# Bioremediation of Hydrocarbons in Landfarms

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## Introduction

Bioremediation by landfarming is often the best, as well as the most cost-effective, technology available for treatment of hydrocarbon impacted soils and is endorsed by state and federal agencies across the U.S. Landfarming eliminates the threat of toxic, mobile hydrocarbons to public health, groundwater, and the environment. Regulations which encourage the use of landfarming will serve to limit the isolation of mobile, toxic hydrocarbons in landfills. Landfarming is effective and easy to implement–it's just good gardening.

## The nature of crude oil and the potential for hydrocarbon biodegradation

Crude oil is made up of a variety of classes of nonpolar hydrocarbons (containing only carbon and hydrogen) and, to a lesser extent, polar hydrocarbons (also containing oxygen, nitrogen, and/or sulfur) as shown in Figure 1. Crude oil compositions vary widely around the world but 95% of the world's crude oils can be characterized as 40-80% saturates, 15-40% aromatics, and 0-20% asphaltenes and resins. Crude oils are also characterized in terms of distillation fractions which make up components of fuels, industrial solvents, and lubricating oil as illustrated by Figure 2. Also shown in Figure 2 are two fractions widely known to the lay person as medicinal products, vaseline and mineral oil.

A common way to characterize hydrocarbons, including crude oil, is by gas chromatography. In this analysis hydrocarbons are flash vaporized and pass through the column containing an adsorbent. In the column individual hydrocarbons are separated on the basis of boiling point and affinity for the adsorbent. In general light hydrocarbons exit the column first followed by hydrocarbons with increasing carbon number. An example of the result of this type of analysis of a crude oil, called a chromatogram, is shown in Figure 3. Notice the large spikes in the chromatogram. This is often a dominant feature of the GC chromatogram of a crude oil and represents the n-alkane series. Each of these large spikes is an unbranched hydrocarbon chain with increasing carbon number from left to right. You will also note a number of small spikes and even an unresolved hump in the chromatogram. The small size of these spikes indicates their low abundance in the crude oil and the hump is composed of many small spikes that cannot be resolved by the instrument. One reason for this multitude of components is structural isomerism. As the number of carbons in a hydrocarbon increases the number of ways those hydrocarbons can be arranged increases exponentially. Since structural isomers are similar in their chemical and physical properties they do not differ significantly in their boiling points or affinity for the adsorbent in the column and, therefore, are not well separated. Likewise structural isomers can behave in a similar manner in the environment.

Hydrocarbons are a natural product resulting from primarily plant material being buried and subjected to heat and pressure over millions of years. Hydrocarbons have been available in the biosphere for millions of years so it should come as no surprise that many types of bacteria and fungi have adapted to use hydrocarbons as food. Microorganisms capable of using hydrocarbons are widely distributed in nature and readily found in soil, surface waters, groundwater, and sea water. In the process of using hydrocarbons for food much of the hydrocarbons are oxidized to carbon dioxide and water with the remaining converted into biomass as the organisms grow and reproduce. Research has shown that a wide variety of hydrocarbons are susceptible to biodegradation. The most readily degradable hydrocarbons are found in the n-alkane series. There are more known examples of microbes capable of using n-alkanes as food than any other class of hydrocarbons. However, many other structural classes of hydrocarbons are also biodegradable by individual types of microbes or by communities of microbes acting together in a process called co-metabolism in which different organisms play different roles in the breakdown of certain hydrocarbons. The net effect is that many different types of hydrocarbons (nonpolar and polar) are degraded by the diverse microbial communities found in soils, surface waters, groundwater, and sea water (although different classes of hydrocarbons are usually degraded at different rates). This is illustrated in Figure 4. In this experiment sea water was supplemented with nitrogen and phosphorous nutrients and a layer of crude oil added. The mixture was agitated on a shaker for 14 days for aeration. Before and after the experiment hydrocarbon was extracted from the mixture and separated into saturate and aromatic fractions with each fraction characterized by gas chromatography. Remembering that each spike represents a different hydrocarbon and the height of the spike represents how much of that hydrocarbon is present in the sample, it is clearly seen that many, many different hydrocarbons were significantly biodegraded after only 14 days. The microbes that degraded these hydrocarbons were naturally present in the sea water. As already noted these types of hydrocarbon degraders are also naturally present in soil and fresh water.

An often asked question is "if the hydrocarbons are biodegradable and hydrocarbon degrading organisms are ubiquitous in nature why doesn't a hydrocarbon spill just go away by itself – eaten by the bugs?" There are several reasons. First, microbes need more in their diet than hydrocarbons. It takes more than carbon and hydrogen to build a bug. The two major nutritional needs of the microbes (other than the hydrocarbons) are nitrogen and phosphorous. These same nutrients are required by plants for growth and microbes need them for the same reason. Soil contains limited amounts of these nutrients, seldom in concentrations that can support growth of microbes on any significant amount of hydrocarbon. So one reason that hydrocarbons persist in soil is that the bugs can't get enough nitrogen and phosphorus. The second reason a hydrocarbons spill tends to persist in soil is that the microbes have to get together with the hydrocarbon before utilization can occur. Just like you and I cannot eat a steak that's across the room, the bugs have to come in contact with the hydrocarbons before they can eat the hydrocarbon. Microbes live in soil moisture. Therefore, either the hydrocarbon has to dissolve in the soil moisture or the soil moisture has to be in physical contact with the hydrocarbon for the microbes to get to it. For a spill then microbes can only eat around the edges. Lastly, efficient biodegradation of hydrocarbons requires oxygen which enters soil by diffusion from the atmosphere. So now you see you have to get the microbe, the hydrocarbon, nitrogen and phosphorous, and oxygen all together in one place for biodegradation to take place. Soil moisture then not only hydrates the microbes so they will grow, it is also the conduit through which all the necessary ingredients come together. Again this can only happen around the edges of a spill. Not only does this explain why a hydrocarbon spill persists in soil it also reveals how to increase hydrocarbon biodegradation to remediate hydrocarbon-impacted soil – just good gardening.

**Bioremediation of hydrocarbon-impacted soil in a landfarm**

As the above discussion illustrates the bioremediation of hydrocarbon impacted soil in a landfarm requires good gardening practice: tilling to supply oxygen, fertilizers to supply nitrogen and phosphorous, supplying moisture, organic matter to prop open the soil for aeration and moisture retention, and lots of good contact between soil moisture and the hydrocarbon. When all these conditions are met and temperature and pH are conducive to microbial growth, the decline in the concentration of hydrocarbon with time generally follows the pattern illustrated in Figure 5. There is characteristically an initial rapid rate of decrease in hydrocarbon concentrations reflecting the biodegradation of readily bioavailable hydrocarbons. This is illustrated by Figure 6 which shows that there is an increase in carbon dioxide production and numbers of hydrocarbon-degrading bacteria while hydrocarbon concentrations are declining. The rate of biodegradation during this phase is dependent upon the nature of the hydrocarbon, environmental conditions, and the availability of oxygen and nutrients. Eventually though the rate of decrease in hydrocarbon concentration slows to essentially zero although some hydrocarbons remain in the soil. This will be the case for most hydrocarbon types even if all other conditions are optimum for microbial growth. The remaining hydrocarbons at this stage consists of a mixture heavy hydrocarbons that have resisted biodegradation either because they are biologically recalcitrant and/or have become sequestered within glassy soil organic matter or within the tiny cracks and pores of soil mineral particles. Hydrocarbons associated with the organic matter and mineral particles become nonbioavailable and only accessible if they diffuse out of their hiding place. This is a very slow process. At this stage the biodegradation of hydrocarbons has become diffusion controlled and we have reached a "bioremediation endpoint".

**Is a bioremediation endpoint an environmentally acceptable endpoint?**

The nature of the bioremediation endpoint, in terms of the residual hydrocarbon concentration and residual toxicity, have been reported in the scientific literature by many authors with very similar results. This topic will be discussed here by way of review of a paper by Salinitro et al. [(Environmental Science and Technology, **31**, 1769-1776 (1997)]. This paper was chosen for the completeness of its treatment of this subject and because it was published in the most highly respected environmental science journal in the world (and, therefore, rigorously reviewed) as well as cited in a EPA publication as being a work of high scientific quality. In this work Salinitro et al. investigated the biodegradation of three crude oils (API gravities of 14, 30 and 55) in soil with different concentrations of organic matter (0.4 and 4.7%). Hydrocarbon or TPH endpoints were determined and residual toxicity in the soil and the composition of the leachate from the soil investigated. Figures 7 and 8 summarize their findings in terms of the concentrations residual hydrocarbon at the bioremediation endpoint. As seen here residual hydrocarbon concentrations in the soil at API gravities of 14 and 30 exceeded 2500 mg/kg either as C11-C44 or C11-C32 (which approximates a TPH-DRO). Figure 9 shows the observed percent reduction in concentrations for three hydrocarbon fractions. Percent reduction was seen to decrease with increasing carbon number reflecting the greater tendency of heavier hydrocarbons to become sequestered in the soil. The percent reduction within each fraction generally decreased with decreasing API gravity (more pronounced at the lower concentration of organic matter) reflecting the greater concentrations of heavy components with decreasing API gravities.

Table 1 shows the observed bioremediation endpoints in terms of BTEX concentrations. Benzene and TEX concentrations were all below the detection limits (< 0.02 mg/kg) of the analytical method employed after the bioremediation endpoints were achieved.

**Table 1. Bioremedation endpoints in terms of BTEX in Salinitro et al. experiments**

| % Soil Organic Carbon | API Gravity | Benzene Untreated (mg/kg) | Benzene Bioremediated (mg/kg) | TEX Untreated (mg/kg) | TEX Bioremediated (mg/kg) |
|---|---|---|---|---|---|
| 0.3 | 14 | <0.02 | <0.02 | 1.6 | <0.02 |
| | 30 | 3.2 | <0.02 | 256 | <0.02 |
| | 55 | 63.7 | <0.02 | 1027 | <0.02 |
| 4.7 | 14 | 1.8 | <0.02 | 43.4 | <0.02 |
| | 30 | 10.0 | <0.02 | 35.0 | <0.02 |
| | 55 | 53.0 | <0.02 | 1624 | <0.02 |

Salinitro et al. also investigated the effect of bioremediation on toxicity in the soil as measured by earthworm survival, Microtox, and seed germination (corn, oats, wheat). Microtox is a lab-based technique for quantifying toxicity in soils. Extracts of the soils are exposed to a marine phosphorescent bacterium. The amount of toxicity in the sample is then related to any diminishing of the light produced by the bacterium. Results of Salinitro et al.'s experiments are shown in Figures 10-12. All of the untreated soils were shown to be toxic by each measure and toxicity was shown to decrease in each soil during bioremediation. At the bioremediation endpoints no toxicity was detected by any of the three methods.

Salinitro et al. also conducted leaching studies on bioremediatied soil from each experiment using both batch soil extraction and column leaching experiments. Results of batch extractions in terms of oil and grease (O&G) in the extracts are shown in Table 2. In each extract TPH concentrations were below 5 mg/L and BTEX concentrations were below 5 μg/L and no heavy metals were observed (data not shown). Results of column leaching studies are shown in Table 3. Benzene concentrations were all < 2 μg/L and again no heavy metals were observed. These results show that the leaching potential of BTEX components from bioremediated soil was very low. Therefore, leaching from bioremediated soil represents a very low risk especially when the very high biodegradability of these compounds is considered (these compounds would be rapidly biodegraded in the soil column).

