



Underground Tank Technology Update

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The benefits of in-situ biodegradation vs. monitored natural attenuation

By Evan K. Nyer and Gus Suarez

After more than 10 years, the remediation industry finally convinced the state regulators and U.S. Environmental Protection Agency to accept monitored natural attenuation (MNA) as an important remediation method. This article will give reasons why this is *not* always the best technology.

The difference between natural attenuation and in-situ biodegradation can be stated quite simply: natural attenuation is limited to natural remediation; in-situ biodegradation is not. Several processes can enhance biodegradation by accelerating the ongoing natural biodegradation, or the processes can stimulate new reactions and destroy organic compounds that were recalcitrant.

Should the use of enhancement methods be advocated to speed remediation times? Most regulators would encourage anything that would speed up cleanups. Stimulating bacteria can also often save money.

The choice of MNA versus in-situ bioremediation is contingent in part on cost. A thorough project examination should be undertaken and include analysis of all costs. Too often, the cost analysis is limited to the technical portion of the project. Consultants think they are doing a good job if they include capital, operating, maintenance, and analytical costs when describing a project. While many consultants are doing a better job of including long-term monitoring costs when considering a project's true costs, they are still neglecting several significant costs.

One key cost area still not included in many analyses

could be called "transactional" costs. These include the money spent interacting with regulators, because there are always monthly, quarterly, and/or yearly reports. There are costs associated with maintaining air and water discharge permits. In addition to costs associated with the regulatory community, there are also management transactional costs. As long as a project is alive, some management time will be spent on that project. Some of that money is easy to record. That is the money well spent on the consultant. The other part, harder to enumerate, is the cost of the management time from the company that owns and/or has hired the consultant. The sum of these "transactional" costs over a long period of time (10 to 20 years or more), reveals their significance.

Calculation of all project costs readily illustrates a significant economic incentive to increase the rate of bacterial degradation. Various methods can enhance bacterial activity. Simple economic analyses can delineate the results.

Biodegradation enhancement methods

Not all bacteria can use all electron acceptors, and not all compounds can be degraded by all bacterial enzyme pathways. However, because most natural environments include a wide variety of bacterial types, several methods can be used to stimulate a portion of the bacterial population to enhance the desired degradation.

There are two main categories for biological enhancement: aerobic and anaerobic. Figure 1 shows the relative energy that bacteria can derive from using different electron acceptors. The important point to understand from Figure 1 is the relative energy that the bacteria gain by the use of different electron acceptors. Each electron acceptor degrades the same amount of organics, but the bacteria are better off using one of the acceptors higher on the chart. The bacteria would

rather use O_2 than NO_3 , and NO_3 rather than SO_4 . They would rather use a particular electron acceptor, and they will also grow faster with the higher electron acceptors.

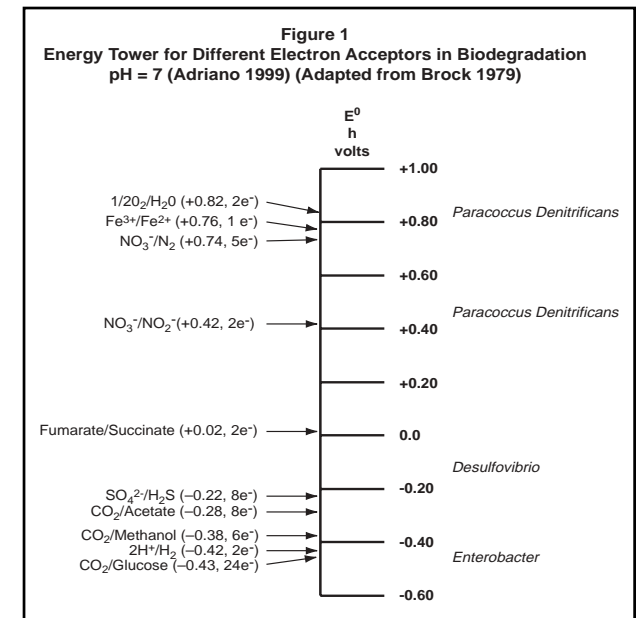


Figure 1. TEA energy tower (Nyer and Suarez, 2002).

Natural attenuation processes typically use the lower electron acceptors, SO_4 and below, for most of their degradation. Therefore, if any of the electron acceptors higher on the figure were available, the bacteria would use them preferentially and degrade the compounds at a faster rate. The bacteria will grow faster with NO_3 and faster still with O_2 . Either compound will stimulate the bacteria. These stimulations are mainly for petroleum hydrocarbons and lower-molecular-weight organics.

Anaerobic biodegradation enhancement, on the other hand, stimulates whole new degradation pathways. Remediators often refer to anaerobic stimulation through in-situ reactive zones, or IRZs.

With the anaerobic stimulation it is important to eliminate the higher electron acceptors and force the bacterial reactions to the less efficient acceptors below SO_4 . This creates new pathways resulting in degradation of chlorinated hydrocarbons. (Reviewer's note: Many chlorinated hydrocarbons can also be degraded under aerobic conditions.)

