Bioremediation of Contaminated Soils: A Comparison of *In Situ* and *Ex Situ* Techniques

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ABSTRACT

When investigating the treatment of contaminated soils, the application of biotreatment is growing rapidly. Factors influencing this rapid growth include that the bioremediation processes are cost-efficient, safe, and nature-based. In the past, thermal, chemical, and physical treatment methods have failed to eliminate the pollution problem because those methods only shift the pollution to a new phase such as air pollution. Bioremediation technology, which leads to degradation of pollutants, may be a lucrative and environmentally beneficial alternative. (Iranzo, et al., 2001.) Two major groups bioremediation treatment techniques are used: *in situ* and *ex situ* remediation. While *in situ* remediation is more cost effective, the thoroughness of this method is less effective than the *ex situ* remediation. *Ex situ* remediation is less cost effective, but is a more thorough remediation method. This paper will evaluate the benefits and costs of each technique. (Koning, et al., 2000).

KEYWORDS

Bioremediation, ex *situ* remediation, in *situ* remediation, landfarming, bioventing, biosparging, bioslurping, phytoremediation

INTRODUCTION

Bioremediation is defined as "The use of biological mechanisms to destroy, transform, or immobilize environmental contaminants in order to protect potential sensitive receptors." (Bioremediation Discussion Group, 2006). Ex *situ* remediation techniques involve removing the soil from the subsurface to treat it. *In situ* remediation techniques involve leaving the soil in its original place and bringing the biological mechanisms to the soil. In the past, thermal, chemical, and physical treatment methods have failed to eliminate the pollution problem because those methods only shift the pollution to a new phase such as air pollution. Bioremediation technology, which leads to degradation of pollutants, may be a lucrative and environmentally beneficial alternative that could produce economic profit. (Iranzo, et a.l, 2001.) *Ex situ* and *in situ* techniques each have specific benefits and costs.

EX SITU REMEDIATION TECHNIQUES

Ex situ remediation includes techniques such as landfarming, biopiling, and processing by bioreactors along with thermal, chemical, and physical processes. (Koning, et al., 2000). *Ex situ* remediation is a more thorough remediation technique, but due to the costs associated not only with the remediation processes, but also will the excavation and transportation of the soil, many people are looking towards in situ remediation techniques.

Ex situ thermal processes involve the transfer of pollutants from the soil to a gas phase. The pollutants are released by vaporization and the burned at high temperatures. *Ex situ* thermal remediation is completed in 3 steps: soil conditioning, thermal treatment, and exhaust gas purification. (Van Deuren, et al, 2002). Soil condition is a process in which broken into small grains and sieved in preparation for thermal treatment. Thermal treatment heats the soil in order to transfer volatile pollutants to a gas phase. Heating is done by using a sintering strand, fluid bed, or rotary kiln plants. The soil is usually heated to a low temperature range of 350-550^{o}C. Combustion of the gases occurs over the top of the soil, but the volatile gases are not destroyed. The gases are then burned in an after-burner chamber at approximately 1200^{o}C and dioxins are destroyed. (Koning, et al., 2000).

Ex situ thermal remediation processes are ideal for use when removing petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAH), benzene, toluene, ethylbenzene, xylenes (BTEX), phenolic compounds, cyanides, and chlorinated compounds like polychlorinated biphenyls (PCB), pentchlorphenol (PCP), chlorinated hydrocarbons, chlorinated pesticides, polychlorinated dibenzodioxins (PCDD), and polychlorinated dibenzofurans (PCDF). (Koning, et al., 2000).

The *ex situ* chemical/physical remediation process known as soil scrubbing uses mechanical energy to separate the pollutants from the soil. The soil is crushed and then separated via sieving. This ensures that the soil sample is homogeneous. The soil is then dispersed in liquid. Water, which is sometimes enhanced with an additive, is used to dissolve the pollutant. The additives are used to overcome the bonding forces between the pollutants and the soil particles. The soil is then separated into two categories: low density and high-density solids. Highly polluted fine particles are then separated out and dewatered. The particles are then rinsed with uncontaminated water. The wastewater and exhaust air are then purified. Soil scrubbing is most effective when removing BTEX, TPH, PAH, PCB, heavy metals, and dioxins. (Koning, et al., 2000).

Ex situ biological processes include: composting, landfarming, biopiling and the use of bioreactors. Composting consists of excavating the soil and then mixing organics such as wood, hay, manure, and vegetative waste with the contaminated soil. . (Van Deuren, et al, 2002). The organics are chosen based on their ability to provide the proper porosity and carbon and nitrogen balances to aid in the breakdown of contaminants. Maintaining thermophilic temperatures 54 to 65°C is an important part of composting. In most cases, the indigenous microorganisms maintain this temperature while degrading the contaminant. Composting is most effective when removing PAH, TNT, and RDX. (Van Deuren, et al, 2002).

Landfarming is a process in which the soil is excavated and mechanically separated via sieving. The polluted soil is then place in layers no more than 0.4 meters thick. A synthetic, concrete, or clay membrane is then used to cover the contaminated soil layer. Oxygen is added and mixing occurs via plowing, harrowing, or milling. Nutrients and moisture may also be added to aid the remediation process. The pH of the soil is also regulated (keeping it near 7.0) using crushed limestone or agricultural lime. (Van Deuren, et al, 2002). Landfarming is most successful in removing PAH and PCP. Figure 1 illustrates the landfarming technique.