In summary, the Salinitro et al. paper makes two important points. First, **the hydrocarbon concentration in soil at the bioremediation endpoint is dependent upon the nature of the hydrocarbon (like API gravity) and soil properties (like percent organic matter).** Salinitro et al.'s observations in this regard are summarized by Figure 13. Others have made very similar observations as illustrated by Figure 14 which summaries experience presented to a DOE workshop on bioremediation. Second, **regardless of the hydrocarbon concentration at the bioremediation endpoint, toxicity was eliminated**. Likewise, Salinitro et al. are not alone in this observation. Table 4 provides a listing of similar observations that have been published in the scientific literature. **Therefore, it is safe to say that the bioremediation endpoint is protective of public health, groundwater, and the environment.**

**Table 2. Batch extraction of bioremediated soils**

| % Organic Carbon | API Gravity | O&G (mg/L) after extraction 1* | 2 | 3 | 5 |
|---|---|---|---|---|---|
| 4.7 | 14 | 15 | 11 | 7 | <5 |
| | 30 | 30 | 17 | 12 | 9 |
| | 55 | 12 | <5 | <5 | <5 |
| 0.3 | 14 | 16 | 11 | 9 | 6 |
| | 30 | 31 | 16 | 14 | 8 |
| | 55 | <5 | <5 | <5 | <5 |

* number of extractions

**Table 3. Results of column leaching of bioremediated soils**

| | | B (μg/L) | B (μg/L) | TEX (μg/L) | TEX (μg/L) |
|---|---|---|---|---|---|
| % Organic Carbon | API Gravity | Untreated | Bioremediated | Untreated | Bioremediated |
| 4.7 | 14 | <2 | <2 | 17 | 2 |
| | 30 | 630 | <2 | 5260 | 8 |
| | 55 | 4900 | <2 | 18270 | 6 |
| 0.3 | 14 | 160 | <2 | 700 | <2 |
| | 30 | 1660 | <2 | 5980 | 48 |
| | 55 | 7690 | <2 | 16980 | 5 |

**Table 4. Reports of removal of hydrocarbon toxicity in soil by bioremediation**

| Reference | Hydrocarbon Type | Toxicity Metric |
|---|---|---|
| Hanna and Weaver, Plant and Soil Science, **240**, 127-132 (2002) | Crude oil | Earthworm survival |
| Visser and Danielson, CAPP Publ. 1995-0004, CAPP (1995) | Crude oil | Earthworm survival<br>Seed germination<br>Plant root elongation |
| Chaineau et al., Water, Air, and Soil Pollution, **144**, 419-440 (2003) | Crude oil | Earthworm survival<br>Seed germination<br>Microtox |
| Tang et al., Environmental Science and Technology, **32**, 3586-3590 (1998) | PAHs | Earthworm survival |
| Hund and Trannspurger, Chemosphere, **29**, 371-390 (1994) | PAHs | Earthworm survival<br>Plant survival<br>Nematode survival |
| Salanitro et al., Environmental Science and Technology, **31**, 1769-1776 (1997) | Light, medium, and heavy crude oils | Earthworm survival<br>Seed germination<br>Plant growth<br>Microtox |

**Table 4. cont.**

| Reference | Hydrocarbon Type | Toxicity Metric |
|---|---|---|
| Siddiqui and Adams, Environmental Toxicology, **17**, 49-62 (2002) | Diesel | Seed germination |
| Marwood et al., Environmental Toxicology and Water Quality, **13**, 117-126 (1998) | Diesel | Seed germination<br>Seedling emergence<br>Root elongation |
| Renoux et al., Microbial Processes in Bioremediation, **3**, 259-264 (1995) | Crude oil | Earthworm survival<br>Seed germination<br>Plant growth |
| Baek et al., Journal of Environmental Science and Health, **39**, 2465-2472 (2004) | Crude oil | Plant growth |
| **Reference** | **Hydrocarbon Type** | **Toxicity Metric** |
| Haeseler et al., Environmental Science and Technology, **24**, 4379-4384 (1999) | PAHs | Microtox<br>Genotoxicity |
| Bundy et al., Soil Biology and Biochemistry, **36**, 1149-1159 (2004) | Paraffin<br>Motor oil | Microtox |
| Saterbak et al., Environmental Toxicology and Chemistry, **19**, 2643-2652 (200) | Crude oil | Earthworm survival<br>Seed germination |
| Wang and Bartha, Biology and Biochemistry, **22**, 501-505 (1990) | Jet fuel<br>Diesel<br>Heating oil | Microtox<br>Seed germination<br>Plant growth |
| Van Gestel et al., Environmental Toxicology and Chemistry, **20**, 1438-1449 (2001) | Crude oil<br>Refined product mixture | Microtox<br>Earthworm survival<br>Plant growth<br>Algae survival<br>*Daphnia magna* survival |
| Molina-Barahona et al., Environmental Toxicology, **20**, 100-109 (2005) | Diesel | Plant growth<br>*Daphnia magna* survival |

**Recommended practice for permitted landfarms**

Clearly bioremediation of hydrocarbon impacted soils is desirable and beneficial to society, as well as easy to implement. The destruction of toxic components of crude oil and condensate is more protective of public health, groundwater, and the environment than landfill disposal which simply attempts to lock the problem away. Attachment A is a summary of recommended practice for permitted landfarms. Lift closure in this document is based on achieving a bioremediation endpoint. Documenting the bioremediation endpoint should be attempted when two conditions are met: 1) the landfarm has been operated following recommended practice for a minimum of 6 treatment months when treating gasoline or gas condensate or 12 treatment months when treating crude oil, tank bottoms and sludges, drill cuttings or diesel and 2) field measurements of TPH levels indicate that the lift is at or near the end of the treatment cycle. A treatment month is defined as a 30-day increment in which the maximum 4-inch bare soil temperature is above 50 °F The bioremediation endpoint can be documented with two successive TPH-DRO and/or TPH-GRO (if condensate is present) measurements at least one treatment month apart that are statistically the same.

As discussed above a well defined bioremediation endpoint based on hydrocarbons (in terms of TPH-DRO and/or TPH-DRO) is protective of public health, groundwater, and the environment. However, depending on the wastes accepted in the landfarm other analyses may be appropriate in addition to the bioremediation endpoint for hydrocarbons. If wastes other than crude oil- or condensate-impacted soil or drill cuttings (including associated produced water) are accepted, lift and facility closure should also include an appropriate risk analysis to ensure protection of public health, groundwater and the environment.

This view is consistent with the tier system proposed by the Industry Committee in which a Tier 1 permitted landfarm would accept only crude oil- or condensate-impacted soil or drill cuttings (including associated produced water) with total chloride concentrations < 1000 mg/kg. Lift closure in a Tier 1 landfarm would require only the establishment of a bioremediation endpoint or achieving a default hydrocarbon concentration and a chloride concentration < 1000 mg/kg. A Tier 2 permitted landfarm would be able to accept additional exempt wastes (such as tank bottoms) which may include WQCC constituents and chloride concentrations >1000 mg/kg. Lift and facility closure in a Tier 2 landfarm then requires a bioremediation endpoint with respect to hydrocarbons, chloride concentrations protective of groundwater based on a site specific model, and a risk-based analysis based on other components as appropriate.

**OCD requirements inconsistent with recommended practice**

The following requirements for landfarm operation are inconsistent with recommended practice for permitted landfarms as described in Attachment A:

1. G(7)(a)(iii): When using the bioremediation endpoint approach there is a requirement for a minimum TPH reduction of 80%. As demonstrated above toxicity due to hydrocarbons is eliminated by the time a bioremediation endpoint is reached irrespective of the residual hydrocarbon concentration. Therefore, a requirement for a minimum TPH reduction is not supported by science as necessary to be protective of human health, groundwater, and the environment. Further, this requirement will effectively prevent the use of the bioremediation

endpoint approach as Figures 13 and 14 clearly illustrate. Personal communication with the OCD staff indicates that the root of this requirement may be a desire to avoid accumulation of large amounts of weathered asphaltic material in the landfarm which could technically be overlooked since these materials do not effectively bioremediate. If that is the case the industry and the OCD are better served by placing an additional requirement on the maximum amount of solid phase hydrocarbon visible in the landfarm, say a maximum 3% cover and particle sizes < ½ inch. Since these materials should not affect revegetation this would be a purely aesthetic standard. If the desire is to avoid an open ended endpoint for fear of abuse or avoiding possible hydrophobicity issues then a standard which allows a bioremediation endpoint but places a maximum on the residual hydrocarbon concentration is more appropriate than specifying a maximum reduction. A maximum of 1% total extractable petroleum hydrocarbons would be both consistent with standards in other states and also allow wide spread use of the bioremediation endpoint approach in New Mexico.

2. G(7)c(iii): There is a requirement in this paragraph for a maximum loading of hydrocarbons in the landfarm of 5%. This value cannot be supported by science as a maximum loading for all conditions. The most efficient loading for any given type of hydrocarbon in terms of rates of bioremediation depends primarily on soil temperature and API gravity. A wide range of hydrocarbon loadings have been reported to be successfully treated in a landfarm. Rather that restrict an operator to this maximum the regulations should be more flexible with the recognition that the maximum loading will be somewhat self regulating. The

prudent operator will be aware that biodegradation rates decrease with increasing hydrocarbon loading and decreasing API gravity of the hydrocarbons. Much of the biodegradation of hydrocarbons in a landfarm occurs at an interface between hydrocarbon and soil moisture. Therefore, biodegradation rates in a landfarm strongly correlate with the interfacial area/mass ratio of the hydrocarbon. Increasing hydrocarbon loading will generally decrease the interfacial area/mass ratio. Decreasing API gravity (and increasing viscosity) of the hydrocarbon results in less effective dispersal of the hydrocarbon and, therefore, lower interfacial area/mass ratios. The operator can balance a need for high rates of biodegradation with the requirement to meet a maximum 1% total extractable petroleum hydrocarbons as suggested above for lift closure. The operator will then be free to optimize his/her landfarm to achieve his/her desired results while meeting remediation standards.

3. G(9)(c)(i): This paragraph contains a long list of soil parameters that are required to be determined in the soil over which the first landfarm lift will be spread. These parameters include soil porosity, soil bulk density, soil pH, moisture content, field capacity, organic matter content, soil structure, SAR, EC, soil composition, soil temperature, soil nutrient (C:N:P) concentrations, and oxygen content. Some of these parameters are vague and difficult to interpret (such as soil structure and soil composition) and all are irrelevant to the bioremediation process which will occur in the lift soil. The only concern in the soil beneath the landfarm lift is the possible migration of contaminants into the vadose zone. The

background and vadose zone testing already required sufficiently address this concern.

4. G(1)(a): In permitted and small registered landfarms there is a restriction against chloride concentrations > 1000 mg/kg. With respect to bioremediation of hydrocarbons, the 1000 mg/kg chloride limitation on materials treated in a landfarm is not supported by science. The peer-reviewed scientific literature shows the following:
   - The bioremediation of hydrocarbons can occur at chloride concentrations in excess of 1000 mg/kg. Chaineau et al. [Environmental Science and Technology **29**, 1615-1621 (1994)] demonstrated the bioremediation of drill cuttings in soil where initial chloride concentrations were 4000 mg/kg. Sublette et al. [Environmental Geosciences, **12**, 115-125 (2005)] demonstrated the bioremediation of crude oil in the presence of initial chloride concentrations of up to 3000 mg/kg. Rates of TPH reduction were comparable to rates observed in similar sites impacted by crude oil only.
   - Over time hydrocarbon-degrading organisms in a landfarm can adapt and become more tolerant of chlorides. Sublette et al. [Oilfield Brine Remediation Symposium, Baton Rouge, LA (2005)] have demonstrated that certain groups of bacteria which contain hydrocarbon degraders actually increase in proportion in the presence of brine. Nicholson and Fathepure [Applied and Environmental Microbiology, **70**, 1222-1225 (2004)] isolated salt-tolerant benzene degraders from brine-impacted soil in Oklahoma which could tolerate chloride concentrations equivalent to about 5000 mg/kg in soil.

- Landfarms can be managed to attenuate the effects of chlorides on the rate of bioremediation of hydrocarbons. Tilling followed by addition of moisture creates a low concentration of chlorides in the most active zone of bioremediation (the upper zone of the lift). Moisture addition drives chlorides down and out of the most aerobic part of the soil profile. Subsequent illing then brings soil from lower in the soil profile to the surface where the process is repeated.

There are also restrictions in the rule governing small registered landfarms that are inconsistent with best practice. First and foremost, the bioremediation endpoint approach is not allowed for small, registered landfarms. There is no scientific justification for this restriction. In place of a bioremediation endpoint approach, lift closure standards are required by the rule, specifically total extractable petroleum hydrocarbons < 1000 mg/kg and TPH-GRO+TPH-DRO < 500 mg/kg [H(5)(a)(iii)]. No small registered landfarm treating crude oil impacted soil with any appreciable hydrocarbon concentrations will be able to meet this requirement. Small registered landfarms should be the, go-to technology of choice for remediating hydrocarbon contaminated soil and would be widely used if the treatment standards are workable. With the treatment standards proposed by the OCD more hydrocarbon-impacted soil will be landfilled. Thus toxic, mobile hydrocarbons will be sequestered rather than destroyed.

The second requirement for small landfarms that is incongruent with recommended practice is the requirement that these landfarms be < 1400 $yd^3$ in size [A(1)e]. Scientifically speaking there is no basis for this restriction. Bioremediation of hydrocarbons will be just as effective (or more so) in small registered landfarms than in large permitted landfarms. Increasing the size of small registered landfarms to just 6400 $yd^3$ (about 2 acres) adds needed flexibility for the operator to decrease the cost of operation by making more effective use of large equipment, water sources, and sources of organic matter. Increasing the size of small registered landfarms also decreases the number of landfarms that the OCD must oversee and allows for more effective placement of landfarms to maximize protection of human health, groundwater, and the environment.