Economic analysis of biodegradation enhancement

Following are two cost/benefit examples of biodegradation enhancements. The first example involves a pump-and-treat system and a chlorinated hydrocarbon. Assume that the source area has been treated already and that a pump-and-treat system is in place at the end of the plume to ensure that the plume does not move any farther. Remediators now wait for a combination of the pumping to flush the aquifer, and the bacteria to degrade the compounds, and reach a concentration at which they can shut down the pumping system. Remediators can enhance the bacteria by adding material that will change the environment to anaerobic.

The second example is less obvious. Assume that remediators have a stable, naturally biodegrading hydrocarbon plume from a gasoline station. Most remediators strive for this situation and want to convince regulators that this situation exists. Increasing the biodegradation rate at this site by stimulating the bacteria with oxygen is an option to consider.

In the first example, the pump-and-treat system must remain in operation for plume containment purposes, whether or not additives are used to enhance bacterial activity. This brings with it certain annual expenses, including operation and maintenance, regular monitoring, laboratory analytical costs, report preparation and submittal, and project management. Use of additives will increase annual costs by introducing the cost of the

substrate and the costs associated with application (injection wells, equipment, subcontractors, staff, monitoring). While the annual costs will initially be greater, the key is that this strategy will expedite degradation such that contaminant concentrations will reach the levels necessary to allow shutdown of the pump-and-treat system more quickly. Annual costs will have been reduced to periodic monitoring to gauge concentration trends within the plume and reapplication of substrate, as needed.

At a chlorinated hydrocarbon plume site (PCE, TCE, cis-DCE and VC), historical groundwater monitoring has shown degradation rates to be such that the system will require operation in excess of 20 years. To expedite this process, remediators conduct an IRZ pilot study at the site to determine the effectiveness of molasses in promoting biological degradation via anaerobic processes. Remediators then perform an economic comparison (Figure 2) between operation of the system with pump-and-treat (option 1) and with biodegradation enhancements (option 2), using analytical results from routine monitoring to gauge current progress and project anticipated future system performance. As shown, initial costs for system operation using biodegradation enhancements were significantly higher than for operating with just the pump-and-treat system. After Year 3, however, degradation rates are anticipated to be such that the pump-and-treat system can be shut down in favor of routine molasses injections. As a result, incremental costs for option 2 will be significantly lower than those of option 1. Cumulative costs for option 2 are shown to continue to exceed option 1 until Year 8, at which time a breakeven point will be reached and the opposite trend will commence. Projected over 20 years, the cumulative costs for option 2 are \$913,558 less than for option 1. Thus, although initial costs are higher, enhancing biodegradation will bring the site to a point

closer to cleanup in a shorter period of time, as well as result in a significant long-term cost reduction. (Reviewer's note: cis-DCE and VC may be readily removed via aerobic processes. The addition of molasses is not required for these contaminants. Only TCE and PCE require the molasses addition. The point is that the economic comparison of alternatives is not straightforward. The exact mixture of contaminants should also be evaluated as part of the remediation alternatives comparison.)

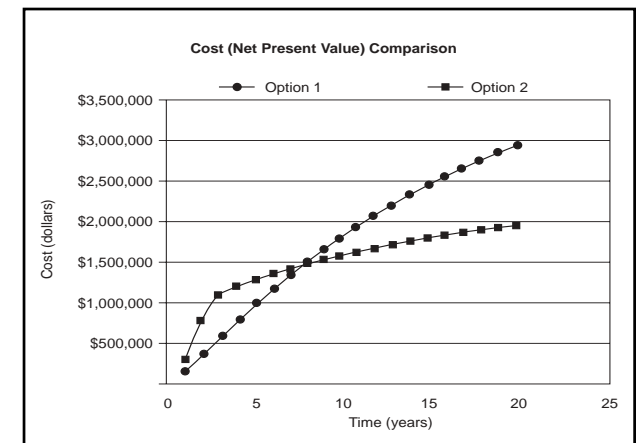


Figure 2. Economic comparison between pump-and-treat (option 1) and biodegradation enhancements (option 2) (Nyer and Suarez, 2002).

In the second example the hydrocarbon plume site had been assessed and had been undergoing remediation for 14 years. Constituents of concern are BTEX, MTBE and naphthalenes contained in shallow and deep surficial aquifers at concentrations exceeding state groundwater cleanup target levels (CTLs). The saving grace of this site is that the plume is stationary and contained within site property boundaries. The plume, however, is primarily beneath an active automobile

sales and service facility. Site investigations over the last five years have shown that anaerobic conditions prevail within the plume, with aerobic conditions at the leading edge. While dissolved hydrocarbon concentrations have decreased in the shallow surficial aquifer during this period, benzene and MTBE concentrations have increased in the deep stratum wells. Thus, anaerobic degradation processes are occurring, although at a rate insufficient to reach site rehabilitation within a reasonable time frame.