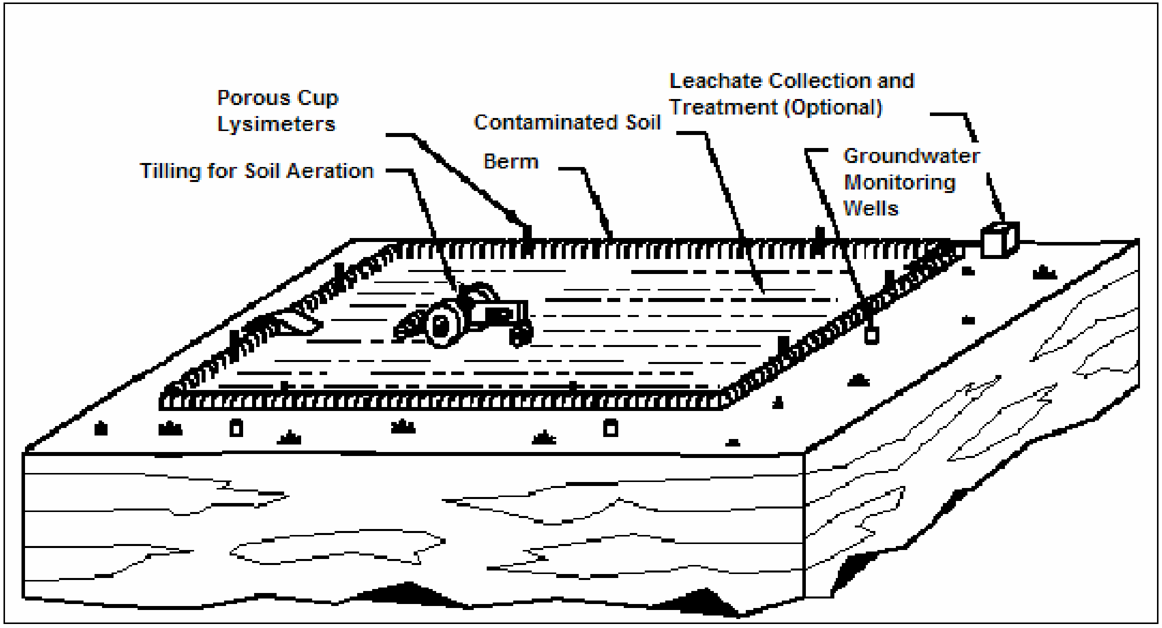

Figure 1: Landfarming Technique
(Source: United States Environmental Protection Agency, 2004)

Biopiling is an *in situ* process that is also known as the heap technique. The first step in the biopiling process is to perform laboratory tests that will determine the biological degradation capabilities of the soil sample. The next step involves the mechanical separation of the soil, which will homogenize the sample and remove any disruptive material such as plastics, metals, and stones. The stones will then be crushed into smaller pieces and then depending on the degree of contamination will either be added to a pile or sent out for reuse. The soil is then homogenized, meaning that the pollution concentration is averaged out across the entire soil sample. Homogenization allows for biopiling to be more effective. (Schulz-Berendt, 2000).

Once the soil is piled, nutrients, microbes, oxygen, and substrate are added to start the biological degradation of the contaminants. The results of the initial laboratory tests indicate to the operators which substrates such as bark, lime, or composts needs to be added to the soil. Nutrients such as mineral fertilizers may also be added. Additionally, microorganisms such as fungi, bacteria, or enzymes could be added. (Schulz-Berendt, 2000.)

Static piles are usually in the form of pyramids or trapezoids. Their heights vary between 0.8 and 2m depending on the type of aeration used (either passive or active). Dynamic biopiles are consistently plowed and turned to maximize their exposure to increase the bioavailability of the contaminants by constantly exposing them to oxygen, water, nutrients, and microbes. (Koning, et al, 2000). No matter which types of heaps are used, the area below each heap must be covered in asphalt or concrete to prevent the seepage of contaminants and the area above the heaps must be covered in order to control temperature and moisture content conditions. (Schulz-Berendt, 2000). A diagram for the heap techniques is shown in Figure 2.

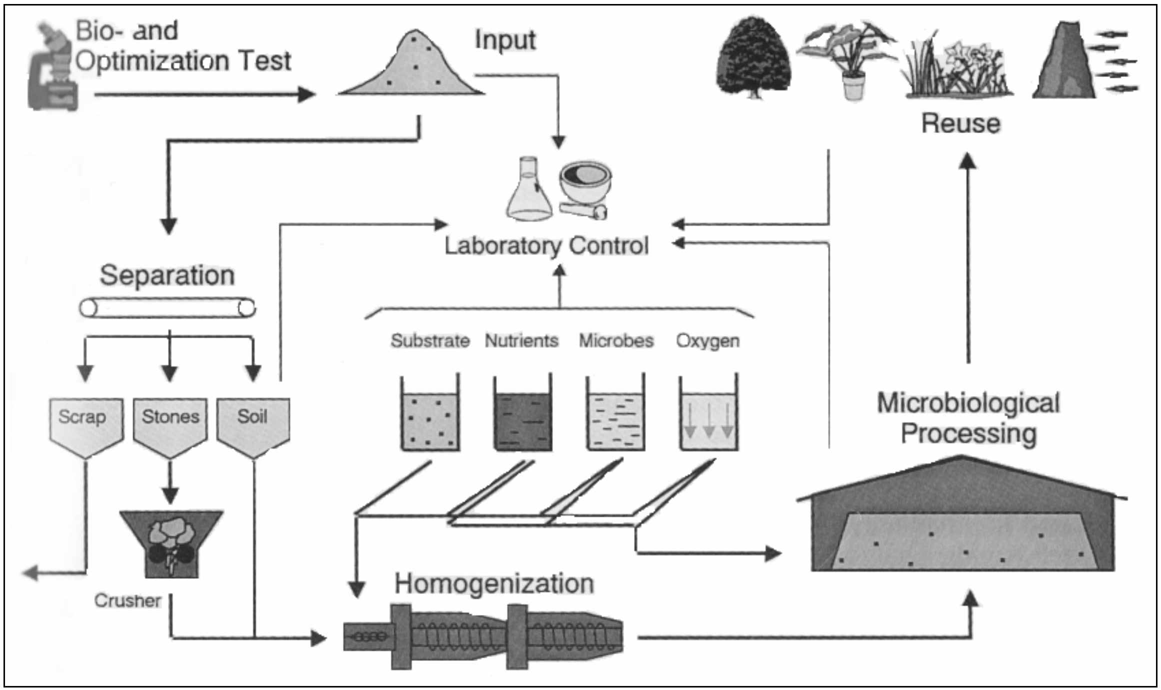

Figure 2: Heap Technique Diagram.
(Source: Schulz-Berendt, 2000).

