.2.2. Key to volume boiling

The key to causing volume boiling, instead of boiling on the surface of the electrodes, is to provide catalytically active electrodes in the soil-water slurry, and to utilize a geometry in which the current flowing between the electrodes is forced to flow through a small cross-sectional area, an orifice in the soil slurry. Forcing the current flow through a small volume of soil slurry is accomplished by placing an orifice in a partition, made of a nonconducting ceramic or polymer, which separates the test cell into two halves, each of which contains a large Nichrome mesh (nickel-chromium) electrode. This very high current flux in the soil slurry adjacent to the orifice causes volume boiling of the slurry, even when the adjacent slurry is far below the boiling point.

It has been hypothesized that the effectiveness of volume boiling is the result of nucleating vapor bubbles on particle surfaces, but the observed success of the volume boiling in removing contaminants from the soil is not dependent upon this hypothesis. Experimental observations of the electric current flowing through the slurry are consistent with this particle nucleated boiling hypothesis.

4.3. Electronic instrumentation to characterize volume boiling

The fluctuations in current and voltage between the electrodes during volume boiling contains considerable information regarding VBfSW process. This information will be useful in understanding the volume boiling phenomenon, and potentially developing automatic controls for a commercial scale process. The digital storage oscilloscope allows the transient electrical voltage patterns to be stored, and then examined on a display screen.

It was hypothesized that the steam bubbles being generated would be large enough to individually block the orifice one at a time and cause a wave pattern shown in Figure 4.1. In the wave pattern shown, T_1 and T_2 are treatment times that correspond to individual steam bubbles blocking the orifice in the VBfSW device. There is negligible flow of current through the orifice, during T_1 and T_2 , due to the non-conductive nature of the bubbles. Recent measurements with this instrument have shown that volume boiling occurs as a

vast array of very small steam bubbles, whose size is so small that their individual influence on the waveforms is negligible, in respect to the 60 Hz voltage applied to the electrodes of the EASW apparatus. Hence, the expected wave pattern of Figure 4.1. could not be seen. The result of these steam bubbles is just an observable increase in the electrical resistance between the two electrodes. This experimental observation is consistent with the early hypothesis that particulate nucleate boiling in the volume of the liquid might be effective in washing soil particles. This observation suggests that absolute diameter of this orifice in the EASW cell is not critical to the operation of the process, so scale-up of the process will not be severely constrained by the need for small orifices. In anticipation of the designing of commercial scale EASW soil washing facilities, experimental observations of this nature need to be continued, along with developing theoretical interpretations of them.

Figure 4.1. Hypothesized wave pattern

CHAPTER V

RESULTS AND DISCUSSION

The details and results of all the experimental runs made in the EASW research have been tabulated in Appendices C, D, E and F. The soils and contaminants used to test the VBfSW device have been described in detail in the following subsections.

5.1. Soil and contaminant characterization¹²

Lubbock top soil was selected for use in laboratory tests of the VBfSW process, based on consultation with soils experts in the Civil Engineering Department at Texas Tech University. The particle size analysis of this soil done in the soils laboratory is shown in Figure 5.1. Figure 5.2 shows the particle size analysis data of the Lubbock soil transposed on an EPA document² regarding soil washing. This comparison illustrates that the Lubbock soil is considered a very difficult soil to wash, based on its particle size distribution. A difficult to wash soil was chosen to demonstrate that the VBfSW process can wash soils which other soil washing processes find difficult or impossible to wash. The contaminant selected for the soil was a straight-run diesel fraction cut from the Fina refinery in Big Spring. It is characterized as shown in Table 3.1. The straight-run diesel fraction was selected as a contaminant for the soil

Figure 5.1. Particle size analysis of Lubbock top soil

Figure 5.2. Particle size analysis of the washed soils

because it was non-volatile, and also it contained a minimum of toxic aromatics which result from cracking operations in other portions of a refinery.

Later in the EASW research, a few authentic contaminated soils were selected to challenge the VBfSW process. The authentic soils used were from Gulf Coast, and from an old petroleum product loading terminal in New Jersey. The contaminants of the both the soils were reported to be very difficult to biodegrade. However, the VBfSW washed these soils to under 50 ppm (>99.5% removal).

5.2. Variables in VBfSW process

For a better understanding of the VBfSW process, an examination of all the variables involved in the process is essential. A total of 14 variables have been identified. A few of these variables are preselected due to their obvious influence on the process. Some of the variables are excluded because of the high cost associated with them. A study of the selected variables have given an idea as to where the optimum conditions lie for this process. The major variables that are involved in the process are:

- (1) Dissolved salt used in the treatment,
- (2) Weight % of dry soil in slurry,
- (3) Electrical conductivity of the soil slurry,
- (4) Electrode size and material of construction,
- (5) Frequency of power supplied,

- (6) Operating pressure,
- (7) Power input,
- (8) Orifice geometry,
- (9) Particle size distribution,
- (10) Soil slurry flow rate through the orifice,
- (11) Contaminants in the soil,
- (12) Temperature of the soil slurry,
- (13) pH of the soil slurry, and
- (14) Solvent used.

The above listed variables are discussed below.

5.2.1. Dissolved salt used in the treatment

Salts are added for three reasons:

- (1) to increase the electrical conductivity of the soil-water slurry, so that volume boiling could be achieved with reasonable applied voltages. Salt is added to the extent of having a certain minimum electrical conductivity in the soil slurry which would ensure a certain minimum power input to the soil slurry.
- (2) to minimize hydration of clays in the soil, which occurs if deionized water alone is used.
- (3) the use of the salt solution, instead of deionized water, raises the pH of the mixture to approximately 11. It is hypothesized that the higher pH would facilitate removal of

contaminants from the soil, by attenuating the strong bonding between contaminants and soil particles.