Remediators developed an aggressive remediation strategy entailing injection of air into the affected area, thereby enhancing the dissolved oxygen availability to use the faster aerobic degradation pathway. Given the location of the plume beneath the building, however, air sparging alone is not possible due to the potential buildup of explosive gases beneath the structure. (Reviewer's note: Many projects have used horizontal biosparge wells under buildings, and in all cases, vapors were not present in concentrations above analytical lower limits. The trick was to operate wells, especially horizontal wells, at lower flow rates as biosparge wells rather than air sparge wells.) Thus, remediators installed a series of horizontal vapor recovery wells within the building to mitigate this situation. The resulting system accomplished two things: first, it established an anaerobic environment to facilitate hydrocarbon degradation. Second, it allowed volatilization and transfer of contaminants from the dissolved and adsorbed phases to the vapor phase within the zone of aeration, thus increasing mass removal. Remediators used granular activated carbon to achieve vapor-phase treatment. (Reviewer's note: Using horizontal biosparge wells here would be more effective than horizontal SVE wells because biosparge wells treat contaminants in both unsaturated and saturated zones).

This site has undergone remediation activities for 14 years. With the exception of one source removal event, the site has simply been monitored for groundwater hydrocarbon concentrations. After all that time, contaminant levels remain well above state groundwater CTLs. Monitoring costs for this site are calculated at \$22,400 per year. To continue with MNA at this site for another 14 years would cost \$313,600. In addition, there is no reasonable assurance that contaminant levels will be at or below the state CTLs. Given contamination extent and degree, remediators anticipate that petroleum constituent concentrations will be reduced below state default natural attenuation levels after two years of active remediation using air sparging. The estimated cost of implementing this remediation system, including one year of post-active remediation monitoring, is \$304,000. The system, after being in operation for seven months, reports concentrations decreasing to below detection levels for vapor phase BTEX and MTBE. Groundwater BTEX, MTBE and naphthalene concentrations have been reduced to below state groundwater CTLs in all but three wells, where trace levels are reported. Consequently, the initial two-year projection for achieving MNA levels is well within reach. Although the initial cost is significant, bringing the site close to cleanup in such a short period by enhancing subsurface conditions more than justifies the expense.

While both of these examples show the cost benefit from stimulation of various bacterial populations, the cost analysis did not include transactional costs. If these costs were added to the analysis, the payback would be even faster for the investment in stimulation.

Conclusions

Too many designers have MNA as their final goal for a remediation. MNA is a very powerful tool in a

remediation design. It can also be the most economical and technically viable treatment method for a site. However, the long-term costs from technical operation of the remediation and from transactional costs of keeping the site active can make bacterial stimulation the proper choice for many sites.

Reference

Nyer, E.K. and G. Suarez, "In-Situ Biodegradation is Better Than Monitored Natural Attenuation," *Ground Water Monitoring & Remediation*, Vol. 22, No.1, Winter, 2002; <http://www.ngwa.org>

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Magnetic resonance imaging

Magnetic resonance imaging was developed in the 1950s to 1970s as a noninvasive diagnostic procedure and imaging technique for the body. Its sensitivity increased dramatically in the 1990s and the technique has since been used to investigate, for instance, the effect of toxic substances in rats, and the details of heavy metal ion exchange in algal biomass (Nestle and others, 2002).

Based on principles of nuclear magnetic resonance, MRI has allowed scientists to acquire chemical and physical information about molecules. "Magnetic resonance imaging is based on the absorption and emission of energy in the radio frequency range of the electromagnetic spectrum... Many scientists were taught that you cannot image objects smaller than the wave-

length of the energy being used to image. MRI gets around this limitation by producing images based on the spatial variations in the phase and frequency of the radio energy being absorbed and emitted by the imaged object" (Hornack, 2002).

Applicability of MRI has expanded. Some scientists believe that in the next few years "MRI should become a versatile tool, especially for three-dimensional visualization of processes involving nonaqueous-phase liquids (NAPLs) in soils and aquifer environments, enabling realistic, in-situ studies of remediation techniques in the laboratory. The technology is poised to become an important tool for studying the adsorption of dissolved materials and filtration of colloidal substances in subsurface matrixes" (Nestle and others, 2002).

How MRI works

Consider the nucleus of a hydrogen molecule. It consists of a single proton. This proton has a property called spin, which causes the proton to behave like a small magnet with a north and south pole. This spin, which can be considered as a small magnetic field, will cause the nucleus to produce an NMR (nuclear magnetic resonance) signal. Liquid and mobile phases give off a detectable NMR signal; rigid solid phases do not.

Most elements in the periodic table have an isotope with a non-zero nuclear spin. These are amenable to MRI detection. However, such isotopes must be of sufficient quantity to be detected. Some of the nuclei of interest to MRI include

- ^1H
- ^2H
- ^{31}P
- ^{23}Na
- ^{14}N

- ^{13}C
- ^{19}F

MRI can image the human body because the body is primarily fat and water, being composed of approximately 63 percent hydrogen atoms. These hydrogen nuclei give an NMR signal.