**Keep it simple and everyone wins**

In addition to allowing a bioremediation endpoint approach the OCD should **encourage** more use of bioremediation by among small producers by simplifying the regulations for small registered landfarms and publishing simple, easy to understand guidelines for bioremediation. Because of their limited size and lifetime small registered landfarms are inherently of low risk to public health, groundwater and the environment. Guidelines could be made available that are technically correct, are easy to understand and implement, and produce the desired result. Taking a simplified approach to these small registered landfarms will pay dividends enhancing bioremediation over landfilling.

An example of a simple but effective cookbook for bioremediation is the bioremediation guideline developed by the Integrated Petroleum Environmental Consortium (IPEC) in Oklahoma. These guidelines are distributed as laminated cards by IPEC, Oklahoma Corporation Commission field inspectors, BIA field inspectors in Osage County in Oklahoma, and on the IPEC website. They are simply based on good gardening concepts. Hydrocarbon loading is based on mixing with soil until there is no hydrocarbon shine in the soil. Simple and cheap agricultural fertilizers are recommended specifying incremental additions in warm months. Organic matter is encouraged to build soil structure and retain soil moisture. Tilling routines are included and moisture is monitored using garden center moisture meters or the soil ball test. Hydrocarbon monitoring is by the sniff test. The endpoint is reached when the operator can no longer smell hydrocarbon. The IPEC guidelines for bioremediation of crude oil are attached as Attachment B. These could readily be adapted for New Mexico. IPEC also distributes guidelines for remediation of brine spills and field kits for monitoring chlorides in soil and surface water which can also be adapted and distributed in New Mexico.

Here is what some OCC field inspectors had to say when asked to comment on the impact of IPEC's guidelines for bioremediation of crude oil-impacted soil and remediation of brine spills:

"Small operators have been afraid to bring up anything about remediation because they felt they would open up a can of worms costing a lot of money. Now they are finally understanding the importance and are willing to clean up around their wellheads and take care of small spills. Using a visual aid such as the guidelines has made it so much easier to explain remediation to the operators plus they have it to refer to when needed."

*Charles Hennessee, District Manager, OCC District III*

"The program has been a great success getting these environmental teachings out to the operators. It has had a vital impact and has resulted in more compliance. I think the video was excellent. The guidelines are a great help especially to the smaller operators. We need this program to continue."

*Ron Smith, Field Supervisor, OCC District III*

"Operators seem to understand the importance of cleaning up the soil more since the IPEC materials have been out."

*Gayland Darity, Field Supervisor, OCC District III*

"They (the bioremediation guidelines) play a good role in helping to diffuse tense situations with landowners when you can pull out the guidelines and read off what needs to be done. The landowners then realize you know what you're doing and have a plan."

*Pat Brown, Field Inspector, OCC District I*

"A positive impact has been made in the Oklahoma Panhandle area because a lot of the operators have never been given any information on spill clean ups, except to dig and carry or cover. Operators now have a more positive outlook on how to treat spills. They now know if they follow the recommendations of IPEC and be pro-active about the spill, all enforcement actions of the OCC will be minimal."

*Richard Kersey, Field Inspector, OCC District II*

Here are two comments from small producers:

"The guidelines have definitely been very helpful, very useful. They are easy to read, easy to understand. My guys can use them which says a lot! They help economically and are very beneficial."

*Ted Walker, Continental Oil & Refining Company*

"Guidelines are great and are very, very useful and we appreciate everything you do.

*Frederick Drummond, Drummond Oil Co.*

These comments clearly show that keeping regulations and the bioremediation process simple and easy to understand will pay dividends in terms of more protection of public health, groundwater, and the environment.

**Landfarm closure**

Upon closure of a landfarm the treated soil can be 1) transferred to a landfill; 2) transferred back to the original source of the contaminated soil; 3) removed for beneficial use; or 4) left in place. Either the treated soil will need to be revegetated if left in place or the landfarm site will need to be revegetated once the lift soil is removed. In either case the goal is sustained revegetation. Treated soil that has reached its bioremediation endpoint will not be toxic to plants or invertebrates. However, there is potential for the soil to be hydrophobic. What do we know about hydrophobicity? Hydrophobicity is caused by the coating of soil particles with hydrophobic or "water repelling" organic matter. Interestingly, many soils are naturally hydrophobic with periodic fire as a major cause. The heat from fire volatizes waxy materials from plant leaves driving them into the soil profile. Li et al. [Plant and Soil, **192**, 219-226 (1997)] showed that bioremediated soil with 2% extractable hydrocarbons failed to support healthy plant growth because the soil would not hold water (not because of any toxicity). Basically the bioremediated soil drained too well. Roy et al. [J. Environmental Quality, **32**, 583-590 (2003)],
in a study of a old, weathered, oil-impacted sites in Alberta, concluded that hydrocarbon-induced hydrophobicity is "relatively rare" and probably a product of a combination of circumstances including: properties of the crude oil, dryness of the soil at the time of first contact with hydrocarbon, and prolonged exposure to hot dry weather.

It is well known in agricultural circles that hydrophobicity is counteracted by hydrophilic (water loving) organic matter (hay or manure, for example) which increases the water holding capacity of the soil and increases contact of water with hydrophobic soil particles making them more likely to wet. So hydrophobicity in soil is treatable and standard agricultural practice can provide treatment recommendations.

Based on these observations and discussions above it seems reasonable that the closure standard for a landfarm could simply be stated as:

- < 1% total extractable petroleum hydrocarbons
- ECs < 4 mmhos/cm (dS/m) and SAR < 13 or site specific $EC_s$ and SAR levels based on current agricultural research and recommendations
- < 3% surface coverage of solid phase hydrocarbon in particles sizes < ½ inch
- Two years of unattended sustained vegetation

If treated landfarm soil were to be hydrophobic (which is not a certainty) the soil would not be able to sustain unattended vegetation for a two-year period. Therefore, to meet this standard the soil would have to be treated with organic matter to relieve this condition to support revegetation and become a candidate for closure. All concerns about chlorides, salinity, and sodicity are addressed by the saturated paste electrical conductivity and SAR standards as well as the revegetation requirement. This proposed closure standard focuses on the desired endpoint and argues for relaxing lift closure standards in favor of the ultimate endpoint. Sustained revegetation is that ultimate endpoint. Aboveground plant productivity and diversity reflect the productivity and diversity below ground. Therefore, a sustained revegetated site will result in a healthy soil food web.

**Conclusions**

Landfarming eliminates the threat of toxic, mobile hydrocarbons to public health, groundwater, and the environment. Landfarming is a short-term (<3 years) and long-term solution to the threat of toxic, mobile hydrocarbons. Landfarming eliminates toxic, mobile hydrocarbons through treatment not isolation. Regulations that facilitate the use of landfarming will minimize the landfilling of hydrocarbon-impacted soil. Landfarming is effective and easy to implement– it's just good gardening.

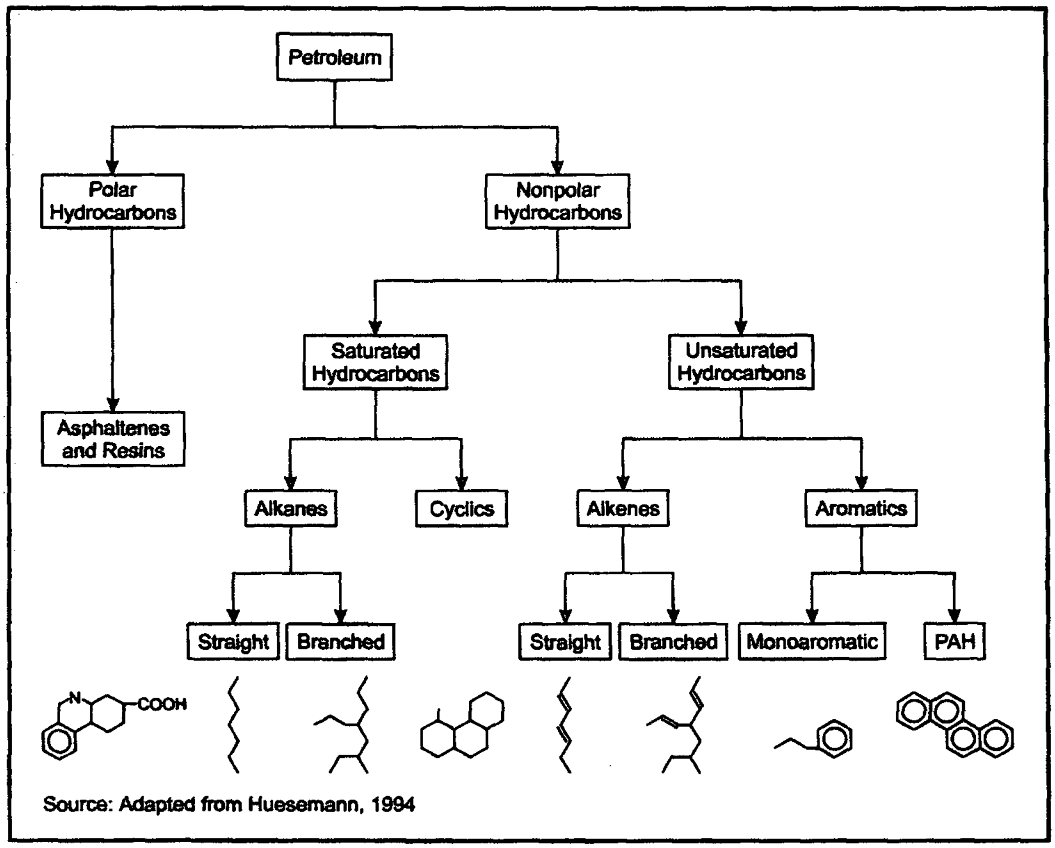



**Illustration of the types of organic compounds in petroleum**

Figure 1

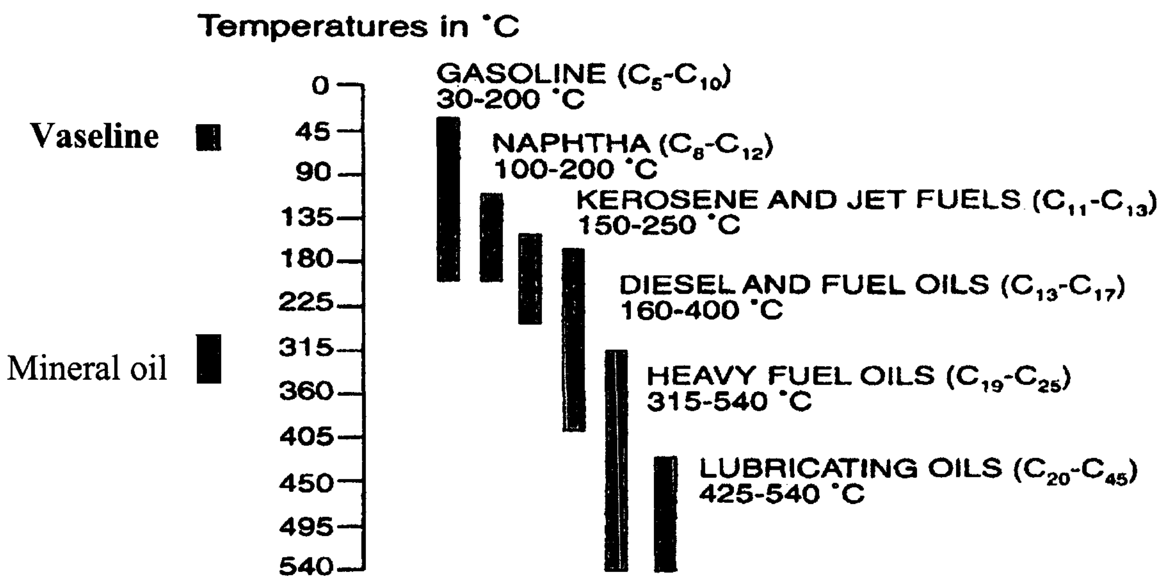



**Figure 2. Distillation fractions of fuels and lub oils from six common crude oils (right) and two common products derived from crude oil (left)**