Biopiling is most effective in treating pollutants such as BTEX, phenols, PAHs with up to 4 aromatic rings, and explosives such as TNT and RDX. (Schulz-Berendt, 2000, Van Deuren, et al, 2002). Each pollutant requires slight modifications to the basic technique. A specific modification is applied to volatile hydrocarbons. These volatile gases must be removed with a soil vapor extraction system and treatment biofilters and activated carbon filters. The heap technique is very economically efficient due to its low installation cost. The cost of operation is also low due to the low cost technology used in the treatment. More and more treatment plants are being built, which reduces the transportation costs, but government regulation are becoming stricter making it more expensive to transport and eventually dispose of the soil. (Schulz-Berendt, 2000).

Bioreactors treat contaminated soils in both solid and liquid (slurry) phases. The solid phase treatment process mechanically decomposes the soil by attrition and mixing in a closed container. The objective of the mixing is to guarantee that the pollutants, water, air, nutrients, and microorganisms are in permanent contact. An acid or alkalinity may also be added to control the pH. (Van Deuren, et al, 2002). In fixed bed reactors, composts is added and significantly increases the degradation rate. In rotating drum reactors, the drum has a screw like mechanism in the middle of it that rotates to mix and transport the soil. The liquid phase treatment process uses suspension bioreactors and treats soils as slurry. The slurry feed enters the system and is rinsed through a vibrating screen to remove debris. Sand is then removed using a sieve or hydrocyclone. If a hydrocyclone is used to remove the sand, the sand falls to the bottom of the cyclone and the fines remain on top. The fines are then treated in a bioreactor. After the treatment, the slurry must be dewatered and the water is then treated with standard wastewater techniques. (Kleinjntnens and Luyben, 2000). A typical slurry bioreactor setup is illustrated in Figure 3.

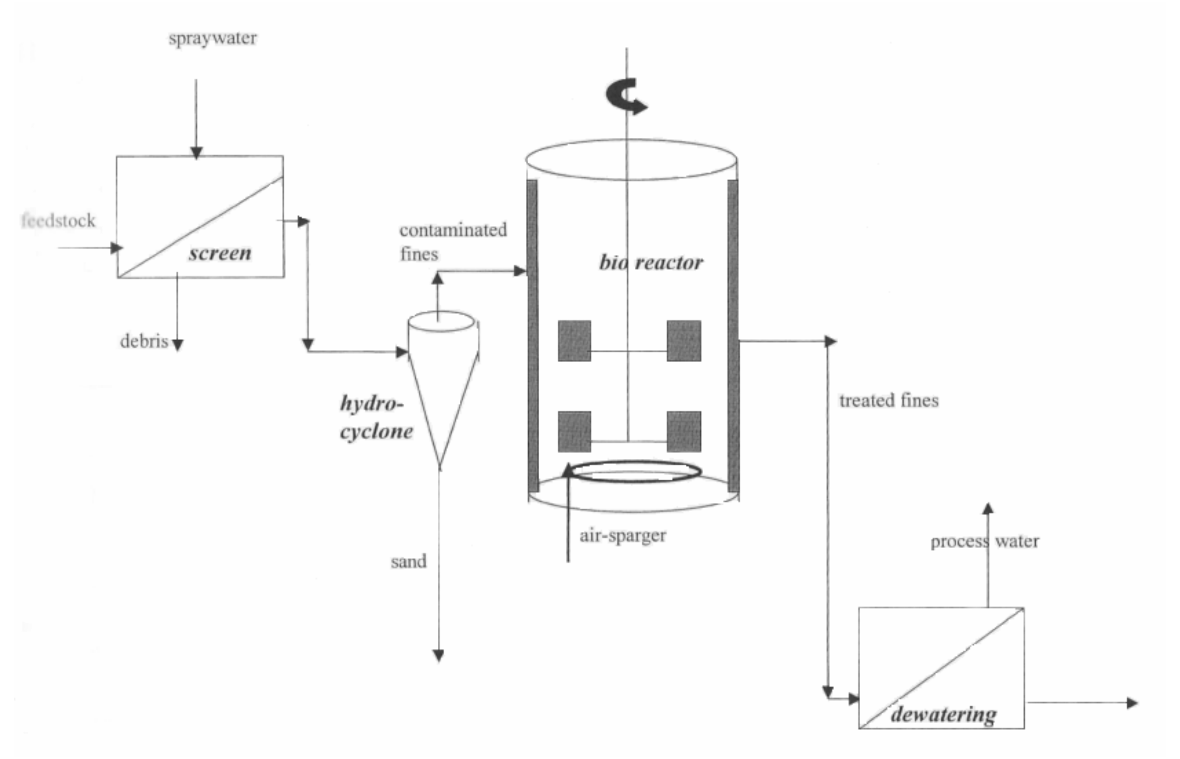

Figure 3: Typical Slurry Bioreactor.
(Source: Kleinjntnens and Luyben, 2000).