To suit the requirements listed above, different salts were tried and they are listed below:

- (1) Potassium carbonate, K_2CO_3 ;
- (2) Potassium hydroxide, KOH;
- (3) Sodium carbonate, Na_2CO_3 ; and
- (4) Calcium hydroxide, $Ca(OH)_2$.

The potassium salts prevent hydration of clays by snugly fitting in between the layers of clay. This is facilitated by the proper size of the potassium ion with respect to the oxygen and hydroxide ions in the clay plate. The use of these salts help better the treatment efficiency by minimizing clay hydration and dispersal. Potassium also serves as a fertilizer for the soil. Hence, any salt that might be left in the cleaned soil after treatment would be good for the soil. One disadvantage of using the potassium salt is that it makes handling of the soil slurry a little more difficult, in batch processes, by compacting the layers of clay in the soil slurry during centrifuging.

The sodium salts have a higher tendency to disperse the clays due to the smaller size of the sodium ion, Na^+ . The sodium ion is not of a proper size for it to fit in between the layers of clay and minimize hydration of the clays in the soil. The tests with Na_2CO_3 resulted in dispersing clays in

the soil to such an extent that prolonged centrifuging was required to produce a clear supernatant liquid.

The potassium ion and the calcium ion are almost the same size. Calcium hydroxide also minimizes the dispersal of the soil into water significantly.

A potassium salt is found most suitable for the purpose.

5.2.2. Weight % of dry soil in slurry

The higher the weight % of dry soil in the soil slurry the better is the efficiency of the VBfSW process in cleaning the contaminated soil. This trend has been observed repetitiously through almost all the experimental runs made so far in this research. The experimental runs 21-22-23, 34-35, 25-27 (refer Appendix C), are all examples that could be cited to support this observation. In all of the three sets of experimental runs mentioned above, weight % of dry soil in the soil slurry is the only significant factor that is varied. Figure 5.3 represents a graph of residual ppm vs the weight fraction of the soil used in the slurry. Figure 5.3 also shows that a higher concentration of the soil slurry is preferable for better removal of the contaminants in the soil.

5.2.3. Electrical conductivity of the soil slurry

Boiling time for the soil slurry being treated is dependent on the conducting capacity of the soil slurry. At low electrical conductivities the treatment times required are

Figure 5.3. Effect of % dry solids on treatment efficiency

high in the present apparatus due to the limit of 440 volts between the electrodes. Electrical conductivity of the soil slurry being boiled can be varied by adding dissolved salts, such as those mentioned in subsection 5.1.1. The electrical conductivity is selected so as to achieve impedance matching with the power supply, but electrical conductivity does not alter the size of the boiling zone. In general, relatively low electrical conductivities are desired, so the current required for a given power input is a minimum. The reason for this statement is that the capabilities of the electrodes are limited by the allowable current flow through them without excessive polarization.⁶ Typically, the electrical conductivity used in the experimental runs is 1.9×10^4 micromhos. This facilitates the usually required electric power input of 1 kilowatt to the soil slurry in the VBfSW device.

5.2.4. Electrode size and material of construction

Electrodes having increased surface area, and increased catalytic activity on their surfaces would directly permit higher current densities before polarization resulted in surface boiling. This concept was demonstrated by replacing the brass electrodes with nickel electrodes. In one trial, it appeared that power levels of up to 2 kW could be achieved without boiling on the electrode surface, as a result of using nickel electrodes. Several soil samples were washed using the

nickel electrodes, but their analysis was not complete. The electrodes were smooth nickel, not porous nickel which would have provided an even greater surface area.¹² This improvement achieved with nickel electrodes was the impetus to seek electrodes with even greater catalytic activity.

This approach has already been implemented in the EASW apparatus to control surface boiling and enhance volume boiling in the soil slurry. Two special kind of electrodes have been used to achieve this. They are a pair of Titanium electrodes (coated with iridium and other precious metal oxides), and a pair of large nichrome mesh (Ni-80%, Cr-20%) electrodes. Only a few experiments were run with the Titanium electrodes (model #8). The Nichrome mesh electrodes replaced the Titanium electrodes in the new model #9. These electrodes are observed to be the most successful for the present EASW batch facility. This is clearly seen in Tables 5.1., 5.2., 5.3., and 5.4. In these tables, the VBfSW device refers to model #9.

For most of the experiments, the electrodes were made very large and electrochemically active so that the size of the electrodes will have little, if any, influence on the volume boiling occurring near the orifice in the cell.

5.2.5. Frequency of the power supplied

The frequency of the power supplied will be limited to 60 Hertz. Higher frequencies would theoretically increase the

effectiveness of the electrodes. By switching the polarity of the electrodes more frequently, fewer reaction products would accumulate on the surface of the electrode to result in polarization.⁶ Typically higher AC frequencies of 200 to 5000 Hertz would be desirable, but these frequencies would be inconvenient to supply at this time. Hence the frequency of the power supplied remained a constant throughout the EASW research.

5.2.6. Operating pressure¹²

Higher pressures would offer the potential advantage of higher temperatures for washing. The operating pressure will be atmospheric, since it would be much more costly to operate either commercial or laboratory scale soil washing processes at elevated pressures.

5.2.7. Power input

Power input to the soil slurry affects the VBfSW process. Higher power levels are desirable. Power input to the orifice will be limited by rate at which steam vapor can leave the vicinity of the orifice, somewhat analogous to the transition from nucleate to film boiling. Lower power levels would increase the time required to achieve boiling in the soil slurry and hence are undesirable.

5.2.8. Orifice geometry

Initially, it was hypothesized that the steam bubbles being generated would be large enough to individually block the orifice one at a time and affect the process significantly. Recent measurements have shown that volume boiling occurs as a vast array of very small steam bubbles, whose size is so small that their individual influence on the process is negligible, in respect to the 60 Hz voltage applied to the electrodes of the EASW apparatus. The result of these steam bubbles is just an observable increase in the electrical resistance between the two electrodes. This observation suggests that the absolute diameter of this orifice in the EASW cell is not critical to the operation of the process, so scale-up of the process will not be severely constrained by the need for small orifices.