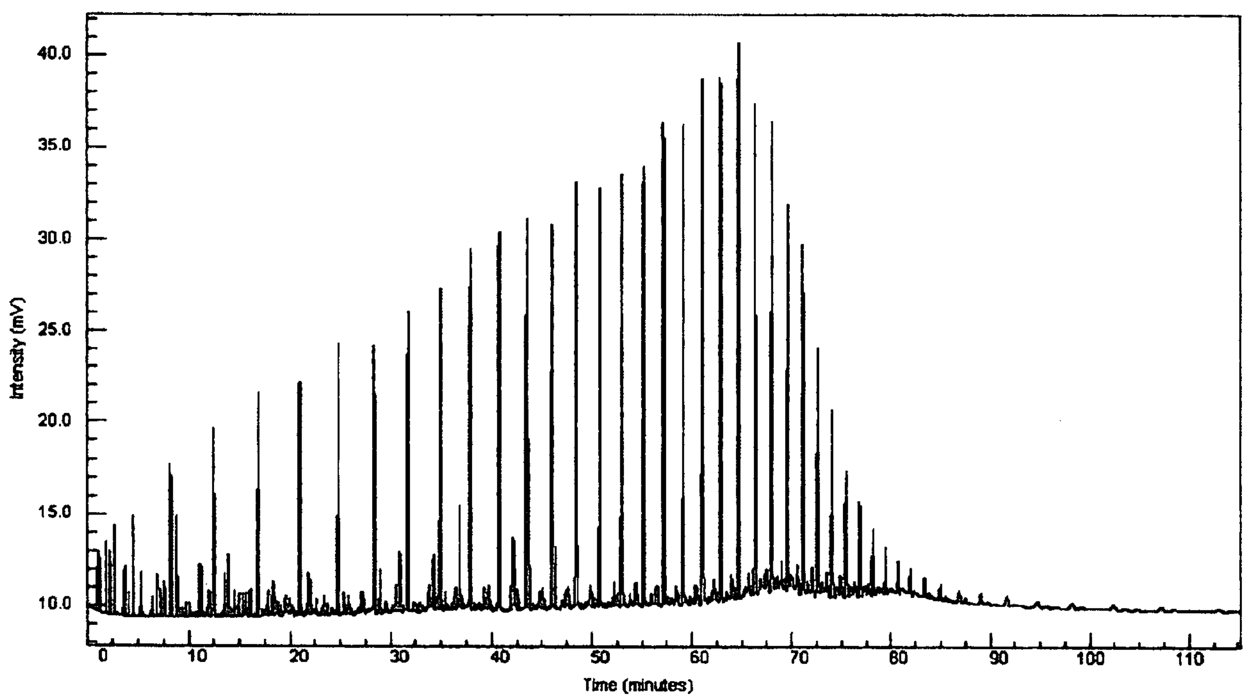



**Figure 3. GC analysis of a crude oil**

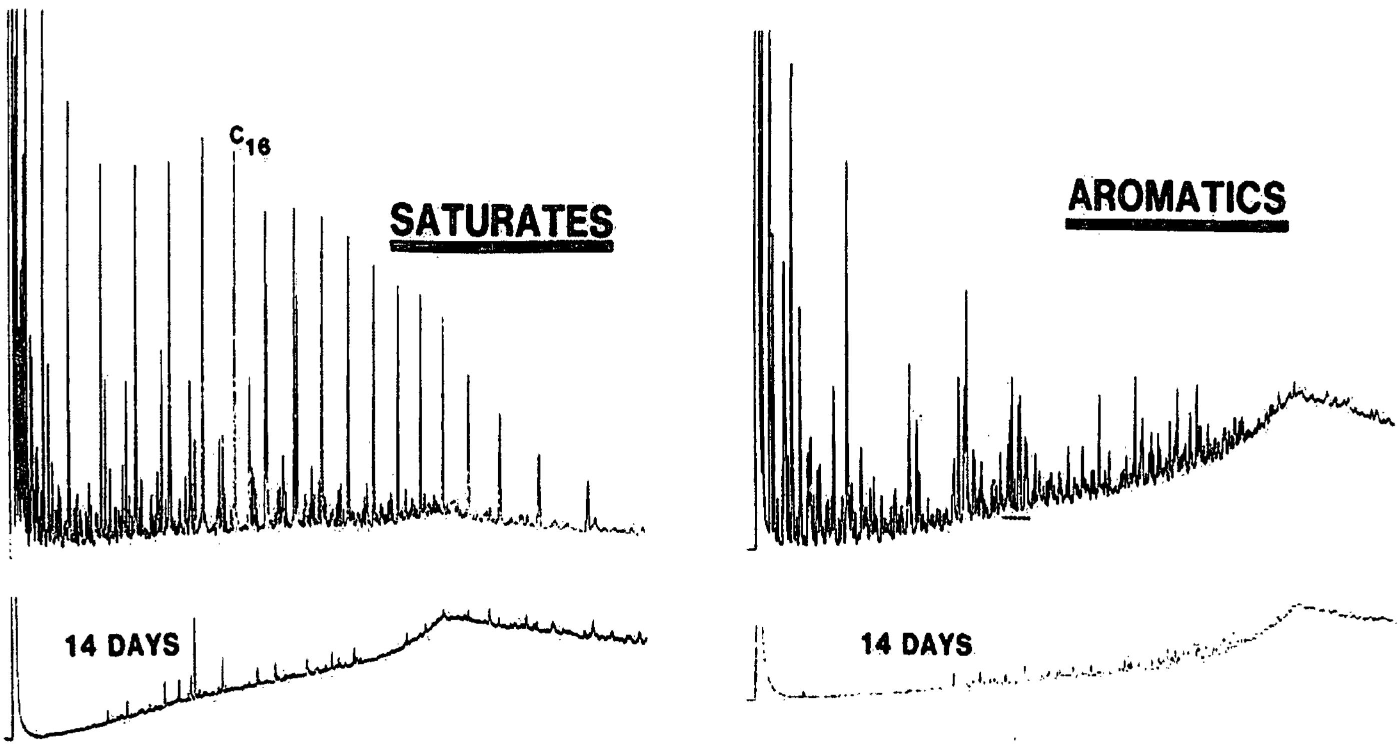



**Figure 4. Biodegradation of saturate and aromatic fractions of a crude oil in sea water supplemented with fertilizer. Top chromatograms are t=0; lower chromatograms are t=14 days**

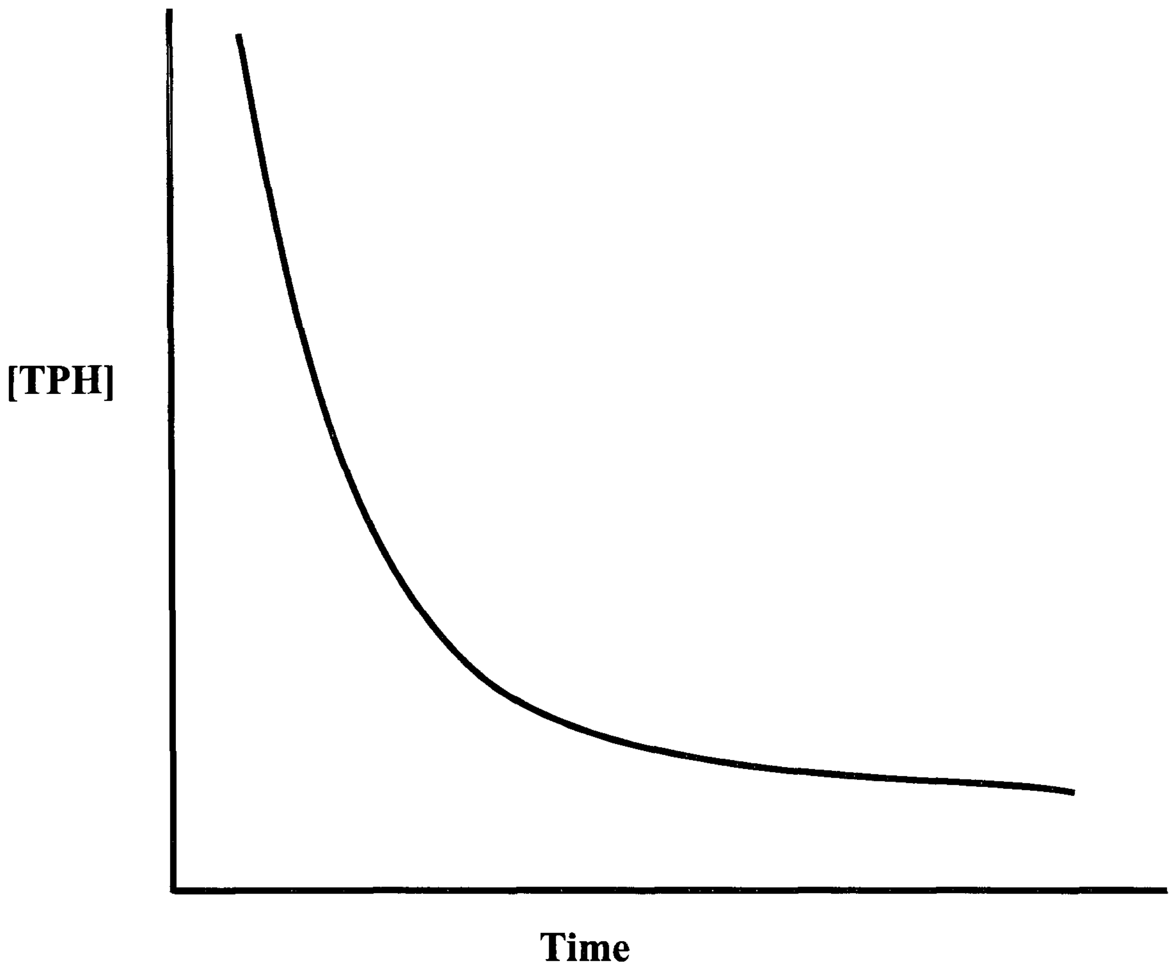



**Figure 5. Concentration of total petroleum hydrocarbons (TPH) over time during bioremediation of hydrocarbons in soil**

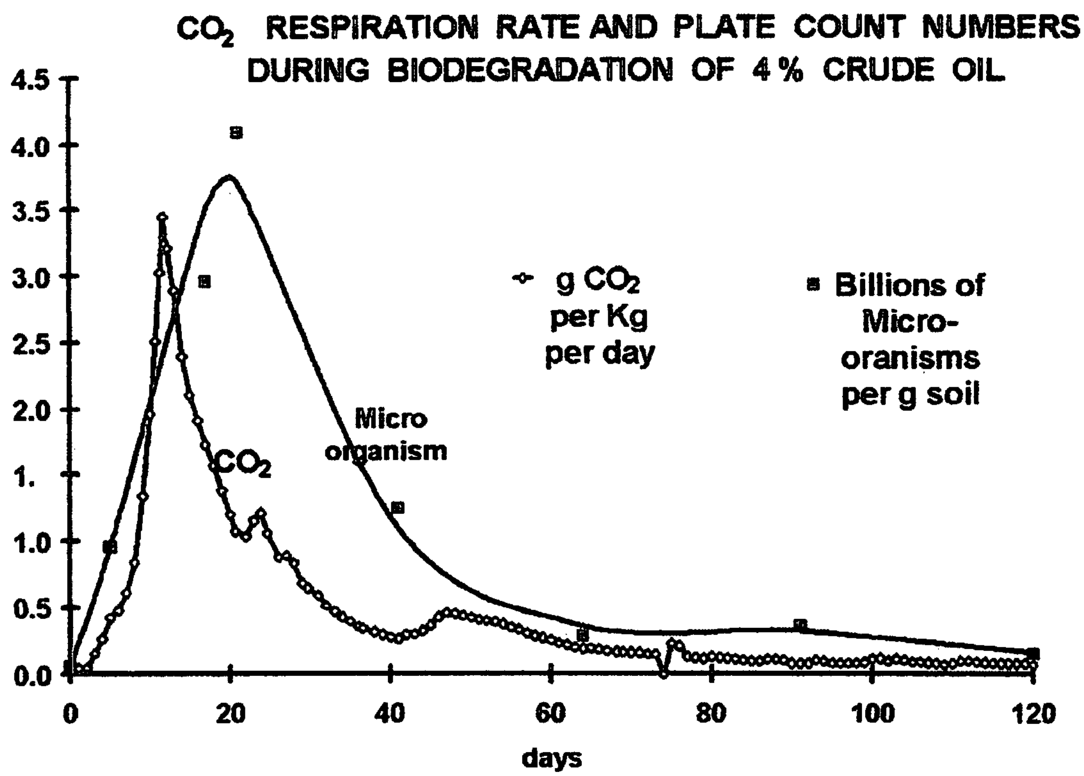



Figure 6. $CO_2$ respiration rate and concentration of hydrocarbon degrading bacteria during bioremediation of hydrocarbons in soil. Compare to Figure 5.