Environmental MRI

Environmental MRI can involve an analysis of the following:

- soil
- unconsolidated sediment
- aquitard materials
- fractured rock with a high mineral content

The NMR (nuclear magnetic resonance properties) of environmental materials are more complex than those of the body. Nestle and others (2002) report, "liquid and mobile phases (which lead to a detectable NMR signal in standard MRI, while spins in solid phases do not) make up only about 25 percent of the sample volume compared with greater than 90 percent in most biological and medical samples. Thus, signal-to-noise ratio at the same spatial resolution is much lower in environmental samples. Moreover, spin relaxation times in the mobile phase tend to be much shorter than in standard medical MRI. This poses a problem because sample imaging requires more intensive magnetic field gradients, which must be switched in shorter times and require more sophisticated gradient control hardware than do medical applications. In addition, spin relaxation (which is responsible for the image contrast in many MRI methods and which limits the signal intensity available at given echo and repetition times) tends to become strongly nonexponential in many environmental materials due to factors such as wide pore size distribution in soils and sediments and local variation in the

content of paramagnetic materials. The nonexponential relaxation can lead to images that are not representative of the whole fluid content in the sample; in certain soil samples, the detected NMR signal can be as small as 0.2 percent of the overall liquid content" (Nestle and others, 2002).

To successfully use MRI, researchers must be able to discriminate the following:

- relaxation specifics for the sample
- any spatially varying concentrations of paramagnetic materials and local magnetic variations
- the difference between water flow and diffusive movement

A potential limitation of the technique relates to sample size: the maximum sample size suitable for MRI is usually significantly smaller than the representative elementary volume of interest. Yet researchers have successfully used MRI to trace dissolved paramagnetic ions such as Ni^{2+} and Cu^{2+} through a sandy aquifer.

Using MRI for detecting NAPL

In environmental studies, the NAPL (nonaqueous phase liquid) relaxation times in most matrices are longer than those in water. Spin density varies depending on the NAPL (halogenated vs. aromatic vs. nitro). To improve image contrast, researchers can

- dope the NAPL or water phase with an MRI tracer (such as a paramagnetic salt)
- use special imaging sequences that provide an appropriate relaxation time or diffusion contract
- use fluorinated NAPLs (for example, hexafluorobenzene) to discriminate NAPL from the water phase

"Signal losses in soils due to short relaxation times reduce the signal-to-noise ratio and may lead to water signals that are not representative of the overall water..."

In unsaturated sandy sediments, conditions are more favorable for MRI studies than in soils because relaxation times for low water contents are not so strongly reduced" (Nestle and others, 2002). The NMR signal originates directly from the liquid phase of interest.

Transport processes such as adsorption or filtration can be studied because they influence the relaxation properties. "Filtration of colloidal particles in the sediment can be observed for many nonmagnetic mineral particles. The filtered particles lead to an increase in the surface of the sediment matrix, which in turn leads to a decrease in the relaxation times that can be exploited for the image contrast. Qualitative mapping of filtrate concentrations can be performed without special calibration, but a quantitative analysis requires additional studies of the relaxation time dependence on the filtrate of interest in its respective matrix... Organic colloids, such as microorganisms or colloidal dead biomass, do not lead to similarly strong changes in the relaxation behavior of the pore water. However, it is possible to tag materials of biological origin with magnetically marked antibodies or by incorporating paramagnetic ions in the microorganisms and thereby establish an MRI contrast" (Nestle and others, 2002).

MRI of the future

One of the limitations facing those who wish to use MRI in the environmental field involves overcoming the relatively short relaxation times of the materials being studied. Nestle and others (2002) project that "dedicated imaging equipment will probably be the option of choice in the future for several reasons. Increasing signal losses due to diffusion in the internal magnetic field gradients present in many environmental matrixes tend to cannibalize the signal intensity gain provided by the high magnetic fields of 1.5 tesla (T) or more, which for medical MRIs are now standard. An MRI system

operating at a lower external magnetic field strength (typically 0.05-0.5 T) is less sensitive to those artifacts. Furthermore, low-field MRI allows direct comparison with field data from NML (nuclear magnetic resonance well-logging) tools. However, low-flow velocities in the environment create a need to use stronger magnetic field gradients of at least several hundred milliteslas/meter (mT/m) which is more than those available in common clinical MRI systems (40 mT/m or less). Working with stronger magnetic field gradients often imposes additional restrictions on sample sizes compared with standard MRI methods, and the electrical power required for generating sufficiently strong magnetic field gradients for studying larger samples becomes unrealistically high when using conventional equipment. This is especially the case with SPRITE (a specialized MRI technique that allows reasonably fast 3-D imaging of materials) and with sequences for mapping small flow velocities or small self-diffusion coefficients."