However, the orifice geometry is difficult to achieve in the present facility. The continuous EASW apparatus to be built would facilitate trial of various orifice geometries.

5.2.9. Particle size distribution

The particle size distribution of the contaminated soil to be washed is also a major variable that demands consideration. Though the VBFSW process has proved to be successful in cleaning very fine clays, the greater the percentage of fines in the soil, the more difficult will be the handling and washing of the contaminated soil, and

therefore the efficiency of the VBfSW process will decrease by a certain extent.

5.2.10. Soil slurry flow rate through the orifice

Experiments reported in this study were conducted with negligible net flow of soil slurry through the orifice. This circumstance is analogous to "pool boiling" studies encountered in traditional heat transfer research.¹² Soil slurry flow rate will be a primary variable in the continuous EASW cell to be built.

5.2.11. Contaminant present in the soil

The type of contaminant present in the soil also plays a role in determining the effectiveness of the VBfSW process. Contaminants like PCB's (Polychlorinated Biphenyls) pose a challenge to the process. PCBs are somewhat polar in nature, and may become adsorbed on the soil with greater affinity than hydrocarbons.¹³ Hence to wash PCBs it might be necessary to find surface active agents and/or solvents which will facilitate the washing of PCBs from the soil. This is just an hypothesis, a PCB contaminated soil should actually be tried on the VBfSW device to make any conclusions. Also, EPA safety regulations regarding the handling of the PCBs will have to be followed very carefully.

The variables like temperature and pH of the soil slurry are dependent on other variables, power input and the amount

of salt added, respectively. The use of solvents has been found to be unnecessary.

5.3. Summary of Results

The successful tests with the VBfSW device are summarized in Tables 5.1¹³., 5.2., 5.3., and 5.4.¹³ A discussion of these results appear in the following subsections.

5.3.1. VBfSW batch tests with diesel

Diesel is one of the primary contaminants that have been used to test the VBfSW device. Lubbock top soil is a Regime III soil which is difficult to wash. Diesel contaminated Lubbock soil has been successfully washed with the VBfSW device. The results of the VBfSW batch tests with diesel contaminated soil are summarised in Table 5.1. Tests A through C provide a basis for measuring the success of the VBfSW tests. Tests A-1 and A-2 are just an analysis of the contaminated soil before washing in the VBfSW device. Tests B-1 and B-2 are an analyses of the soil after dispersal with the high-speed mixer, but without treatment in the VBfSW device. Just mixing with high-pH, sodium carbonate containing water, removed a considerable amount of the diesel from the soil. However, this will not be enough to meet the standards for a clean soil. Tests C-1, C-2, and C-3 are treatments in which boiling was accomplished with an immersion electrical heater (also called the resistance heater), while stirring

Table 5.1. Results from the VBfSW batch tests with diesel

Test No.	Diesel left ppm	Device used	Treatment time and Power input				Soil slurry treated		
			min	kW	min	kW	H ₂ O ml	soil g	SC [†] g
A-1	47,620	NONE - This is the diesel on the contaminated soil before any treatment							
A-2	47,620								
B-1	7819	NONE - Just high speed mixing with H ₂ O & Na ₂ CO ₃ for 30 secs					600	80	2.0
B-2	8400						600	80	2.0
C-1	1200	RH*	4.5	1.0	1.5	0.5	600	40	2.0
C-2	1200	RH*	4.5	1.0	1.5	0.5	600	40	2.0
C-3	1049	RH*	4.5	1.0	1.5	0.5	600	80	2.0
D	122	VBfSW	4.0	1.0	3.0	0.5	600	80	2.0
E	46	VBfSW	4.0	1.0	3.0	0.5	600	160	2.0
F	18	VBfSW	4.0	1.0	3.0	0.5	600	160	2.0
G	9	VBfSW	3.0	1.0	2.5	0.5	600	80	2.0
H	ND*	VBfSW	2.0	1.0	3.0	0.5	300	80	2.0

* - Non-Detectable

† - Sodium Carbonate, Na₂CO₃

* - Resistance Heater

with a stirbar. It is important to note that boiling was not accomplished by volume boiling in test C. The relatively high hydrocarbon content, remaining after these three tests, 1000 to 1200 ppm, is the basis for demonstration of the particular effectiveness of volume boiling in removal of contaminants from soil. This is reflected by the experiments D through H of Table 5.1.

Unlike the tests A, B, and C, tests D through H prove that the VBfSW process is effective in removal of contaminants from fine-grained soils such as the Lubbock soil which is categorized as very difficult to wash (illustrated in Figure 5.2). As shown in the central portion of the table the VBfSW treatment cycle consisted of applying 1 kW of power to the soil slurry until the entire slurry was at the boiling point. After the entire slurry was at the boiling point, the power input was reduced to 0.5 kW to minimize splashing. Tests D through H prove that the VBfSW process can effectively remove over 99.5% of the contaminant, diesel, from a Regime III soil such as the Lubbock soil.

5.3.2. VBfSW batch tests with crude oil

Crude oil (26.2 API) is another contaminant that has been tried in the VBfSW device. The results of the VBfSW batch tests with crude oil are in Table 5.2. Tests A-1 and A-2 are just an analyses of the contaminated soil before treatment on the VBfSW device. Test B reflects the result of high speed

Table 5.2. Results of the VBfSW batch tests with crude oil

Test No.	Crude left ppm	Device used	Treatment time and Power input				Soil slurry treated		
							H ₂ O	soil	PC [†]
			min	kW	min	kW	ml	g	g
A-1 A-2	15,000 15,000	NONE - This is the crude in the contaminated soil before any treatment							
B	3408	NONE - Just high speed mixing with H ₂ O & K ₂ CO ₃ for 30 secs					600	80	2.6
C	19	VBfSW	5.0	1.0	-	-	600	80	2.6
D	ND [‡]	VBfSW	6.0	1.0	4.0	0.25	600	80	2.6
E	ND [‡]	VBfSW	4.0	1.0	2.0	0.5	600	160	2.6
The following tests were done with KOH, not K ₂ CO ₃									
F	53	VBfSW	5.0	1.0	-	-	600	160	1.0
G	34	VBfSW	5.0	1.0	-	-	300	80	1.0

† - Potassium Carbonate, K₂CO₃

‡ - Non-Detectable

Table 5.3. Results of the VBfSW batch tests with the authentic contaminated soil from Gulf Coast.