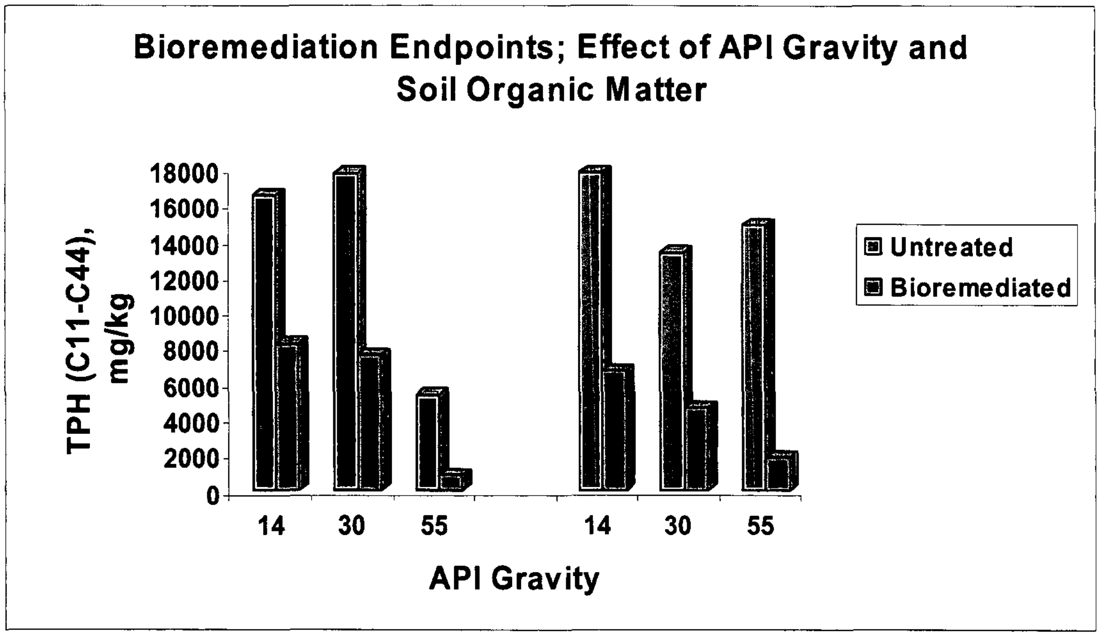



**Figure 7. Bioremediation endpoints (C11-C44) : Effect of API gravity and soil organic matter (Salinitro et al. study)**

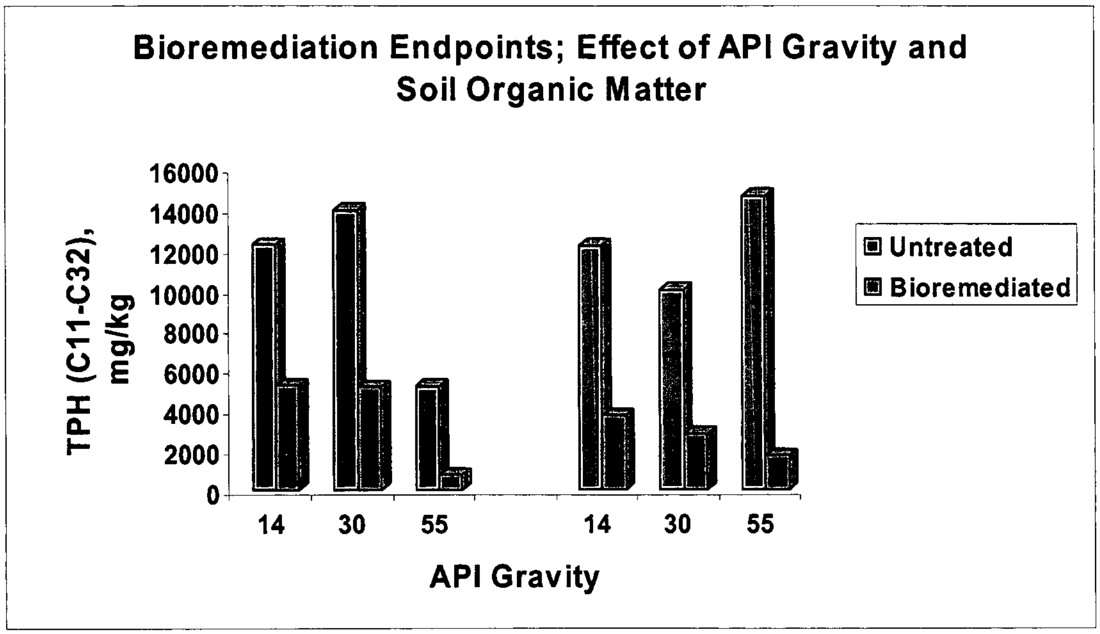



**Figure 8. Bioremediation endpoints (C11-C32) : Effect of API gravity and soil organic matter (Salinitro et al. study)**

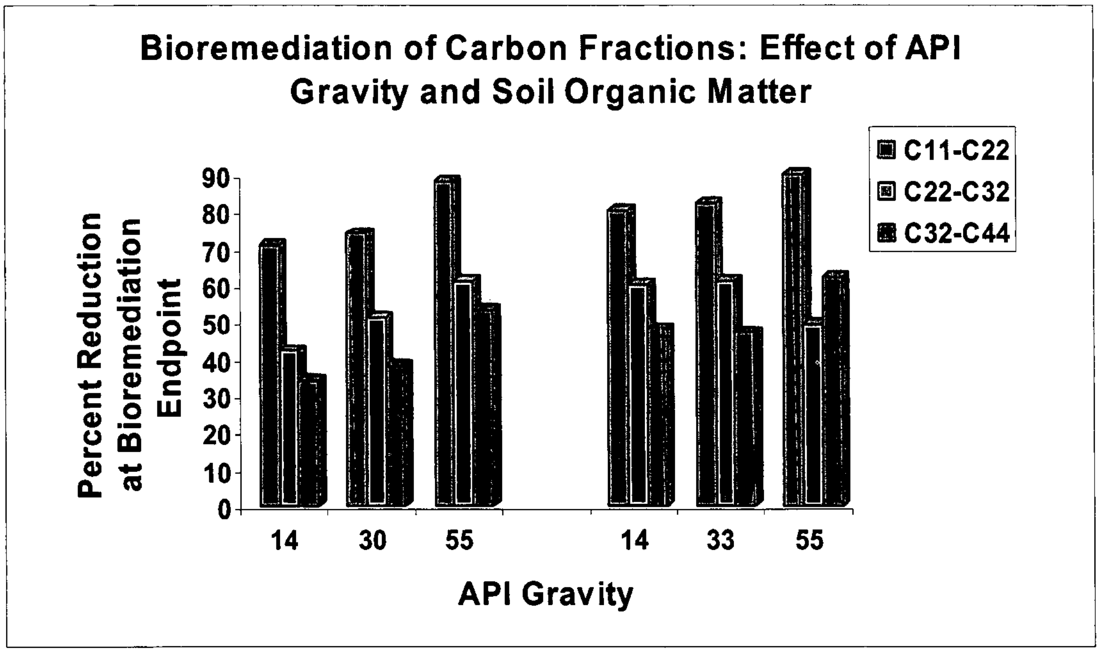
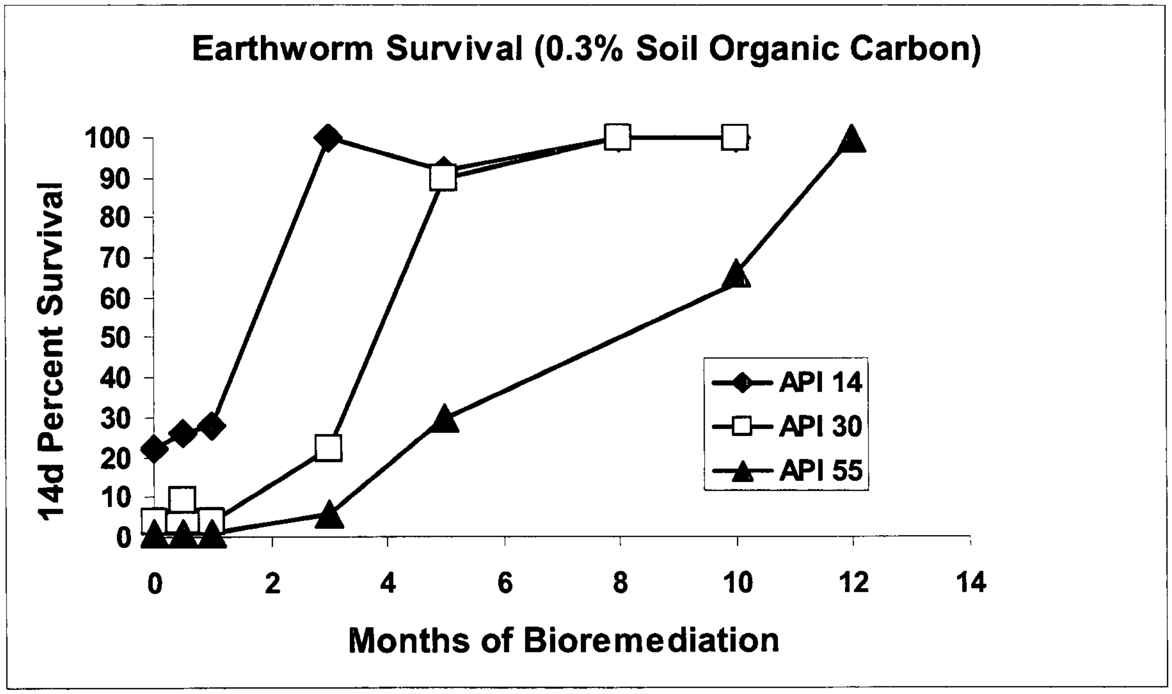



**Figure 9. Percent reduction of different carbon number fractions at the bioremediation endpoint (Salinitro et al. study)**



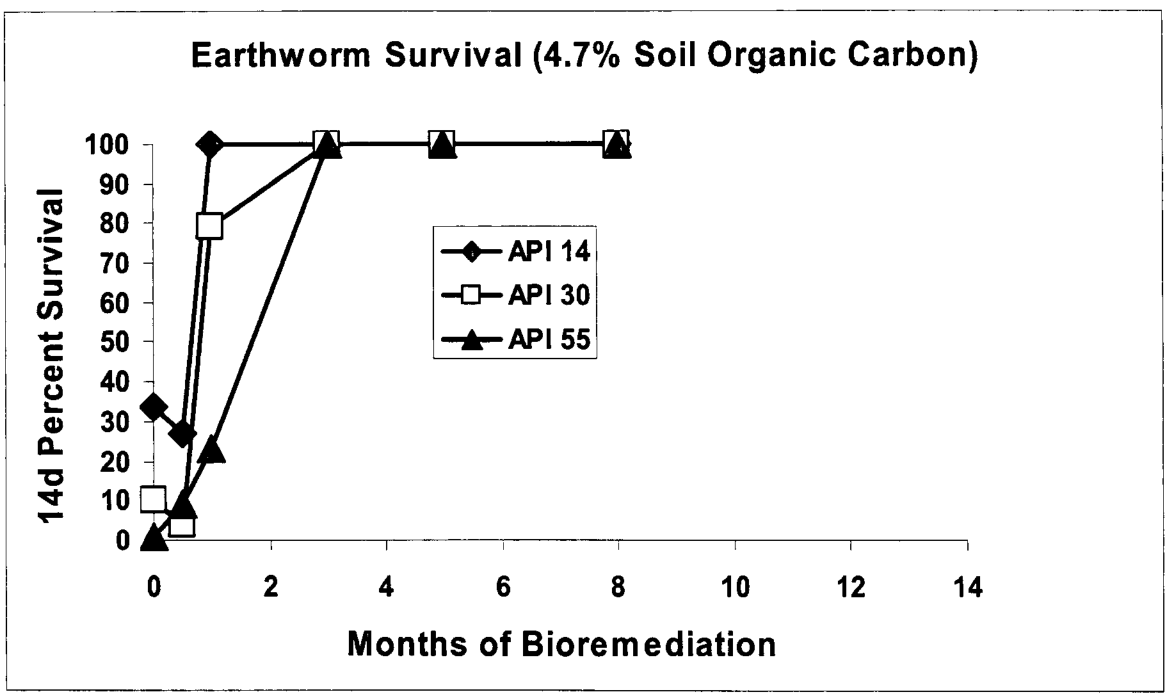
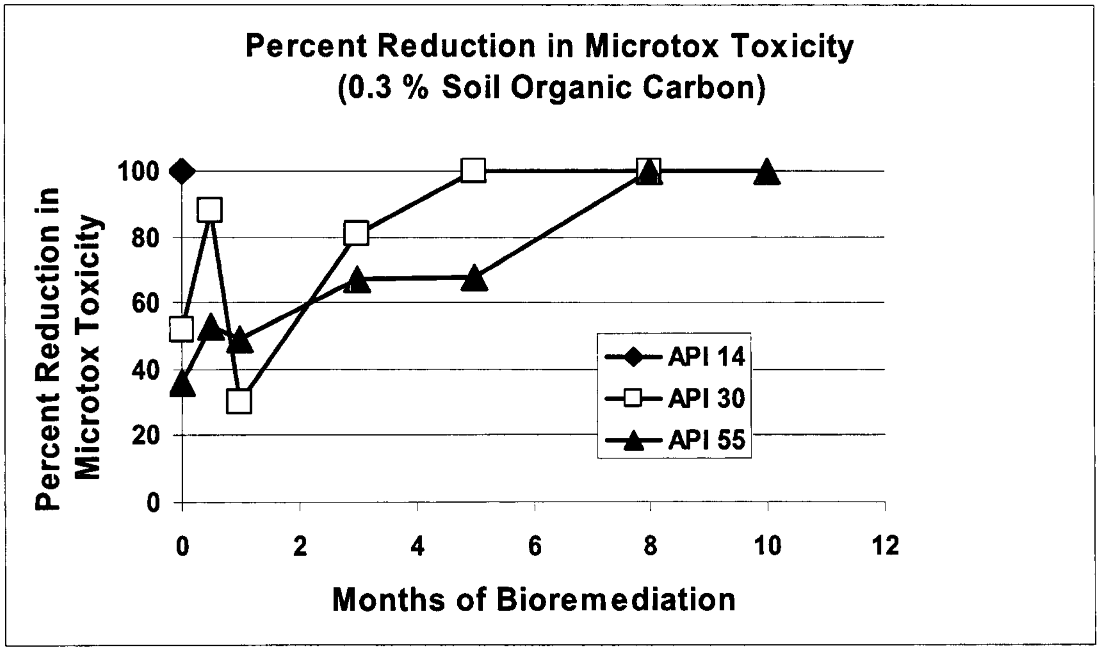