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Integrity assurance program for USTs

By David H. Kroon

This article focuses on electrochemical corrosion of steel and the establishment of integrity assurance programs for underground steel tank systems. All of the following

pertains not only to steel tanks but also steel components (e.g., pipe, fittings) of UST systems. Operators of existing USTs are faced with the problem of how best to manage their systems. In recent years, concerns for safety, environmental protection and public liability have risen dramatically. An integrity assurance program (IAP) is necessary to ensure safe tank system operations that comply with applicable regulations and limit exposure to unnecessary liabilities.

Corrosion of steel tanks

The forms and mechanisms by which steel corrodes underground are well established. When tanks corrode uniformly, their useful life can easily satisfy the normal 20-year design, and possibly extend to a 40-year-plus lifetime. Concentrated corrosion, can, however, result in premature failure within several years. For USTs, the rate of external corrosion, leading to penetration of the tank wall, is largely determined by

- wall thickness
- quality and longevity of dielectric coating
- differential in oxygen concentration from top to bottom
- homogeneity of backfill
- groundwater composition and fluctuation
- chemical and electrical properties of the surrounding soil
- impact of stray DC earth currents

Much of our knowledge regarding the performance of steel underground has resulted from the study of pipelines. There are, however, two very significant differences between the corrosion of underground tanks and pipelines: one, a tank is of much larger diameter, and two, the operation of a tank system is far different than that of a pipeline.

In the first instance, the larger diameter inevitably

increases the difference between the available oxygen at the top of the tank vs. that at the bottom. This, therefore, creates intense oxygen concentration corrosion cells. The large diameter also enhances accelerated rates of corrosion due to fluctuations in the water table, temperature variations and non-homogeneous backfill.

The tank operation itself also contributes to corrosion. The cyclical nature of filling and emptying causes changes in temperature, pressure, tank end deflection and other factors. Probably the most significant impact, however, is on the dielectric coating. Product spillage regularly deteriorates the coating to the extent that the top surfaces of many older petroleum-product tanks coated with coal tar enamel are virtually bare.

All of these factors contribute to increasing the rate of corrosion of USTs, and in particular, concentrate the corrosion at holidays—voids—of tank bottom coating. The larger area of steel exposed by coating deterioration on the top of the tank is the cathode in the corrosion cell, with the anodic reactions concentrated at small coating flaws along the tank bottom. The area of relationship (small anode, large cathode) contributes to increasing the magnitude of corrosion current density that is discharged from a localized point on the tank bottom. For this reason, the American Petroleum Institute (API) tank leak survey indicates that 95.6 percent of the leaks reported on USTs were confined to the lower two-thirds of the tank.

Contrary to other reports, the author's experience has been that internal corrosion of steel tanks is not the incipient problem that some have suggested. The most susceptible location for corrosion is under the fill tube where both the filling and gauge sticking operations remove protective films on the metal surface. This area is made more active than the remainder of the internal tank surface and pitting attack is occasionally initiated.

Since this is the dominant internal corrosion mechanism, it is not surprising that it most often occurs in small tanks, at high-volume outlets, where deliveries are more frequent.

The use of strike plates, welded to the bottom of the tank, under the fill tube, provides an allowance for this type of corrosion. The strike plate should be sealed to prevent corrosion in the annulus between the plate and tank wall.

Additional internal corrosion protection can also be afforded through the use of coatings, linings and cathodic protection. Although not common practice for USTs, a partial liner or coating system on the bottom quadrant, where the internal surface could be exposed to water, is certainly an alternative to complete interior coating. Coating and lining systems have been successfully used for years to provide internal corrosion protection of ground storage tanks in the oil industry. Typically the bottom and 12 to 18 inches up the sides are coated where produced water collects during storage.

Data collection

To obtain the data necessary for an accurate analysis of a UST system, researchers need to conduct information research, field inspections, field tests and laboratory testing. All test methods should be in accordance with standard engineering practices.

Information research is performed to include a review of site drawings, construction specifications and operational history at each location. The following specific information is collected, where available, concerning the underground tank installation:

- location, contents, capacity and dimensions
- coating and backfill material
- age and leak history
- piping materials and location

• electrical isolation and use of insulating fillings
Upon arrival at a UST site, a visual inspection is performed and the following observations recorded:

- existing utilities
- DC transit systems
- presence of an aquifer
- basements
- potable water supply
- navigable waterways
- public buildings

A stray DC earth current monitor is established to detect the presence, if any, of DC interference currents from foreign sources. The monitor consists of a microprocessor-controlled field data collection unit in conjunction with a reference cell data collection unit in conjunction with a reference cell placed in contact with the soil. Electrolytic (stray current) corrosion can result from the operation of DC transit systems, improper grounding of DC welders, mining equipment, or foreign cathodic protection systems. Electrolytic corrosion of UST systems can be very severe when stray currents are affecting the structures.