Test No.	Oil left ppm	Device used	Treatment time and Power input				Soil slurry treated		
			min	kW	min	kW	H ₂ O ml	Soil g	SC [†] g
A	39,000	NONE - This is the contamination level in the soil before treatment							
B	1080	NONE - Just high-speed mixing with H ₂ O and Na ₂ CO ₃ for 120 secs					550	130	2.0
C-1	34	VBfSW	4.8	1.0	.25	0.5	550	130	2.0
C-2	22	VBfSW	4.2	1.0	.75	0.5	500	260	2.0
The following tests were made with Ca(OH) ₂ , not Na ₂ CO ₃									
D	980	NONE - Just high-speed mixing with water & Ca(OH) ₂ for 120 secs					600	130	1.4
E-1	325	RH*	5.0	1.0	-	-	600	130	1.4
E-2	305	RH*	5.0	1.0	-	-	600	260	1.4
E-3	285	RH*	5.0	1.0	-	-	300	130	1.4
E-4	270	RH*	5.0	1.0	-	-	300	130	1.4
F-1	46	VBfSW	5.0	1.0	-	-	600	130	1.4
F-2	38	VBfSW	5.0	1.0	-	-	600	260	1.4

† - Sodium Carbonate

mixing of the contaminated soil with water and potassium carbonate, K_2CO_3 , for 30 seconds. Tests A and B provide a basis for the comparison of performance of the VBfSW process. Tests C through G clearly show the effectiveness of the VBfSW process in removing crude oil from a difficult to wash soil such as the Lubbock top soil. Tests F and G were run with a different salt, potassium hydroxide, KOH, not K_2CO_3 .

5.3.3. VBfSW batch tests with the Gulf Coast soil

A summary of the results with washing the Gulf Coast soil is shown in Table 5.3. These results which report the washing of "tar" from soil are important in that they are samples from the "real world," not samples prepared in the laboratory. A particle size analysis of the Gulf Coast soil, transposed on the EPA document showing the various regimes of soil washing, is shown in Figure 5.2. Tests A and B, provide the basis for comparing the effectiveness of the VBfSW device in washing a contaminated soil. Test A reflects the contamination level in the soil before any treatment. Test B is the result after high-speed mixing with water and Na_2CO_3 for 120 seconds. It removes a major portion of the contaminants present, but does not help in complete cleaning of the soil. The success of the tests C-1 and C-2 which used the VBfSW device can be easily seen. The VBfSW process was effective in reducing the contamination level of the Gulf Coast soil to under 50 ppm. Again, that is a removal of over 99.5% of the contaminants

present in the soil. The results of the VBfSW process using Calcium hydroxide, $\text{Ca}(\text{OH})_2$, are shown in tests D, E, and F. The VBfSW process used in test F is seen to be successful again as compared to tests D and E. Test D is just high-speed mixing with water and $\text{Ca}(\text{OH})_2$. In tests E-1, E-2, E-3 and E-4 boiling is accomplished in the soil slurry utilizing an immersion heater, not the VBfSW device.

5.3.4. VBfSW batch results with the New Jersey soil

The particle size distribution of this authentic contaminated soil is transposed on the EPA document showing the various regimes of soil washing and is shown in Figure 5.2. This soil is from an old petroleum product loading terminal, and the contamination is reported very difficult to biodegrade. Washing with the VBfSW process reduced the hydrocarbon content from 4300 to 28 ppm. These results are reflected by tests C and D, in Table 5.4. Tests A and B provide the baseline data for comparison. The initial contamination level on the New Jersey soil was 4350, as shown by tests A-1 and A-2. Tests B-1 to B-4 were done without employing volume boiling, by utilizing an immersion heater to cause boiling. As seen in Table 5.4., these tests were not very successful when compared with tests C and D.

Table 5.4. Results of the VBfSW batch tests with the soil from New Jersey

Test No.	Oil left ppm	Device used	Treatment time and Power input				Soil slurry treated		
							H ₂ O	Soil	PC [†]
			min	kW	min	kW	ml	g	g
A-1	4,357	NONE - This is a sample of the contaminated soil before treatment							
A-2	4,350								
B-1	222	RH*	5.0	1.0	-	-	600	80	2.6
B-2	183	RH*	5.0	1.0	-	-	300	80	2.6
B-3	195	RH*	5.0	1.0	-	-	600	160	2.6
B-4	208	RH*	5.0	1.0	-	-	600	80	2.6
C	43	VBfSW	5.0	1.0	-	-	600	80	2.6
D	13	VBfSW	5.0	1.0	-	-	600	160	2.6

† - Potassium Carbonate

* - Resistance Heater

CHAPTER VI

COST ANALYSIS

The success of any technology depends on the cost that is associated with its implementation in the real world. A technology can be said to be truly successful only when a reasonable cost is associated with it. Hence, although the VBfSW process has been proven to be successful on a laboratory scale, it will be imperative to do a cost estimation of the process to determine its viability in the real world. This chapter includes an approximate estimation of the cost associated with using the VBfSW in the real world. The major cost of the process is associated with its electric power and chemical requirements.