**Figure 10. Reduction in earthworm toxicity during bioremediation (Salinitro et al. study)**



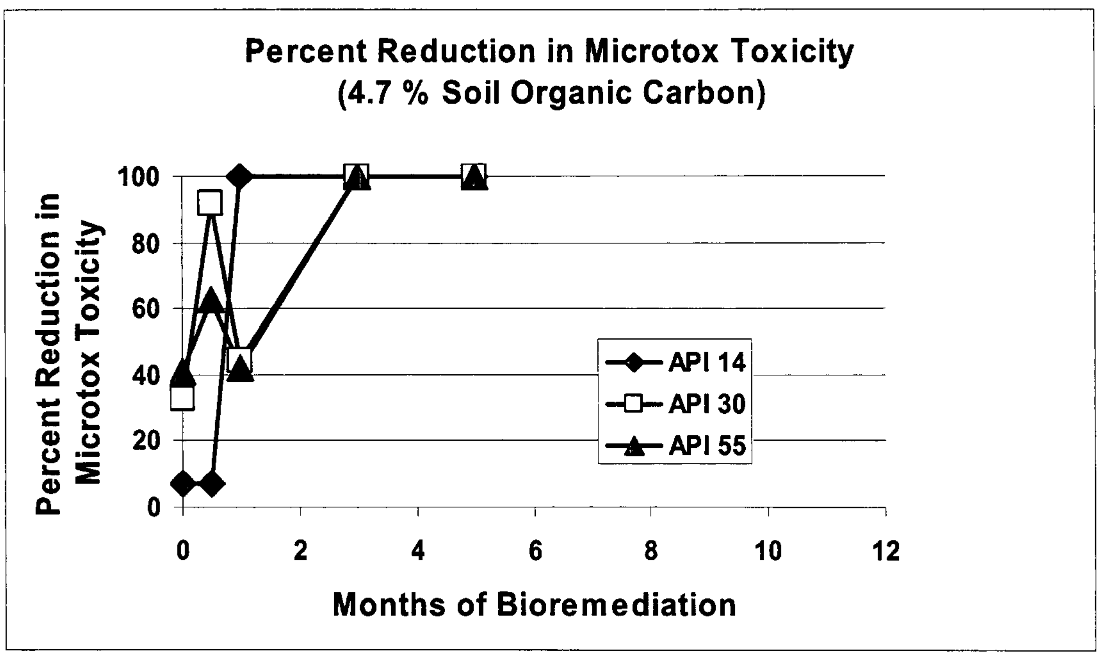
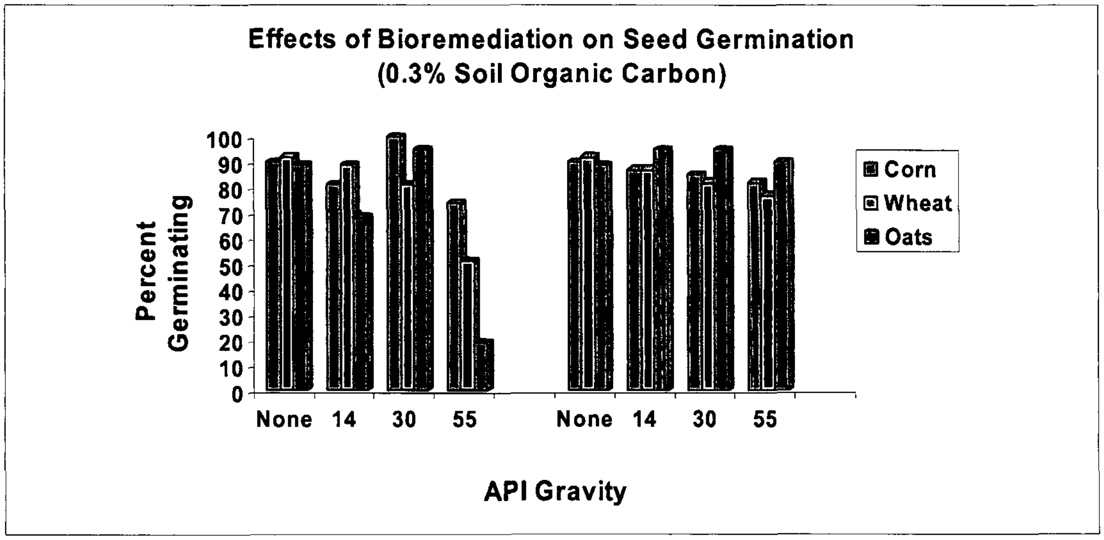




**Figure 11. Reduction in toxicity by Microtox during bioremediation (Salinitro et al. study)**



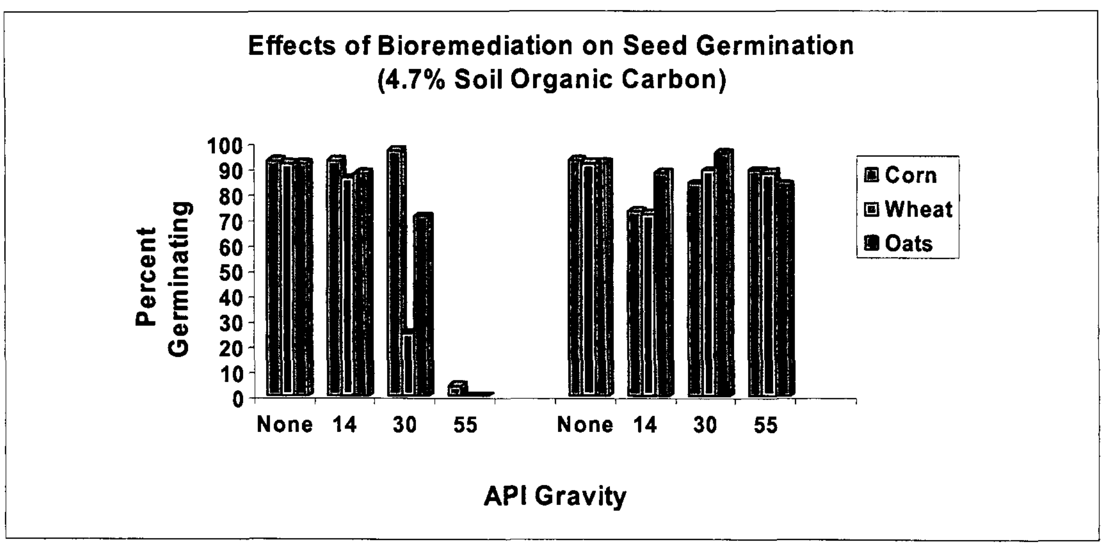




**Figure 12. Reduction in toxicity as measure by seed germination during bioremediation (Salinitro et al. study)**

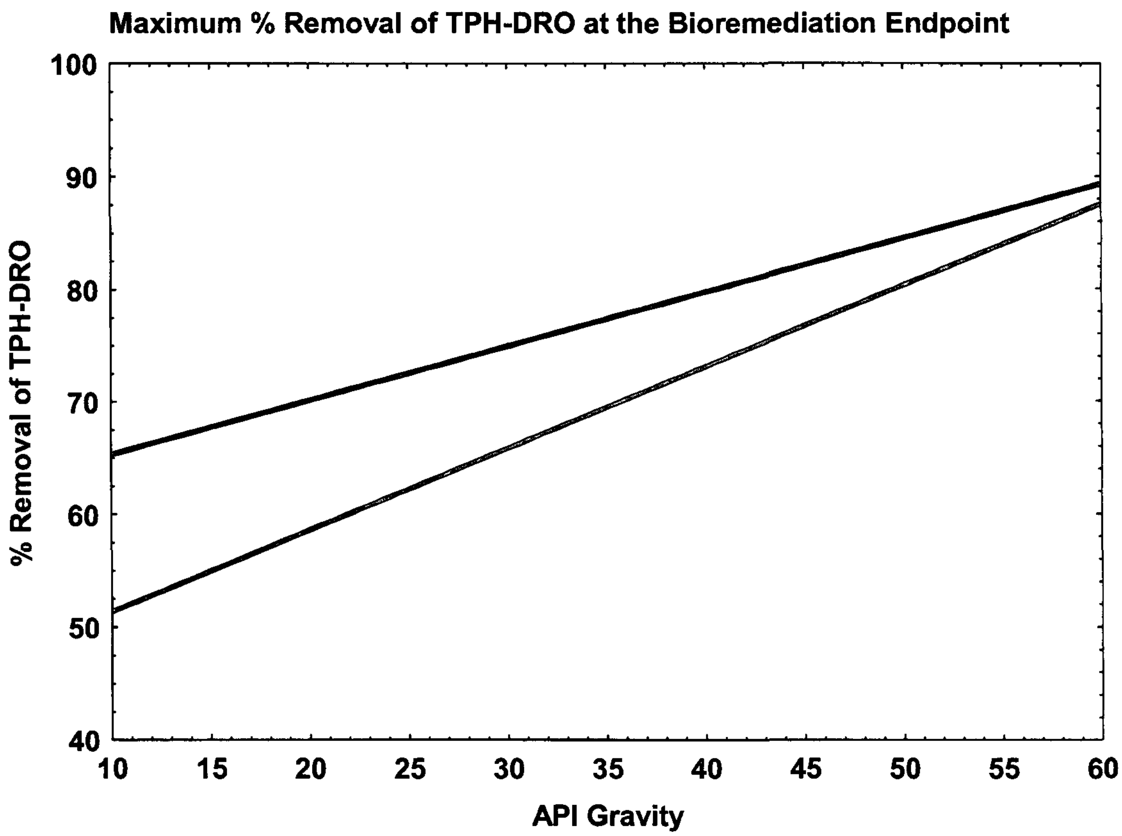
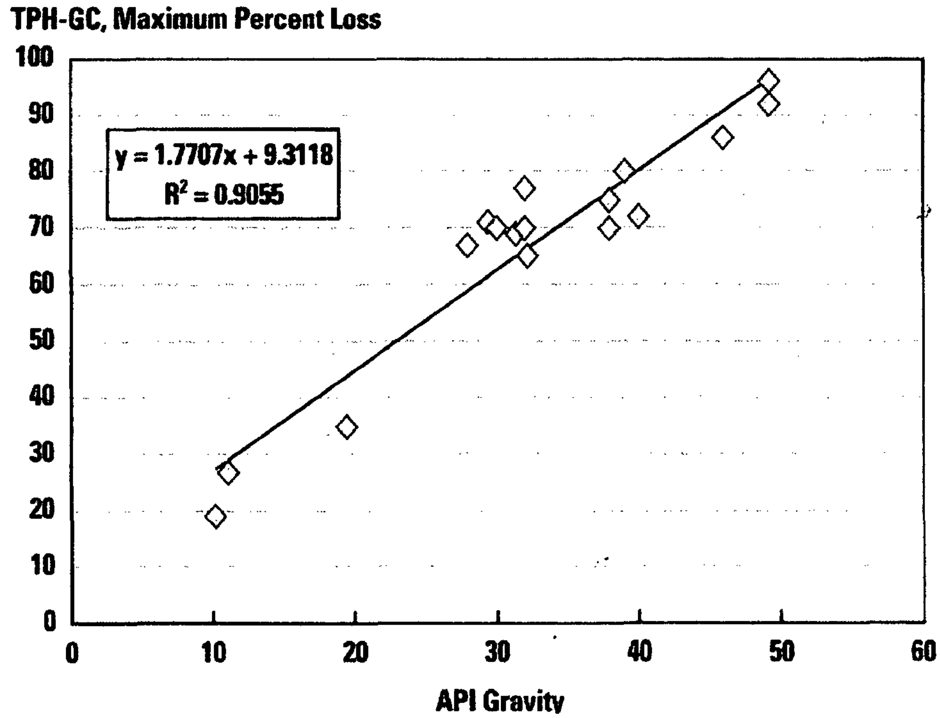