Using a tank gauge stick equipped with a pointed probe, researchers can record the extent of internal corrosion immediately below the fill cap. Field workers select locations for soil borings, and for each test hole they record a number of measurements as the boring progresses:

- soil pore vapors
- tank-to-soil potential profile
- soil resistivity profile
- depth of water table

Researchers extract soil samples from the boreholes and place them in sealed sample jars for laboratory

analysis. They are sent to a soils laboratory where the following tests are performed:

- conductivity
- pH
- sulfide ion concentration
- chloride ion concentration
- moisture content
- type classification

Using a soil vapor detector, field workers analyze for gasoline during the boring operation. The detector generally indicates concentrations ranging from 30 to 1,000 ppm. Field workers use colorimetric tubes to detect other compounds. Field workers can also test soil for recoverable petroleum hydrocarbons.

Data analysis

Testing as described above was performed on USTs in 44 of the 48 contiguous United States. Tables 1 through 8 summarize test data from 2,894 of these sites, encompassing 7,590 tanks ranging from 1 to 31 years of age. The most significant observations include:

- at 53 percent of the sites, the mean soil resistivity is less than 10,000 ohm-centimeters (Table 1)
- at 87 percent of the sites, the mean conductivity is greater than 100 micro-ohms (10,000 ohm-centimeters equivalent), confirming the great variation in the electrical properties of soil with moisture content (Table 2)
- within 57 percent of the borings, the variation in resistivity was more than 10,000 ohm-centimeters (Table 3)
- the tank-to-soil potential profile varied within a boring by 40 millivolts or more, in 47 percent of the cases (Table 4)

- stray currents causing fluctuations in tank-to-soil potential of 100 millivolts or greater were recorded at 2 percent of the locations
- one penetration was detected due to internal corrosion under the fill
- soil vapor indicated the presence of product in 24 percent of soil samples; however, concentration was greater than 30 ppm in only 9 percent of the tests
- at 55 percent of the sites, the mean value of the soil pH fell between 8 and 10 (Table 5); the alkaline conditions are largely due to the use of degreasers to clean the tank pad
- in 64 percent of the cases, the mean soil moisture content was less than 10 percent (Table 6)
- chloride ion concentrations in excess of 100 ppm were detected in soil samples at 10 percent of the sites (Table 7)
- sulfide ions were detected in the soil at 34 percent of the sites, with a concentration of 1.0 ppm or greater at 10 percent of the locations (Table 8)

Ohms-centimeters	% occurrence
< 3,000	16.1
3,000-9,900	37.1
10,000-19,900	20.7
20,000-49,900	16.5
> 50,000	9.6

Table 1. Soil resistivity (mean value at site).

Micro-ohms	Ohm-cm	% occurrence
< 20	> 50,000	0.1
20-49	50,000-20,000	2.6
50-99	20,000-10,000	10.7
100-999	3,000-1,000	21.2
> 999	> 1,000	66.0

Table 2. Soil conductivity (mean value at site).

Ohms-centimeters	% occurrence
<3,000	17.4
3,000-9,990	25.3
10,000-19,900	19.4
20,000-49,900	20.2
> 50,000	17.7

Table 3. Variation in soil resistivity (maximum-minimum per boring).

Millivolts	% occurrence
< 20	25.3
20-39	27.8
40-59	17.7
60-79	11.2
> 80	18.0

Table 4. Variation in tank-to-soil potential (maximum-minimum per boring).

pH	% occurrence
< 4.0	0.1
4.1-6.0	5
6.1-7.0	10
7.1-8.0	27
8.1-10.0	55
> 10.0	3

Table 5. Soil pH (mean value at site).

% dry weight	% occurrence
< 5.0	15.2
5.0-9.9	48.3
10.0-14.9	27.0
15.0-19.9	7.6
20.0-24.9	1.2
> 25	0.7

Table 6. Soil moisture content (mean value at site).

ppm	% occurrence
0-9	43.4
10-19	19.9
20-49	16.3
50-99	7.8
> 100	12.6

Table 7. Chloride ion concentration (maximum at site).

ppm	% occurrence
0.000	66.2
0.001-0.999	23.9
1.000-4.999	8.0
> 5.000	1.9

Table 8. Sulfide ion concentration (maximum at site).

Field data and laboratory test results were entered and analyzed by a computer model to predict the mean time to corrosion failure (MTCF) for each of the tank sites. The model has been developed through the use of linear regression techniques and various statistical programs. The data from confirmed sites of corrosion failure were used to develop a regression equation with the actual age-to-failure as the dependent variable. The sets of field data and laboratory test results are the independent variables. Most of the test data are normally distributed; however, transformations were required to normalize some independent variables.

The calculated MTCF gives the age at which the majority of steel tanks in that particular environment will leak due to corrosion. Because the computer program models the "mean time" to corrosion failure, it must be recognized that the predicted MTCF at any specific site may vary from the actual time to corrosion failure. The model simply reflects the average age at which a tank will fail from corrosion in that particular environment. The model does not predict leaks due to other causes, such as metallurgical or mechanical defects, and cannot account for improper tank installation.

Giving full recognition to the limitations of the analysis, the calculation of MTCF is an economical method by which to develop an excellent planning tool.