A major advantage of *ex situ* bioremediation processes is that most of the decontaminated soil can be reused. Due to the *ex situ* techniques used to decontaminate the soil, much of the soil cannot be used as filling or agricultural material. The soil can, however, be used for landscaping purposes. If soils are treated with thermal processes or a wet scrubber they may be reused as filling material. A key factor in determining the applicability of soil reuse is the toxicological assessment. Bioassays must be conducted in order to determine the impacts the soil will have on the surrounding area. (Koning, et al., 2000).

IN SITU REMEDIATION TECHNIQUES

In situ remediation includes techniques such as bioventing, biosparging, bioslurping and phytoremediation along with physical, chemical, and thermal processes. *In situ* remediation is less costly due to the lack of excavation and transportation costs, but these remediation techniques are less controllable and less effective. (Koning, et al., 2000). Figure 4 illustrates the localization of selected *in situ* bioremediation processes.

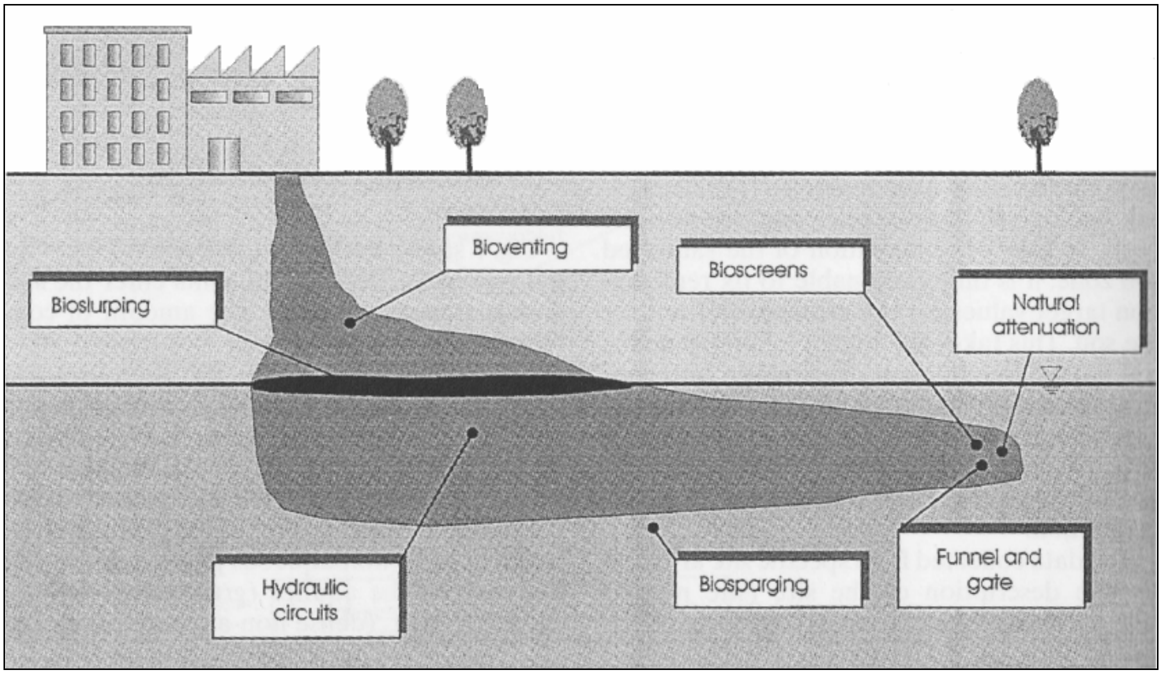

Figure 4: Localization of different microbial *in situ* technologies.
(Source: Held and Dörr, 2000).

In situ thermal processes are still in the developmental phase. The process involves injecting a steam-air mixture at 60-100°C into the soil. In order to avoid the transport of pollutants to the groundwater, the steam-air mixture must stay in that temperature range. After the injection, volatile and semi-volatile compounds transport from the soil to the gas phase. The gases are then removed from the subsurface using a soil vapor extraction system and then treated at the surface. *In situ* thermal remediation is limited for use in only certain soil types, namely homogeneous soils with high permeability and low organic content. *In situ* thermal processes are only appropriate for removing pollutants, which can be stripped in the lower temperature range (e.g. BTEX) (Koning, et al., 2000).

In situ chemical/physical processes are sometimes referred to as pump and treat processes. The pump and treat process pumps water into the subsurface in order to draw out the contaminants. Surfactants are sometimes added to the water to increase the solubility of the pollutants. The water is then treated with standard wastewater treatment techniques. The pump and treat process is extremely limited by the permeability of the soil. Chemical oxidation is also employed to destroy contaminants such as PAHs and trychloroethylene (TCE). (Koning, et al., 2000). Chemicals such as ozone, permanganate, and peroxide have all been injected into the soil and used to accelerate the destruction of toxic organic compounds. (Van Deuren, et al, 2002).

Another *in situ* chemical/physical process used is soil vapor extraction. Vacuum blowers are used to extract volatile pollutants for the soil through perforated pipes. The volatile pollutants are then treated at the site using activated carbon filters or compost filters. The effectiveness of this technique is dependent on soil characteristics such as moisture content, temperature, and permeability. A high percentage of fine soil or a high degree of saturation can also hinder the effectiveness of soil vapor extraction. (Van Deuren, et al, 2002). Complete decontamination of the soil is rarely achieved with this technique.