6.1. Electric power and chemical requirements for the VBfSW process¹³

Commercial application of the VBfSW process requires the amounts of electric power and chemicals used not to be excessive. Based on test #E in Table 5.1, the electric power supplied is 520 kw-hr per ton of soil processed. This experimental observation was confirmed by a theoretical calculation without heat losses of 450 kw-hr per ton of soil. At 5¢/kw-hr this represents cost for power of about \$25/ton of soil processed. This is not an unreasonable cost to pay to be able to wash a soil slurry which is considered unwashable by present commercial processes. Preheating the slurry entering

the VBfSW cell by exchanging heat the with hot fluids leaving the treatment cell, shorter treatment times and optimizing the electrode and orifice geometries are all additional opportunities to reduce the power requirements. These options have not yet been investigated.

The chemicals used in the VBfSW process, sodium carbonate or potassium carbonate, are rather economical. Also, most of the chemical used will be recycled in the process water. Hence the cost for chemicals will be low, less than \$15/ton of soil processed. This results in a total cost of \$40/ton for electricity and chemicals to apply the VBfSW process to soils which cannot be washed by conventional processes. These estimates are preliminary and are given only to give the reader an idea as to where the VBfSW process stands in the real world.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

EASW research was successful in yielding a technology to wash fine-grained contaminated soils, which state-of-the-art technologies find it difficult, if not impossible, to wash. The conclusions and recommendations for the EASW research follow in the subsections.

7.1. Conclusions

A list of all the conclusions that could be drawn from this research effort is given below:

- (1) The objective of this research, to experimentally demonstrate a technology to wash contaminated soils with a high percentage of fines, has been accomplished.
- (2) Washing contaminated soils with the VBfSW device yields removal efficiencies of over 99.5%.
- (6) To strengthen the credibility of the VBfSW process, a few authentic contaminated soils from the real world were successfully washed with the VBfSW process. The removal efficiency was once again over 99.5%.
- (3) Volume boiling is the key to the success of the VBfSW device in washing contaminated soils. This fact is supported throughout the EASW research by

utilizing an immersion heater which is known to cause surface boiling, unlike the VBfSW device which causes volume boiling with the same amount of electric power applied.

- (4) The primary variables in the VBfSW process are:
 - (a) electrode size and material of construction;
 - (b) viscosity of the soil slurry;
 - (c) salt used; and
 - (d) particle size distribution of the soil being washed.
- (7) Electronic instrumentation (a digital storage oscilloscope) used to study the VBfSW process showed that the absolute diameter of the orifice in the VBfSW device is not critical to the operation of the process. Hence scale-up of the process will not be severely constrained by the need for small orifices.

7.2. Recommendations

The following recommendations are made for future research on this novel EASW process:

- (1) Develop a continuous EASW process which would minimize the generation of waste wash water and treat contaminated soil at a faster rate.
- (2) Heavy metals and PCBs contaminated soils will have to be tested on the VBfSW device.

- (3) Develop a firm experimental basis for extrapolation of laboratory measurements to the design of pilot-scale and commercial-scale facilities.
- (4) Instrumental methods for on-line monitoring of this soil washing process, suitable for both the pilot-scale and commercial-scale operations need to be developed.

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APPENDIX A

DETAILED DRAWINGS OF THE EASW FACILITY

Figure A.1. Electrodes and electrode support

Figure A.2. Condenser unit

APPENDIX B

METHOD 418.1 (SPECTROPHOTOMETRIC, INFRARED)

Method 418.1 was used in the TPH analysis described earlier in chapter III (section 3.5). This method is used for the measurement of fluorocarbon-113 (freon) extractable petroleum hydrocarbons from contaminated soil. The Soxhlet extraction apparatus is used to extract the contaminants (petroleum hydrocarbons) from the soil. The extract is then analysed on a Beckman infrared spectrophotometer which can scan around a wavelength of 2950 cm^{-1} . The petroleum hydrocarbons collectively give a peak around this wavelength of 2950 cm^{-1} . During analysis, the extract is placed in cells having a pathlength of 10mm. The calibration mixtures used to calibrate the spectrophotometer are prepared as follows:

- (1) Reference oil: 15.0 ml n-hexadecane, 15.0 ml isooctane, and 10.0 ml chlorobenzene are pipetted into a 50 ml glass stoppered bottle. The integrity of the mixture is maintained by keeping it stoppered except when withdrawing aliquots.
- (2) Stock standard: 1.0 ml reference oil is pipetted into a tared 200 ml volumetric flask and immediately stoppered. This is weighed and diluted to volume with fluorocarbon-113.
- (3) Working standards: Appropriate volumes of stock standard are pipetted into 100 ml volumetric flasks

according to the cell pathlength to be used. Dilute to volume with fluorocarbon-113. Calculate concentration of standards from the stock standard.

A calibration plot of absorbance vs. mg petroleum hydrocarbons per 100 ml solution is prepared. The concentration of petroleum hydrocarbons in the extract is determined by comparing the response against the calibration plot. The petroleum hydrocarbons in the sample can be calculated by using the formula:

$$\text{mg/l petroleum hydrocarbons} = (R \times D) / V$$

where:

R = mg of petroleum hydrocarbons as determined from the calibration plot

D = extract dilution factor, if any

V = volume of sample, in liters.

In this EASW research, the dilution factor, D, was not used (i.e., D=1).

APPENDIX C

EASW RESULTS WITH DIFFERENT CONTAMINANTS

Table C.1. EASW results with diesel contaminant.

SAMPLE NUMBER	1	2	3	4	5
CONTAMINANT PPM	47620	47620	47620	47620	47620
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	20	20	20	20	20
AMOUNT OF Na ₂ CO ₃ , GMS	5.0	7.0	5.0	5.0	5.0
AMOUNT OF D.WATER, ML	600	600	600	600	600
OSTERIZER TIME, SECS	30	30	30	30	30
TREATMENT TIME, SECS	300	300	-	300	300
POWER INPUT SECS @ KW	210 @ 2	240 @ 2	-	210 @ 2	210 @ 2
	90 @ ½	60 @ ½	-	90 @ ½	90 @ ½
PEAK TEMPERATURE C	96.0	97.5	-	96.0	97.2
CELL MODEL NUMBER	3	3	-	3	3
AMOUNT OF TOLUENE, ML	2	-	2	2	1
CONTAMINANT LEFT, PPM	246	243	2250	295	410

Table C.1. Continued.