IAP program development

The field survey, testing and analysis provide three key site-specific factors to consider during the development of the underground tank system integrity assurance program (IAP):

- probable leakage
- mean time to corrosion failure
- risk identification

The probability of a present leak in an underground tank is evaluated by the results of the gasoline (or other product) soil vapor testing. In general, as the product concentration increases with depth, the probability that the tank is presently leaking increases accordingly.

The MTCF is used to calculate a priority index (PI) by subtracting the MTCF from the actual age of the tank. This PI is then used to assign priorities to each of the tank sites.

The site information regarding the location of public buildings, water supplies, etc., is used to identify risk factors related to a tank failure, should leakage occur.

The results for each underground tank system are placed in three general categories:

- probable leakage
- high PI
- low PI

Within each category, locations are prioritized as to the order of importance. The integrity assurance program includes a number of recommended actions for each category of tasks. These may include

- inventory analysis
- precision tank testing
- repairs and/or replacement
- external/internal corrosion protection

For reasons of reduced liability by improved leak

detection techniques and regulatory requirements, other elements of the program may include

- leak detection systems
- inventory control systems
- monitoring wells
- overfill protection

Where leakage is probable, the presence of an existing leak should be confirmed and appropriate steps taken to evaluate the degree of contamination and cleanup requirements. A business decision then needs to be made whether to repair, replace or abandon the tank. If repairs are made, the tank should be retrofitted with external cathodic protection. Internal corrosion protection can also be considered at the time. If the tanks are to be abandoned, proper closure or removal procedures must be followed. If the tanks are to be replaced, then choose either fiberglass or steel with cathodic protection. In both cases, corrosion protection is recommended for steel piping incorporated in the underground tank systems. To reduce the current required for cathodic protection and to eliminate the bimetallic couple, coated steel piping should be used in lieu of the more common galvanized pipe. The need for monitoring wells, inventory control systems, leak detection systems, and overfill protection should also then be evaluated to coordinate all construction activities.

At sites with a relatively high PI, a detailed inventory analysis or precision tank testing should be performed to determine if the system is presently tight. If a leak is detected, the procedures outlined above should be followed. If there is no leakage, retrofitting with external cathodic protection is recommended. The decision whether or not to include these additional elements in the IAP is largely based upon considerations for reducing exposure to public liability, and meeting regulatory requirements.

For the low PI category, the indices present the order of importance for addressing the sites. If a decision is made to maintain the existing underground tank systems, then retrofitting with external cathodic protection for the tank and piping should be considered in addition to other elements of the IAP.

All decisions must be reached after due consideration for safety, economics and regulations.

Economic benefits

Some of the greatest direct economic benefits to the tank system owner/operator accrue during the construction staging and coordination and monitoring and maintenance phases of the IAP. By properly planning the construction of all elements of the program, owners can realize tremendous savings in site work (e.g. excavations, concrete). Following installation and commissioning of the systems, a most important element of the overall IAP remains to be addressed: data collection, transmission and management systems. These are essential for maximizing the program's economic benefits, which result from improved trend analysis, forecasting and budgeting.

The decision regarding which elements to incorporate in an IAP should give top priority to leak prevention. Leak detection is a secondary, after-the-fact, concern.

Past experience with operators of underground tanks indicates that a comprehensive approach to the problem of controlling corrosion and reducing exposure to public liability usually costs less than 25 percent of overall tank system replacement.

Conclusion

The testing and evaluation procedures presented offer an economical method by which a great deal of information can be collected for good planning and budgeting. When the appropriate business factors are

incorporated with the results of the indexing, decisions can be made concerning such related factors as expansion, remodeling and abandonment.

The test program not only evaluates the potential for corrosion and defines a priority index for each site but also alerts the operator to concerns for existing spillage and the possibility of system leakage. Immediate steps can then be taken to protect the environment and the company.

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UTTU thanks James T. Lary, Corpro Companies, Inc. (<http://www.corpro.com>) Medina, Ohio, for contributing this article.



Mass balance of terminal electron acceptors

To determine if a site is adequately undergoing natural attenuation, remediators will usually analyze if the groundwater plume is expanding, decreasing or at steady state, and assess the aquifer's current and future assimilative capacity. To assume sustained rates of bioattenuation may be invalid, because TEA (terminal electron acceptor) sources can become depleted. Researchers devised a mass balance approach for determining abundance of TEAs in LNAPLs (light nonaqueous-phase liquids). This article outlines some of the theory and essential features of their model.

TEA favorability and occurrence

TEAs facilitate biochemical redox reactions. Microorganisms, through biochemical redox reactions (in which electrons are transferred from organic contaminants to TEAs), obtain energy and carbon for new cell material. The microorganisms then degrade contaminants into relatively harmless water and carbon dioxide.