Bioventing is the only *in situ* bioremediation technique that allows for the treatment of unsaturated soil. Bioventing is not effective if the water table is within several feet of the surface. (Van Deuren, et al, 2002). uses a vacuum enhanced soil vapor extraction system. Due to the pressure gradient in the soil, atmospheric oxygen flows into the subsurface. This oxygen starts an aerobic contaminant decomposition process. In many cases it is necessary to add nitrogen salts as an additive by sprinkling a nutrient solution on top of the soil or by injecting them into the soil above the contaminated soil zone. (Held and Dörr, 2000).

Sufficient airflow is very important in the design of a bioventing system. The geometry of the exfiltration wells and the need for active or passive air injections are two particular design concerns. If a high concentration of pollutants exists, clogging of the soil pores may occur. In this case, pulsed soil vapor extraction is needed. Low permeability will also hinder Bioventing. If the soil vapors are volatile, they must be treated at the surface with an activated carbon filter or a biofilter. Bioventing is effective in removing petroleum hydrocarbons, aromatic hydrocarbons, and non-volatile hydraulic oils. (Held and Dörr, 2000). Low temperatures hinder the effectiveness of bioventing. Bioventing is normally only effect in areas with high temperatures(Van Deuren, et al, 2002). Figure 5 illustrates a typical bioventing system.

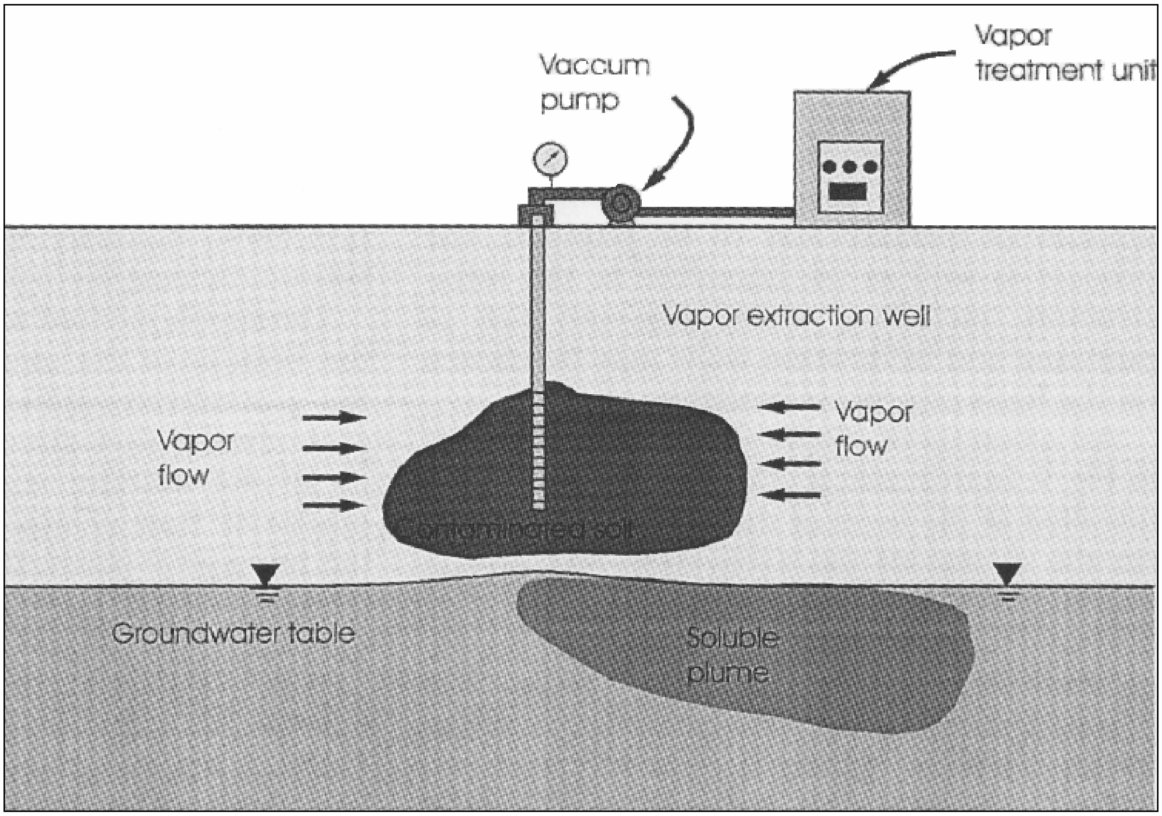

Figure 5: Illustration of bioventing system.
(Source: Held and Dörr, 2000).

Biosparging is the injection of atmospheric air into the aquifer. It is used in both saturated and unsaturated soil zones. The technique was developed to reduce the consumption of energy. The injection of air into the aquifer results in small channels for the air to move to the unsaturated soil zone. In order to form the necessary numerous branches in these channels, the air must be pulsed into these soil. Biosparging results in volatile contaminants being transported to the unsaturated zone, therefore soil vapor extraction is usually used to extract the volatile vapors and then treat them at the surface. (Held and Dörr, 2000).

In order for biosparging to be effective, the sparge points must be installed below the contamination zone because air always flows upward. The upflow of air will form an influence cone. The degree of branching and the angle of the cone are determined by the amount of air pressure during the injection. The degree of influence for each sparge point is determined by a pilot test. Monitoring wells are installed around the point and then the groundwater level and dissolved oxygen content are measured to determine the zone of influence for the sparge point. In order to effectively remove contaminants from the soil using biosparging, the soil should be relatively homogeneous throughout the contamination zone. (Held and Dörr, 2000). Figure 6 illustrates a biosparging system.