SAMPLE NUMBER	6	7	8	9	10
CONTAMINANT PPM	47620	47620	47620	47620	47620
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	20	20	20	20	20
AMOUNT OF Na ₂ CO ₃ , GMS	5.0	5.0	5.0	5.0	5.0
AMOUNT OF D.WATER, ML	600	600	600	600	600
OSTERIZER TIME, SECS	30	30	30	30	30
TREATMENT TIME, SECS	300	300	420	420	600
POWER INPUT KW, SECS	195 @ 2	210 @ 2	270 @ 2	240 @ 2	240 @ 2
	105 @ ½	90 @ ½	150 @ ¼	180 @ ¼	360 @ ¼
PEAK TEMPERATURE °C	95.2	97.4	96.7	94.0	94.1
CELL MODEL NUMBER	3	3	3	3	3
AMOUNT OF TOLUENE, ML	4	-	-	2	2
CONTAMINANT LEFT, PPM	480	651	972	489	403

Table C.1. Continued.

SAMPLE NUMBER	11	12	13	14	15
CONTAMINANT PPM	47620	47620	47620	47620	47620
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	40	20	20	20	40
AMOUNT OF Na_2CO_3 , GMS	2.5	2.5	2.5	2.5	2.5
AMOUNT OF D.WATER, ML	600	600	600	600	600
OSTERIZER TIME, SECS	30	30	30	30	30
TREATMENT TIME, SECS	300	300	300	300	300
POWER INPUT KW, SECS	180 @ 2	180 @ 2	195 @ 2	210 @ 2	135 @ 2
	120 @ $\frac{1}{2}$	120 @ $\frac{1}{2}$	105 @ $\frac{1}{2}$	90 @ $\frac{1}{2}$	165 @ $\frac{1}{2}$
PEAK TEMPERATURE C	90.4	91	92.5	95.0	91.0
CELL MODEL NUMBER	6	6	6	6	7
AMOUNT OF TOLUENE, ML	4	2	1	-	4
CONTAMINANT LEFT, PPM	342	250	458	582	250

Table C.1. Continued.

SAMPLE NUMBER	16	17	18	19	20
CONTAMINANT PPM	47620	47620	47620	47620	47620
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	40	40	40	40	40
AMOUNT OF Na_2CO_3 , GMS	2.5	2.5	1.0	1.0	1.0
AMOUNT OF D.WATER, ML	600	600	600	600	600
OSTERIZER TIME, SECS	30	30	30	30	30
TREATMENT TIME, SECS	300	300	300	300	300
POWER INPUT KW, SECS	140 @ 2	135 @ 2	135 @ 2	300 @ 1	240 @ 1
	160 @ $\frac{1}{2}$	165 @ $\frac{1}{4}$	165 @ $\frac{1}{4}$	120 @ $\frac{1}{4}$	180 @ $\frac{1}{4}$
PEAK TEMPERATURE C	96.0	90.0	93.0	95.1	91.3
CELL MODEL NUMBER	7	7	7	8	3
AMOUNT OF TOLUENE, ML	-	4	2	-	-
CONTAMINANT LEFT, PPM	1000	1470	1230	135	86

Table C.1. Continued.

SAMPLE NUMBER	21	22	23	24	25
CONTAMINANT PPM	47620	47620	47620	47620	47620
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	40	80	160	80	80
AMOUNT OF Na_2CO_3 , GMS	2.0	2.0	2.0	2.0	2.0
AMOUNT OF D.WATER, ML	600	600	600	300	600
OSTERIZER TIME, SECS	30	30	30	30	30
TREATMENT TIME, SECS	300	420	420	300	420
POWER INPUT KW, SECS	210 @ 1	240 @ 1	240 @ 1	120 @ 1	255 @ 1
	90 @ $\frac{1}{4}$	180 @ $\frac{1}{2}$	180 @ $\frac{1}{2}$	180 @ $\frac{1}{2}$	165 @ $\frac{1}{2}$
PEAK TEMPERATURE C	93.0	95.5	96.0	90.5	95.7
CELL MODEL NUMBER	9	9	9	9	9
AMOUNT OF TOLUENE, ML	-	-	-	-	-
CONTAMINANT LEFT, PPM	274	122	46	60	114

Table C.1. Continued.

SAMPLE NUMBER	26	27	28	29	30
CONTAMINANT PPM	47620	47620	47620	47620	47620
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	80	160	80	80	80
AMOUNT OF Na ₂ CO ₃ , GMS	2.0	2.0	2.0	2.0	2.0
AMOUNT OF D.WATER, ML	600	600	600	600	600
OSTERIZER TIME, SECS	30	30	30	30	30
TREATMENT TIME, SECS	420	420	420	-	-
POWER INPUT KW, SECS	240 @ 1	240 @ 1	280 @ 1	-	-
	180 @ ½	180 @ ½	140 @ ½	-	-
PEAK TEMPERATURE C	95.1	97.3	95.9	-	-
CELL MODEL NUMBER	9	9	7	-	-
AMOUNT OF TOLUENE, ML	2	-	-	-	2
CONTAMINANT LEFT, PPM	128	18	846	7819	8400

Table C.1. Continued.