**Figure 13. Summary of Salinitro et al. observations of TPH-DRO concentrations at the bioremediation endpoint. Blue line is for high soil organic matter; red line is for low soil organic matter**



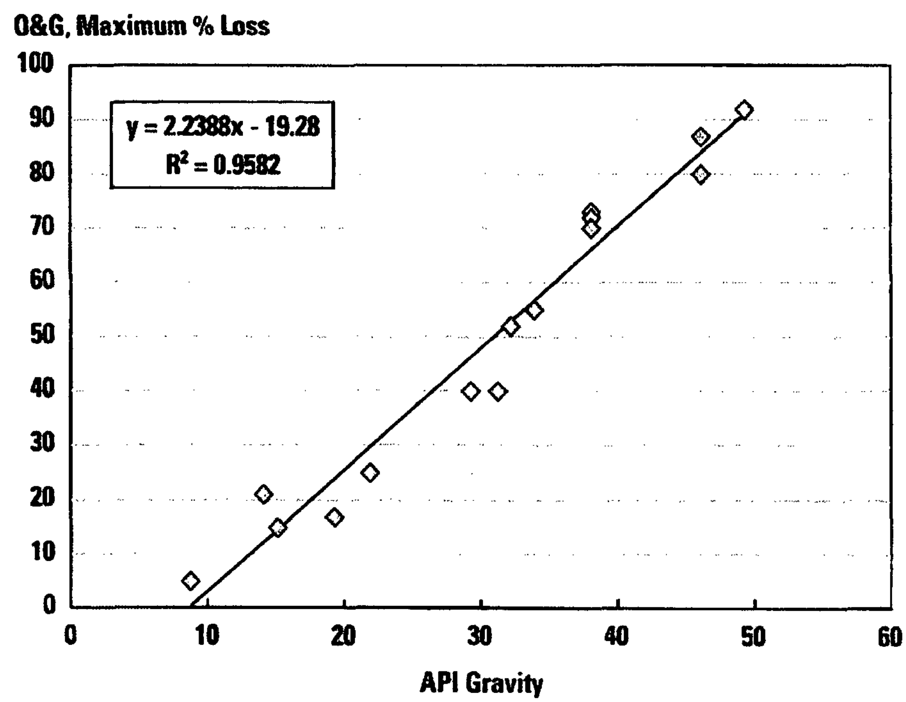




**Figure 14. Summary of industry experience regarding TPH bioremediation endpoints. Source: "A Summary of the DOE/PERF Bioremediation Workshop" (2003).**

## Attachment A
## Recommended Practice for Permitted Landfarms Treating Hydrocarbons

### Kerry L. Sublette, Ph.D.

**Summary Recommendations**

| OPERATION | REQUIREMENT | TIMING |
|---|---|---|
| Documentation | All operations documented in an activities log | Available on site for review by OCD |
| pH | 6 – 8 | Test monthly |
| Tilling | Depth of lift | Minimum twice monthly |
| Nutrients (Nitrogen) | 50 – 200 mg/kg (inorganic) | Test monthly |
| Nutrients (Phosphorous) | 25 – 50 mg/kg (bioavailable) | Test monthly |
| Moisture Content | 60 – 80 % of field capacity | Minimum weekly |
| Lift Monitoring (field TPH) | Periodic field testing on 3 composite samples, 20 discrete points per composite sample | One initial sampling event after lift added, then 30 days apart after 6 months of treatment for condensate or 12 months of treatment for crude oil. A treatment month is defined as a 30-day increment in which the maximum 4-inch bare soil temperature is above 50 °F. |
| Bioremediation Endpoint: Laboratory TPH – GRO or TPH-DRO<br><br>or<br><br>At the operator's discretion, a 14-day earthworm survival test | Three (3) representative composite samples for laboratory testing, 20 discrete points per composite sample. Two laboratory tests 30 days apart must be statistically the same using the Student's t test with $\alpha = 0.10$.<br><br>or<br><br>Three (3) representative composite samples for earthworm survival testing. 20 discrete points per composite sample. 100% survival required. | Two laboratory tests, 30 days apart, if field testing indicates endpoint.<br><br>or<br><br>Earthworm survival tests when TPH field testing indicates an endpoint |

### 1.0 Hydrocarbon Loading

A wide range of hydrocarbon loadings have been reported to be successfully treated in a landfarm. However, the operator should be aware that biodegradation rates decrease with increasing hydrocarbon loading and decreasing API gravity of the hydrocarbons. Much of the biodegradation of hydrocarbons in a landfarm occurs at an interface between hydrocarbon and soil moisture. Therefore, biodegradation rates in a landfarm strongly correlate with the interfacial area/mass ratio of the hydrocarbon. Increasing hydrocarbon loading will generally decrease the interfacial area/mass ratio. Decreasing API gravity (and increasing viscosity) of the hydrocarbon results in less effective dispersal of the hydrocarbon and, therefore, lower interfacial area/mass ratios.

## 2.0 Organic Matter

Blending organic matter into landfarm lift soil, while not required for successful landfarming, can have several benefits including:

- Improved moisture retention
- Improved soil structure and better aeration
- Establishing a fertility base to improve re-vegetation upon closure

The best organic matter to use will be material which is biodegradable such as hay, straw, or similar agricultural waste products. Woody material such as sawdust, wood chips, or bark can give short-term benefits with respect to water retention and aeration but are not as beneficial in supporting future re-vegetation. The amount of organic matter amendment is highly variable depending on soil and waste types. If organic matter is used the operator can determine the appropriate amount based on that required to produce adequate structure in the soil for good aeration. In general a high clay content will require more incorporation of organic matter for optimum performance. The operator should be aware that organic matter does increase nutrient demand in the lift.

## 3.0 pH

The optimum pH range for biodegradation activity in the landfarm soil is 6 – 8. pH should be monitored monthly and amendments added to adjust pH if necessary. Soil pH monitoring kits from a home and garden supply store are adequate for pH monitoring. If pH adjustment is necessary, agricultural amendments for pH adjustment are readily available at farm supply stores. Recommendations on amendment rates can be obtained from an agricultural extension service. A composite soil sample will be required (See 10.0). The operator should inform the lab that the sample contains hydrocarbons.

## 4.0 Tilling

The benefits of frequent tilling of the landfarm lift include:

- Maintaining a soil structure in the lift conducive to good oxygen transfer from the atmosphere
- Vertical mixing of the lift ensures that the entire soil depth in the lift spends some time in the upper most active zone of biodegradation
- Watering after tilling drives chlorides downward in the soil profile out of the most active treatment zone; repeated tilling and watering cycles then allow the entire lift profile over time to see a lowering of chloride concentration while in the most active zone of biodegradation
- More uniform distribution of nutrients in the soil profile

The landfarm lift should be tilled at least twice monthly with a tillage depth equal to the depth of the lift. Soil moisture at the time of tilling is important to achieving desired results. If the soil is too wet when tilled mixing will be inadequate and when the tilled soil dries clumps will have hard-packed faces that will inhibit oxygen transfer. Tilling should then be timed to precede watering (or nutrient additions). Tilling tends to mix along the tractor line of travel; therefore, tilling should be carried out in varying directions.

**5.0 Nutrients**

The most effective nutrients for landfarms are inorganic sources of nitrogen (ammonium ion and nitrate) and phosphorous, i.e. common agricultural fertilizers. Organic sources of nitrogen such as urea are also effective but large additions of organic nitrogen should be avoided if the soil pH is alkaline (pH>7). If the soil pH is alkaline a large influx of organic nitrogen can result in transient accumulation of nitrite which is biocidal. Manures are good sources of both nitrogen and phosphorous as well as a good soil conditioner, but the same precaution regarding pH applies.

Nutrient levels should be monitored monthly for optimum performance of the landfarm. Nitrogen concentrations should be maintained in the range of 50-200 mg/kg (ppm). Phosphorous levels should be maintained in the range of 25-50 ppm. Caution is called for in fertilizer application. Experience has shown that inorganic nitrogen levels above 500 ppm can be inhibitory to biodegradation.

Nutrients can be effectively monitored using field kits available from several vendors [such as Hach Co. (www.hach.com) or CHEMetrics (www.chemetrics.com)]. Both ammonium-N and nitrate-N should be monitored with the sum being the available soil inorganic nitrogen. Phosphorous analysis should be specific for bioavailable or plant available phosphorous. Phosphorous tends to become sequestered in soil over time and unavailable to soil microbes. Do not use a total phosphorous test since this test will give you both available and unavailable phosphorus. An alternative to using field kits is an agricultural extension service laboratory. These labs can provide inexpensive analyses of bioavailable nutrients but do not give you the real-time results of a field kit.

Coordinate nutrient additions with watering (6.0) and tilling (4.0). When required broadcast nutrients just before tilling and watering.

**6.0 Moisture Control**

Moisture plays a critical role in the performance of a landfarm. Microbes must be sufficiently hydrated for optimum growth rates and, therefore, optimum biodegradation rates. Soil moisture also plays a key role in nutrient availability since soil water is the principal conduit for nutrients to reach microbes. Optimum moisture contents are typically stated in terms of percent of field capacity, and therefore, depend somewhat on the texture of the soil. Optimum soil moistures for biodegradation are typically 60-80% of field capacity. At these levels there is plenty of moisture available to the microbes but large macropores also exist in the soil for oxygen transfer.

Moisture content should be monitored at least weekly. Actual moisture content can be determined by weighing a sample of moist soil and then oven drying the sample and reweighing. However, decisions to water or not to water can also be made using simple moisture meters obtained from lawn and garden centers or based on experience and observation. For example, soil that will form a stable ball in your hand has enough moisture to support biodegradation. If the ball of soils easily falls apart in your hand, it's time to water.

When watering, care should be taken to avoid long periods of saturation or ponding. Filling soil macropores with water greatly decreases the rate of oxygen diffusion into the soil and the soil environment becomes anaerobic. Under these conditions biodegradation of hydrocarbons slows significantly and denitrification results in losses of soil nitrogen to the atmosphere as elemental nitrogen.

**7.0 Hydrocarbon Analysis for Operational Monitoring**

Periodic hydrocarbon analysis is required to monitor the performance of landfarm operations. In 2000 – 2001 the US EPA SITE Program evaluated a number of field devices or kits for TPH analysis in soil comparing performance and cost to a conventional, lab-based analytical method (Method 8015B modified). The devices or kits evaluated were:

CHEMetrics RemediAid™ Total Petroleum Hydrocarbon Starter Kit
Wilks Enterprise, Inc., Infracal TOG/TPH Analyzer, Models CVH and HATR-T
Horiba Instruments, Inc., OCMA-350 Oil Content Analyzer
Dexsil Corp., PetroFLAG™ Hydrocarbon Test Kit for Soil
Environmental Systems Corp., Synchronous Scanning Luminoscope
siteLab®Corp., Analytical Test Kit UVF-3100A
Strategic Diagnostics, Inc., Ensys Petro Test System

Results of these evaluations are summarized in the Table 1. Several of these kits showed potential value as screening tools and two (CHEMetrics RemediAid™ Total Petroleum Hydrocarbon Starter Kit and siteLab®Corp., Analytical Test Kit UVF-3100A) were identified as producing results comparable to the lab-based method and were recommended as reliable field test kits. Therefore, the landfarm operator has several options available for routine monitoring of hydrocarbon concentrations which can be used to evaluate the performance of a landfarm lift and need not be restricted to a lab-based method except for lift closure.