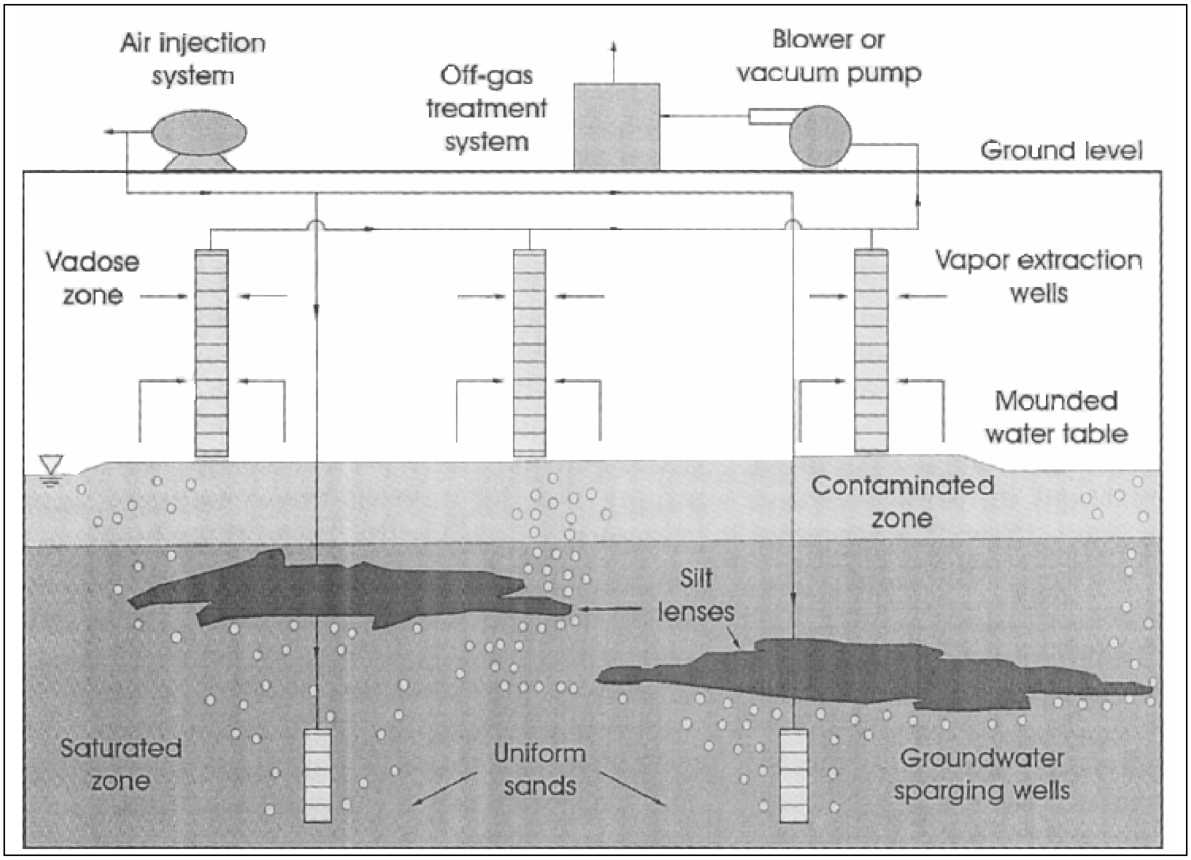

Figure 6: Illustration of biosparging system.
(Source: Held and Dörr, 2000).

A case study performed in the Damodar Valley in Eastern India showed that biosparging was effective at removing 75% of contaminants present within a one year time period. The first results were obtained in the field, but these results were enumerated using a laboratory tests and computer programs. The results from the study were used to set the optimum conditions for remediation including: proper moisture content, pH, temperature, nutrients, and carbon sources. The field tests used six separate tests sites. Different parameters were tested in each site in order to investigate the optimum conditions. (Gogoi, et al, 2002).

Bioslurping is a unique *in situ* treatment technique in that it also treats free product phases floating on top of the groundwater. This technique applies a vacuum to extract, soil vapor, water, and free product from the subsurface. Each of those products is separated and then treated. This technique is cost effective because only a small amount of groundwater and soil vapor are pumped at a time, therefore the treatment plant used to treat the vapor and free product can be small. (Held and Dörr, 2000).

Bioventing, biosparging, and bioslurping are only effective if the soil being treated is homogeneous. If a remediation area has non-homogeneous soil, it may be best to consider passive treatment techniques. Passive treatment involves applying treatment techniques at the ends of contamination plumes. There are 4 different types of passive treatment: activated zones, bioscreens, reactive walls, and reactive trenches. (Koning, et al., 2000).

Activated zone consists of a line of narrow wells. The wells alternate pumping and reinfiltration of groundwater in closed, directly linked loops. Nutrients are injected through the wells to the subsurface. These nutrients stimulate autochthonous microbial populations. This technique is only effective if the hydraulic conductivity in the same in the activated zone as it is in the surrounding aquifer. (Held and Dörr, 2000).

Bioscreens are an attractive treatment option because they have high longevity, no significant maintenance, and no nutrient replenishment. These screens are composed of organic wastes and limestone. The organic wastes not only serve as a high permeability structure, but also as a source of nutrients and bacteria. The bioscreens also have high contaminant retentions and increased bioactivity. The hydraulic conductivity of the material in the bioscreens is 10 times higher than that of the surrounding aquifer. The thickness of the bioscreens depends on groundwater flow rates, the contaminant concentrations, and the degradation rates. (Held and Dörr, 2000).

Phytoremediation is an *in situ* technique that uses plants to remediate contaminated soils. Phytoremediation is most suited for sites where other remediation options are not costs effective, low-level contaminated sites, or in conjunction with other remediation techniques. Deep rooted trees, grasses, legumes, and aquatic plants all have application in the phytoremediation field. Phytoremediation has been used to remove TPH, BTEX, PAH, 2,4,6-trinitrotoluene (TNT), and hexahyro-1,3,5-trinitro-1,3,5 triazine (RDX). (Schnoor, 2000).