SAMPLE NUMBER	31	32	33	34	35
CONTAMINANT PPM	47620	47620	47620	47620	47620
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	40	40	80	80	160
AMOUNT OF Na_2CO_3 , GMS	2.5	2.5	2.0	2.0	2.0
AMOUNT OF D.WATER, ML	600	600	600	600	600
OSTERIZER TIME, SECS	30	30	30	30	30
TREATMENT TIME, SECS	360	360	360	300	360
POWER INPUT KW, SECS	270 @ 1	270 @ 1	270 @ 1	210 @ 1	270 @ 1
	90 @ $\frac{1}{2}$	90 @ $\frac{1}{2}$	90 @ $\frac{1}{2}$	90 @ $\frac{1}{2}$	90 @ $\frac{1}{2}$
PEAK TEMPERATURE C	97.0	97.1	97.0	93.0	96.7
CELL MODEL NUMBER	7	7	7	9	9
AMOUNT OF TOLUENE, ML	-	-	-	-	-
CONTAMINANT LEFT, PPM	1200	1200	1049	141	109

Table C.1. Continued.

SAMPLE NUMBER	36	37	38	39	40
CONTAMINANT PPM	47620	47620	47620	47620	47620
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	80	80	80	80	160
AMOUNT OF Na_2CO_3 , GMS	2.0	2.0	2.0	2.0	2.0
AMOUNT OF D.WATER, ML	600	600	600	300	600
OSTERIZER TIME, SECS	30	30	30	30	30
TREATMENT TIME, SECS	330	420	390	300	390
POWER INPUT KW, SECS	180 @ 1	240 @ 1	255 @ 1	120 @ 1	255 @ 1
	150 @ $\frac{1}{2}$	180 @ $\frac{1}{2}$	135 @ $\frac{1}{2}$	180 @ $\frac{1}{2}$	135 @ $\frac{1}{2}$
PEAK TEMPERATURE C	97.3	94.0	96.8	97.0	97.3
CELL MODEL NUMBER	9	9	9	9	9
AMOUNT OF TOLUENE, ML	-	4	-	-	-
CONTAMINANT LEFT, PPM	9	18	ND [†]	ND [†]	ND [†]

† - Non-Detectable

Table C.1. Continued.

SAMPLE NUMBER	41	42	43	44	45
CONTAMINANT PPM	47620	47620	47620	47620	47620
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	80	80	80	80	80
AMOUNT OF Na ₂ CO ₃ , GMS	2.0	2.0	2.0	2.0	2.0
AMOUNT OF D.WATER, ML	300	600	600	600	600
OSTERIZER TIME, SECS	30	30	30	30	30
TREATMENT TIME, SECS	300	180	-	300	300
POWER INPUT KW, SECS	180 @ 1	180 @ 1	-	180 @ 1	180 @ 1
	120 @ ½	-	-	120 @ ½	120 @ ½
PEAK TEMPERATURE C	97.0	83.1	-	97.0	97.0
CELL MODEL NUMBER	9	9	-	7	7
AMOUNT OF TOLUENE, ML	-	-	-	-	-
CONTAMINANT LEFT, PPM	ND [†]	ND [†]	8094	1049	1092

† - Non-Detectable

Table C.1. Continued.

SAMPLE NUMBER	46	47	48	49	50
CONTAMINANT PPM	15,000	15,000	47620	15,000	15,000
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	80	40	40	80	80
TYPE OF SALT	$\text{Ca}(\text{OH})_2$	Na_2CO_3	Na_2CO_3	K_2CO_3	K_2CO_3
AMOUNT OF SALT, GMS	1.4	2.5	2.5	2.6	2.6
AMOUNT OF D.WATER, ML	600	600	600	600	600
OSTERIZER TIME, SECS	30	30	30	30	30
TREATMENT TIME, SECS	240	300	300	300	600
POWER INPUT KW, SECS	240 @ 1	140 @ 1	135 @ 2	140 @ 1	420 @ 1
	-	160 @ $\frac{1}{2}$	165 @ $\frac{1}{4}$	160 @ $\frac{1}{2}$	180 @ $\frac{1}{2}$
CELL MODEL NUMBER	9	7	9	7	9
CONTAMINANT LEFT, PPM	ND [†]	1470	250	1450	24

† - Non-Detectable

Table C.2. EASW results with crude oil.

SAMPLE NUMBER	1	2	3	4
CONTAMINANT PPM	15,000	15,000	15,000	15,000
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	40	80	160	80
TYPE OF SALT	KOH	KOH	KOH	KOH
AMOUNT OF SALT, GMS	1.0	1.0	1.0	1.0
AMOUNT OF D.WATER, ML	600	600	600	300
OSTERIZER TIME, SECS	30	30	30	30
TREATMENT TIME, SECS	300	300	300	300
POWER INPUT KW, SECS	300 @ 1	300 @ .8	300 @ 1	300 @ 1
	-	-	-	-
CELL MODEL NUMBER	9	9	9	9
CONTAMINANT LEFT, PPM	159	148	53	34

Table C.2. Continued.

SAMPLE NUMBER	5	6	7	8
CONTAMINANT PPM	15,000	15,000	15,000	15,000
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	80	80	80	160
AMOUNT OF K_2CO_3 , GMS	2.6	2.6	2.6	2.6
AMOUNT OF D.WATER, ML	600	600	600	600
OSTERIZER TIME, SECS	30	30	30	30
TREATMENT TIME, SECS	-	300	600	360
POWER INPUT SECS @ KW	-	300 @ 1	360 @ 1	240 @ 1
	-	-	240 @ $\frac{1}{4}$	120 @ $\frac{1}{2}$
CELL MODEL NUMBER	-	9	9	9
CONTAMINANT LEFT, PPM	3408	19	ND [†]	ND [†]

† - Non-Detectable

Table C.2. Continued.