**Table 1. US EPA SITE Program Evaluation of TPH Field Test Kits**

| Field Kit | Findings | Recommendations |
|---|---|---|
| CHEMetrics RemediAid™ | Good accuracy and precision;<br>Easy to use;<br>Some non-petroleum hydrocarbons can cause significant measurement bias;<br>Minor sensitivity to soil moisture | Reliable field measurement device |
| Infracal TOG/TPH Analyzer | Sensitive to non-hydrocarbon interferents;<br>Poor precision for environmental samples;<br>Results did not compare well with lab-based method;<br>Results significantly impacted by soil moisture | Use for screening only |
| OCMA-350 Oil Content Analyzer | Results did not compare well with lab-based method;<br>Results significantly impacted by soil moisture; | Use for screening only |
| PetroFLAG™ | Some interference with some non-hydrocarbons;<br>Increasing soil moisture results in low bias for weathered gasoline-impacted soil;<br>Results compared well with lab-based method but with some high bias | Use with caution for specific field TPH measurements |
| Synchronous Scanning Luminoscope | Good precision;<br>Lack of sensitivity to moisture content and non-hydrocarbon interferents;<br>Low cost;<br>Moderate sample throughput;<br>Results did not compare well with lab-based method;<br>Operator requires significant skill base | Use for screening only |
| Analytical Test Kit UVF-3100A | Good accuracy and precision;<br>Lack of sensitivity to non-hydrocarbons<br>Easy to use;<br>Minor sensitivity to soil moisture; | Reliable field measurement device |
| Ensys Petro Test System | Good precision;<br>High sample throughput;<br>Results did not compare well with lab-based method;<br>High positive bias | Use for screening only |

## 9.0 Hydrocarbon Analysis for Lift Closure

For lift closure a bioremediation endpoint must be demonstrated. The bioremediation endpoint in soil is the point at which the rate of reduction in TPH concentration is essentially zero and dependent upon the bioavailability of residual hydrocarbon.

The bioremediation endpoint is dependent upon the nature of the hydrocarbon and the soil; however, research has shown that at the bioremediation endpoint hydrocarbon toxicity has been removed irrespective of the TPH concentration. The recommended metric for defining the bioremediation endpoint is TPH-DRO when the hydrocarbon source is crude oil, tank bottoms and sludges, drill cuttings, and diesel and heavier refined products. The recommended metric for gasoline and gas condensate hydrocarbons is TPH-GRO. For mixed wastes containing both types of materials TPH-DRO is the recommended metric.

Documenting the bioremediation endpoint should be attempted when two conditions are met: 1) the landfarm has been operated following recommended practice for a minimum of 6 treatment months when treating gasoline or gas condensate or 12 treatment months when treating crude oil, tank bottoms and sludges, drill cuttings, and diesel and heavier refined products and 2) field measurements of TPH levels indicate that the lift is at or near the end of the treatment cycle. A treatment month is defined as a 30-day increment in which the maximum 4-inch bare soil temperature is above 50 °F The bioremediation endpoint can be documented with two successive TPH-DRO or TPH-GRO measurements at least 30 days apart that are statistically the same. Each measurement should consist of three composite samples (10.0) and successive measurements should be compared using the Student's t test with $\alpha = 0.10$.

At the operator's discretion, the bioremediation endpoint may also be documented by means of a 14-day earthworm survival test. One hundred percent (100%) survival in triplicate composite samples (10.0) from the landfarm lift indicates removal of toxicity which is characteristic of the bioremediation endpoint and is the ultimate goal of landfarming.

**10.0 Composite Sampling**

No matter how much you till a landfarm lift the soil will still be heterogeneous with respect to the distribution of nutrients and hydrocarbons. Therefore, obtaining a sample representative of the average concentration of nutrients or hydrocarbon requires composite sampling. In composite sampling many discrete samples are taken at random over a site and then pooled in equal amounts to obtain a sample for analysis. Obviously the more discrete samples that go into making your composite the closer your subsequent analysis will be to the true average concentration of the analyte. How many discrete samples are enough? Research has shown that a minimum of 20 discrete samples are required to obtain a truly representative sample. This is illustrated in the figure below showing the results of composite sampling of an agricultural field for nitrate nitrogen.

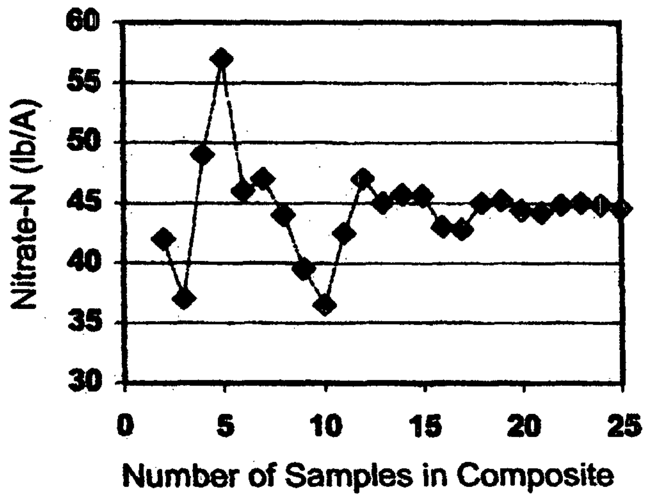
It is not the size of the area being sampled that determines the number of discrete samples required to give a representative result; instead it is the variability of the area in terms of soil types or other distinguishing characteristics. In a landfarm these distinguishing characteristics could be:

- Areas with different wastes applied (hydrocarbon type, loadings, chloride concentrations, etc.)
- Areas with distinctly different soil textures

- Areas with distinctly different drainage patterns

Each area of the landfarm lift with distinguishing characteristics should be sampled separately, each with 20 discrete samples per composite sample.

Discrete samples should be obtained with a soil corer or trowel being careful to sample the entire vertical depth of the landfarm lift in each discrete sample. Equal amounts of discrete samples are blended to form the composite. Sampling should be coordinated with other operational events such as tilling. Don't sample one month just before tilling and the next month just after tilling. Sampling should be done when the soil is sufficiently dry that the discrete samples can be well mixed.




**11.0 Introducing a New Lift**
Each new lift should be tilled to incorporate the top two inches of the lift below. This will provide an inoculum of bacteria already adapted to the hydrocarbon and environmental conditions.

**12.0 Temperature**
The landfarm operator typically has little control of temperature in the landfarm. However, the operator should be aware that biodegradation rates decrease with decreasing soil temperature. Therefore, in cold periods the operator should expect slower rates of hydrocarbon removal and slower rates on nutrient utilization. For the purposes of meeting the minimum treatment time requirements of 6 treatment months for condensate and 12 treatment months for crude oil or similar materials a treatment month is defined as a 30-day increment in which the maximum 4-inch bare soil temperature is above 50 °F

# Attachment B
# IPEC Guidelines for Bioremediation of a Crude Oil Spill

ENERGY ENVIRONMENT ECONOMY

Integrated Petroleum Environmental Consortium

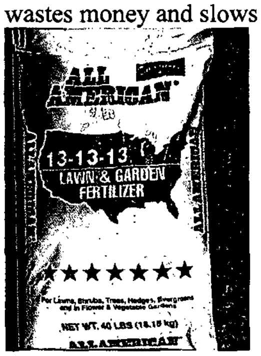
***Why use bioremediation?***
Bioremediation is frequently the most cost-effective way to clean up an oil spill on soil and is endorsed by state and federal regulatory agencies. Cleaning up spills quickly will minimize future liabilities and costs by helping you maintain a good relationship with the landowner and regulatory agencies.

***When can I use bioremediation?***
If you have any pooled free oil, it is important to vacuum up the free fluids and, if possible, recycle them back to the stock tank or properly dispose of them. Use absorbent material to pick up any fluid that can't be vacuumed and legally dispose of that material. When that's done, you need to ask two questions: (1) Is the contamination deeper than 8 inches? and (2) Is there shallow groundwater under the contamination?

If you answered "no" to both of these questions, then a basic form of bioremediation called landfarming should work well for you.

***Basic landfarming***
When you landfarm a crude oil spill, you are cultivating microorganisms in the soil to eat hydrocarbons. These microorganisms need the same things as crops to thrive: fertilizer, moisture, good soil structure, and warm temperatures. Follow the steps below and you will be on your way to cleaning up that spill:

Step 1. Add fertilizer to the contaminated soil. 13-13-13 is a good choice. Add 1/2 lb per square yard of stained soil if it is a recent spill and 1/4 lb per square yard if it is an old spill. Just step off the site to estimate the size. Don't add too much. You can have too much of a good thing. This wastes money and slows the process down.

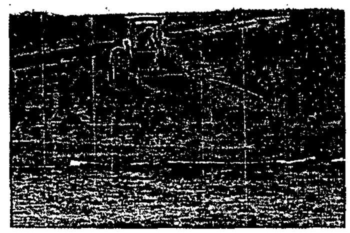



**One-half Pound of 13-13-13**

Step 2. Add organic matter to the contaminated soil. Organic matter builds soil structure and allows the soil to breathe. Hay or straw works well. Add the equivalent of about 5 square bales of hay per 1000 square feet.

Step 3. Till the fertilizer and organic matter into the soil to a depth of 6 - 8 inches. Was the soil wet with hydrocarbon? If so you need to blend in some uncontaminated soil from around the edges or below the contamination during tilling. After tilling you should be left with a mixture that crumbles in your hand. Try to keep heavy equipment and cattle off the site - compacting the soil slows the process down.

**An Example of the Desired Soil Structure in a Landfarm**



**Tractor Tilling**

Step 4. Repeat the addition of fertilizer and tilling every 30 days during the warm months (March through November) for the first 3 months of remediation. After 3 months add fertilizer every other month but continue tilling in the months between fertilizer additions too. You are done when the hydrocarbon odor is gone. Once the hydrocarbon odor is gone revegetate to prevent erosion.

***What about moisture?*** We can speed up the process of bioremediation by keeping the soil moist but most of the time we just depend on rainfall. If you do water the site, don't saturate the soil - that actually slows everything down.

***What is the best time to start a bioremediation project?*** If you have a spill in December - February go ahead and till in organic matter to keep the hydrocarbon from moving offsite until warm weather returns. If the impacted area is sloped, it may be necessary to construct a low earthen dike at the bottom of the site to prevent runoff. If the spill occurs at any other time of year, go ahead and get started as soon as possible.

***How long does it take to bioremediate a site?*** That depends on a lot of things, some you have control of and others you don't have any control over. You can speed up the process by sticking to the tilling and fertilizing schedule. But you can't control the rain. Another factor that has an effect on the rate of the process is how old the spill is. You can expect that crude oil that has been in the ground for a while will degrade slower than a recent spill. All things considered, you should see significant results in one or two growing seasons.

***What if you couldn't answer "no" to both of those questions?*** If the contamination is deeper than 8 inches but there is no shallow groundwater, following these guidelines should result in at least some restoration of the surface although the deeper contamination will remain. Remediation of all of the contaminated soil would require the soil to be excavated, spread out in a layer less than 8 inches deep, and the four steps of basic landfarming applied.

If there is shallow groundwater under the contamination, you should consult a qualified technical expert to show you how to do landfarming without groundwater becoming contaminated.

***What about brine?*** As you know, crude oil spills often contain brine. In this case you have two contaminants to remediate. Bioremediation will clean up the oil, but the brine must be washed away. Fortunately, the four steps of basic landfarming, which make bioremediation of the oil possible, also make it easier for rainfall to wash brine from the site. When brine is present though, we need to think about drainage of the site—the salt must have a way out. Other IPEC products provide more detail on the process of salt remediation. Contact the IPEC office for these products or a qualified technical expert for help.

For more information or to request additional copies of these guidelines, contact Steve Hall at the IPEC office at (918) 631-2257 or stephen-hall@utulsa.edu. These guidelines were developed by Kerry L. Sublette, University of Tulsa, who may be contacted at (918) 631-3085 or kerry-sublette@utulsa.edu. Comments are welcome.

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