Plants are able to remove pollutants from the groundwater and store, metabolize, or volatilize them. Also, roots also help support a wide variety of microorganisms in the subsurface. These microorganisms can then degrade the contaminants. The roots also provide organic carbon sources to promote cometabolism in the rizosphere. The rizosphere is the soil in the area of the vegetative roots. Figure 7 illustrates different phytoremediation techniques.

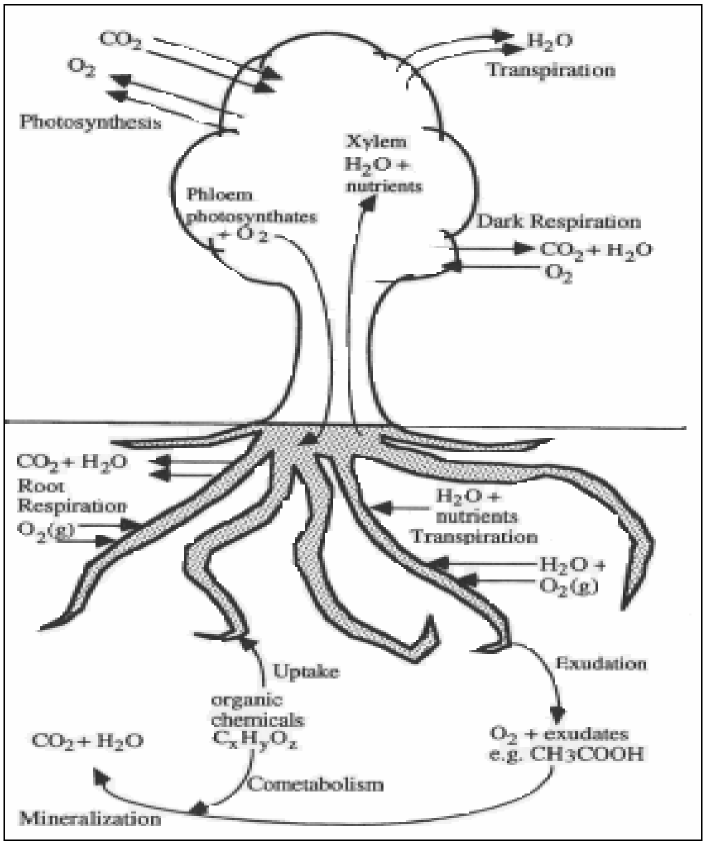

Figure 7: Illustration of phytoremediation.
(Source: Schnoor, 2000.)

CONCLUSIONS

Many processes are explained in the paper above. Choosing the process that is "best" can be a difficult task. "Proper evaluation of bioremediation options begins by determining what constitutes an acceptable cleanup goal; for example, one must determine whether destruction, detoxification, or physical removal of the chemical target(s) is the goal of the remediation. Only after making this decision can one choose, design and conduct an appropriate means of bioremediation." (Shannon and Unterman, 1993).

As state many times before, in situ techniques have the advantage that the soil does not have to be removed or transported, but the techniques lack contaminant removal efficiency. Ex situ techniques remove are more effectively remove the contaminants, but sacrifice economic feasibility due to the costs involved with excavating and transporting the soil. The question becomes, how much can one afford to spend in order to increase the effectiveness of the remediation technique? A summary of which techniques remove specific compounds and which soil parameters are necessary for remediation is shown below in Table 1. The summary is a compilation of information from the paragraphs above.

Remediation Technique	Effectively Removed Compounds	Soil Constraints
Ex Situ Techniques		
Thermal Remediation	TPH, PAH, BTEX, PCB, PCP, PCDD, PCDF	No specific constraints
Soil Scrubbing	TPH, BTEX, PAH, PCB, heavy metals, dioxins	Must be made homogeneous to treat
Landfarming	PAH, PCP	No specific constraints
Biopiling	BTEX, PAH, TNT, RDX	Must be made homogeneous to treat
Bioreactors	PAH, PCB	Must be separated by particle size in order to treat
In Situ Techniques		
Thermal Remediation	BTEX	Must be homogeneous, have high permeability and low organic content
Chemical Oxidation	PAH, TCE	Must be permeable
Soil Vapor Extraction	BTEX	Must have low percent fines and correct moisture content
Bioventing	PAH, nonchlorinated solvents	Must be homogenous, may be unsaturated
Biosparging	PAH, nonchlorinated solvents	Must be homogenous and saturated
Bioslurping	Free Product (Petroleum)	Must be homogenous and saturated
Phytoremediation	TPH, BTEX, PAH, TNT, RDX	Must have contamination in shallow soil

Table 1: Compound Removal and Soil Constraints for Various Remediation Techniques

The difficult part of evaluating bioremediation techniques is that there are no standard criteria for evaluating among methods. This hurdle can be attributed to each site being different. The applicability of bioremediation techniques requires particularly close evaluation of each site. Soil conditions such as porosity, pH, moisture content, and presence terminal electron acceptors all affect which remediation technique can me used. Technique selection also depends on the pollutant that is targeted. Soil conditions, the presence of microbes, and the presence of pollutants must be measured in a treatibility study. These studies take time and money and cause some opposition to bioremediation. (Boopathy, 2000). Table 2 provides a cost comparison for common remediation techniques and some of the conditions of the cost analysis.