SAMPLE NUMBER	9	10	11	12
CONTAMINANT PPM	15,000	15,000	15,000	15,000
TYPE OF SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL	LUBBOCK SOIL
AMOUNT OF SOIL, GMS	80	160	80	80
AMOUNT OF Na ₂ CO ₃ , GMS	2.0	2.0	2.0	2.0
AMOUNT OF D.WATER, ML	600	600	600	300
OSTERIZER TIME, SECS	30	30	30	30
TREATMENT TIME, SECS	-	360	480	300
POWER INPUT SECS @ KW	-	300 @ 1	360 @ 1	240 @ 1
	-	60 @ $\frac{1}{4}$	120 @ $\frac{1}{4}$	60 @ $\frac{1}{2}$
CELL MODEL NUMBER	-	9	9	9
CONTAMINANT LEFT, PPM	3380	35	48	38

Table C.3. EASW results with Gulf Coast soil.

SAMPLE NUMBER	1	2	3	4
AMOUNT OF SOIL, GMS	130	260	130	130
TYPE OF SALT	Na ₂ CO ₃	Na ₂ CO ₃	Na ₂ CO ₃	-
AMOUNT OF SALT, GMS	2.0	2.0	2.0	-
AMOUNT OF D.WATER, ML	550	500	550	-
OSTERIZER TIME, SECS	120	180	120	-
TREATMENT TIME, SECS	300	300	-	-
POWER INPUT KW, SECS	285 @ 1	255 @ 1	-	-
	15 @ ½	45 @ ½	-	-
CELL MODEL NUMBER	9	9	-	-
CONTAMINANT LEFT, PPM	34	22	1080	1700

Table C.3. Continued.

SAMPLE NUMBER	5	6	7	8
AMOUNT OF SOIL, GMS	130	260	130	130
TYPE OF SALT	Ca(OH) ₂	Ca(OH) ₂	Ca(OH) ₂	-
AMOUNT OF SALT, GMS	1.4	1.4	1.4	-
AMOUNT OF D.WATER, ML	600	600	600	-
OSTERIZER TIME, SECS	180	120	180	-
TREATMENT TIME, SECS	300	300	-	-
POWER INPUT KW, SECS	300 @ 1	300 @ 1	-	-
	-	-	-	-
CELL MODEL NUMBER	9	9	-	-
CONTAMINANT LEFT, PPM	46	38	980	388/110

Table C.3. Continued.

SAMPLE NUMBER	9	10	11	12
AMOUNT OF SOIL, GMS	130	260	130	130
TYPE OF SALT	K ₂ CO ₃	K ₂ CO ₃	K ₂ CO ₃	K ₂ CO ₃
AMOUNT OF SALT, GMS	2.0	2.0	2.0	2.0
AMOUNT OF D.WATER, ML	550	500	275	550
OSTERIZER TIME, SECS	120	180	120	120
TREATMENT TIME, SECS	300	300	300	-
POWER INPUT KW, SECS	270 @ 1	270 @ 1	255 @ 1	-
	30 @ ½	30 @ ½	45 @ ½	-
CELL MODEL NUMBER	9	9	9	9
CONTAMINANT LEFT, PPM	28	10	20	710

Table C.3. Continued.

SAMPLE NUMBER	13	14	15	16
AMOUNT OF SOIL, GMS	130	260	130	130
TYPE OF SALT	Ca(OH) ₂	Ca(OH) ₂	Ca(OH) ₂	Ca(OH) ₂
AMOUNT OF SALT, GMS	1.4	1.4	1.4	1.4
AMOUNT OF D.WATER, ML	600	600	300	300
OSTERIZER TIME, SECS	180	120	180	180
TREATMENT TIME, SECS	300	300	300	300
POWER INPUT KW, SECS	300 @ 1	300 @ 1	300 @ 1	300 @ 1
	-	-	-	-
CELL MODEL NUMBER	9	9	9	9
CONTAMINANT LEFT, PPM	325	305	285	270

Table C.4. EASW results with New Jersey soil.

SAMPLE NUMBER	1	2	3	4
AMOUNT OF SOIL, GMS	80	160	80	80
TYPE OF SALT	K ₂ CO ₃	K ₂ CO ₃	-	-
AMOUNT OF SALT, GMS	2.6	2.6	-	-
AMOUNT OF D.WATER, ML	600	600	-	-
OSTERIZER TIME, SECS	30	30	-	-
TREATMENT TIME, SECS	300	300	-	-
POWER INPUT KW, SECS	300 @ 1	300 @ 1	-	-
	-	-	-	-
CELL MODEL NUMBER	9	9	-	-
CONTAMINANT LEFT, PPM	43	13	4357	4350

Table C.4. Continued.

SAMPLE NUMBER	5	6	7	8
AMOUNT OF SOIL, GMS	80	80	160	80
TYPE OF SALT	K ₂ CO ₃	K ₂ CO ₃	K ₂ CO ₃	K ₂ CO ₃
AMOUNT OF SALT, GMS	2.6	2.6	2.6	2.6
AMOUNT OF D.WATER, ML	600	300	600	600
OSTERIZER TIME, SECS	30	30	30	30
TREATMENT TIME, SECS	300	300	300	300
POWER INPUT KW, SECS	300 @ 1	300 @ 1	300 @ 1	300 @ 1
	-	-	-	-
CELL MODEL NUMBER	7	7	7	7
CONTAMINANT LEFT, PPM	222	183	195	208

Table C.5. EASW results with Bentonite clay.

SAMPLE NUMBER	1	2	3	4
CONTAMINANT TYPE	CRUDE	CRUDE	CRUDE	CRUDE
AMOUNT OF SOIL, GMS	80	80	80	80
TYPE OF SALT	K ₂ CO ₃	-	K ₂ CO ₃	-
AMOUNT OF SALT, GMS	2.6	-	2.6	-
AMOUNT OF D.WATER, ML	600	-	300	-
OSTERIZER TIME, SECS	30	-	30	-
TREATMENT TIME, SECS	180	-	180	-
POWER INPUT KW, SECS	180 @ 1	-	180 @ 1	-
	-	-	-	-
CELL MODEL NUMBER	9	-	9	-
CONTAMINANT LEFT, PPM	231	12109	195	13200

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