Remediation Technique	Cost Range, $\$/yd^3$	Influencing Factors
Ex Situ Techniques		*Excavation and Transportation costs not included
Thermal Remediation	40 -1171	The use of incineration or desorption, fuel cost and quantity of soil treated in each batch
Soil Scrubbing	53-142	The quantity of soil treated in each batch and the pollutants being removed
Landfarming	75	Does not include cost of pilot study or lab tests which are substantial
Biopiling	30-60	The contaminant being treated, the need for pre and post treatment, and the possible need for emission control
Bioreactors	100-160	The use of a slurry or solid reactor; does not include infrastructure costs
In Situ Techniques		
Thermal Remediation	25-100	The specific method of thermal remediation used
Chemical Oxidation	No Data Found	No Data Found
Soil Vapor Extraction	300-1100	The contaminant being treated, the amount of time available to perform treatment, the number of wells needed for treatment
Bioventing	60-742	The contaminant concentration, the number of vent wells needed, the soil conditions
Biosparging	60-742	The contaminant concentration, the number of sparge points needed, the soil conditions
Bioslurping	No Data Found	No Data Found
Phytoremediation	112-1775	The number of trees planted in a specific area and the amount of contaminant present

Table 2: Remediation Technique Cost Comparison
(Source: Van Deuren, et al, 2002).

Contrary to what some people in the industry believe, bioremediation really does work to remove many different pollutants for soils. One of the greatest obstacles to overcome is the need for an engineering and scientific knowledge base. For bioremediation to be successful, researches, regulators, design engineers, and contractors need to understand the basic science behind these techniques and how that science can be applied to specific contaminated sites. (Shannon and Unterman, 2000).

Another obstacle hindering wide scale bioremediation application is regulatory factors. The government regulates how a waste must be cleaned up. Because bioremediation is a relatively new technique compared to more established methods such as chemical and thermal removal methods, and the government sees encouraging bioremediation as a risk. If bioremediation of a certain site does not meet certain clean up goals set forth by a certain time, it is seen as a greater liability. The government also has many health and safety regulations to control the remediation processes. In addition, because microbes are injected into the soil that some crops are grown in, the Food and Drug Administration regulates soil remediation techniques as well. Genetically engineered microorganisms are also regulated through the toxic substance control act. Due to all of the “red tape” surrounding bioremediation regulations, some design engineers have avoided bioremediation processes. (Boopathy, 2000).

Due to the fact that specific microorganisms are needed to remove specific contaminants much more basic research is needed to find matches between the two. The money for this type of research and development is quickly disappearing. Bioremediation at this time does not turn a high profit, so many venture capitalist are looking to other technologies to invest in. Because of this, the research and development on bioremediation is much slower than that of other technologies. Academia may also be partially to blame for the skepticism behind bioremediation. No universities offer a program for bioremediation engineering.

Bioremediation needs people with a background in geology, hydrogeology, microbiology, environmental engineering, ecology, and geotechnical engineering. A person with one of those degrees must receive years of field experience before being properly trained to fully perform in the bioremediation field. (Boopathy, 2000).

As research and development of bioremediation slowly continues and becomes more proven to work, the government is easing their regulations of the use of this technology. (Boopathy). Research will continue and eventually bioremediation will become easier and more time and cost effective. More and more matches between microorganisms and the contaminants they can remove will be made. Eventually a standard method of directly comparing bioremediation techniques will be developed. It is also that hope that eventually microorganisms will be able to make in situ bioremediation more efficient at degrading contaminants to make it the front runner in bioremediation techniques. For now, the industry is left with the task of choosing between the degree of biodegradation and cost effectiveness of the method.

LIST OF REFERENCES

"Bioterms." Bioremediation Discussion Group. BioGroup. 1 Oct. 2006 <http://www.bioremediationgroup.org/BioTerms/Home.htm#B>.

Boopathy, R., (2000) Factors Limiting Bioremediation Technologies, *Bioresources Technology,* 74,1,63-67.

Gogoi, B.K., Dutta, N.N., Goswami, P., Krishna Mohen, T.R., (2002) A Case Study of Petroleum-hydrocarbon Contaminated Soil at a Crude Oil Site, *Advances in Environmental Research,* 7,4, 767-782.

Iranzo, M., Sainz-Padro, I., Boluda, R., Sanchez, J., and Mormeneo, S., (2001) The Use of Microorganisms in Environmental Engineering, *Annals of Microbiology,* 51, 135-143.

Held, T., and Dörr, H. (2000) *In Situ* Remediation, *Biotechnology*, 11b, 350-370.

Klein, J. (2000) Possibilities, Limits and Future Developments of Soil Bioremediation, *Biotechnology*, 11b, 466-476.

Kleijntjens, R. H., and Luyben, K. C. A. M. (2000) Bioremediation, *Biotechnology*, 11b, 329-347.

Koning, M., Hupe, K., and Stegmann, R. (2000) Thermal Processes, Scrubbing/Extraction, Bioremediation and Disposal. *Biotechnology*, 11b, 306-317.

"Landfarming." How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: a Guide for Corrective Action Plan Reviewers. May 2004. Environmental Protection Agency. 1 Oct. 2006 <http://www.epa.gov/OUST/pubs/tum_ch5.pdf>.

"Remediation Technologies Screening Matrix." Jan. 2002. Federal Remediation Technologies Roundtable. 1 Oct. 2006 <http://www.frtr.gov/matrix2/section1/toc.html>.

Schnoor, J.L. (2000) Degradation by Plants-Phytoremediation, *Biotechnology*, 11b, 372-384.

Schulz-Berendt, V. (2000) Bioremediation with Heap Technique. *Biotechnology*, 11b, 320-328.

Shannon, M.J.R., and Unterman, R., (1993) Evaluation Bioremediation: Distinguishing Fact from Fiction, *Annual Review of Microbiology,* 47, 715-738.

Van Deuren, J., Lloyd, T., Chhetry, S., Raycharn, L., Peck, J., (2002) Remediation Technologies Screening Matrix and Reference Guide, *Federal Remediation Technologies Roundtable*, 4.