If the environment is aerobic, oxygen is the most favorable TEA. When anaerobic conditions result (because dissolved oxygen (DO) is rapidly depleted from groundwater), the order of TEA utilization is as follows:

- nitrate (NO_3^-)
- manganese (Mn(IV))
- ferric iron (Fe(III))
- sulfate (SO_4^{2-})
- carbon dioxide (CO_2)

Occurrences of the TEAs are as follows:

- oxygen, nitrate, sulfate and carbon dioxide are normally found in the aqueous phase
- in sulfate-rich environments, sulfate can be found in sediments
- ferric iron is present in the solid phase near a neutral pH; the occurrence of ferrous iron (Fe(II)) indicates reduction of Fe(III) and anaerobic biodegradation

Obtaining accurate measurements of CO_2 is made difficult by the presence of carbonate in water. The reaction byproduct, methane (CH_4), can be a quantitative indicator of CO_2 .

Solid-phase TEA

In this analysis, researchers considered that Fe and Mn species and reducible organic matter would be the primary sources of solid-phase TEA in aquifers. Mn contributes 2-5 percent of the total transferable electron

equivalents, thus researchers assumed all solid-phase TEA was composed of Fe. Bioavailability, however, is another matter. Investigation of samples from five sites indicated the following:

- natural and man-made amorphous iron oxides are readily reduced (microbially), whereas the more crystalline varieties are poorly reduced
- Fe(II) produced from Fe(III) reduction may limit Fe(III) oxide reduction by sorption and saturation of the Fe(III) surface
- precipitation of Fe(II) can influence bioavailability of Fe(III) , causing "fouling" of the Fe(III) surface, reducing the rate of iron reduction
- one method to evaluate bioavailable Fe, which uses a weak HCl extraction, indicated 70 percent of the total iron from an aerobic, uncontaminated aquifer was not bioavailable
- another method using Fe-reducing bacteria indicated (at the same site) that average bioavailable Fe(III) ranged from 18.1 to 20.9 $\mu\text{mol/kg}$
- bioavailable TEA is site-specific and dependent on soil mineralogy
- no definite correlation exists between aquifer mineralogy and TEA concentrations; not enough samples have been acquired to make such correlations

The nature of LNAPLs

LNAPLs have the following characteristics:

- density less than 1 g/cm^3
- existence as separate, immiscible liquid phase

BTEX can be a LNAPL. Factors that will affect its mass transfer from the LNAPL to the aqueous phase include groundwater velocity, contact time and area, attenuation mechanisms, LNAPL saturation, solubility, temperature and permeability.

Model development

Researchers developed a model to determine total TEA required to completely mineralize BTEX present in LNAPL, solid and aqueous phases. Basic equations include:

$$\text{TEA}_R = \text{TEA}_{R\text{-AQ}} + \text{TEA}_{R\text{-S}} + \text{TEA}_{R\text{-LNAPL}}$$

where

- TEA_R = total TEA required for complete mineralization of BTEX (mol e^-)
- $\text{TEA}_{R\text{-AQ}}$ = fraction of TEA_R attributed to BTEX in the aqueous phase (mol e^-)
- $\text{TEA}_{R\text{-S}}$ = fraction of TEA_R attributed to BTEX in the solid phase (mol e^-)
- $\text{TEA}_{R\text{-LNAPL}}$ = fraction of TEA_R attributed to BTEX in the LNAPL (mol e^-)

To balance the deficit between TEA_R and TEA_T , researchers developed PV (aqueous pore volume) and equivalent solid-phase volume (ESV), where

$$\text{PV} = (\text{TEA}_R - \text{TEA}_T) / (\text{TEA}_{T\text{-AQ}})$$

$$\text{ESV} = (\text{TEA}_R - \text{TEA}_T) / \text{TEA}_T$$

"PV provides a conceptual estimate of the volume of ground water containing $\text{TEA}_{T\text{-AQ}}$ that must be transported into the representative volume (source area) to balance the TEA deficit. ESV provides a conceptual estimate of the additional aquifer volume, including both the aqueous and solid phases, required to balance the TEA deficit" (Huling and others, 2002).

Although BTEX is a concern for regulators, other biodegradable compounds such as alkanes, cycloalkanes, branched alkanes and naphthalenes can be a sink for TEAs. Two terms existing in the model (BTEX/TOC and BTEX/BOD) can be adjusted to compensate for the other biodegradable compounds.

Jet fuel release site

Researchers examined a site that released a large volume of jet fuel (JP-4) LNAPL. They collected samples from nine wells during three sampling events and analyzed for BTEX. Researchers ascertained the following from using their mass balance approach:

- no site-specific data were available for $TEA_{T,S}$, so 31 $\mu\text{mol/l}$ of bioavailable Fe(III) was assumed
- SO_4^{2-} and NO_3^- in uncontaminated wells were 200 mg/l and 8.5 mg/l respectively
- no solid-phase contribution of sulfate, manganese and organic matter TEA was assumed
- upgradient DO was assumed to be 7 mg/l
- CH_4 was estimated to be 0.5 mg/l
- the majority of the TEA_R was due to the LNAPL (98 percent); solid fractions contained 1.7 percent and aqueous, 0.3 percent
- the contribution of $TEA_{R,AQ}$ to TEA_R is relatively small
- solid-phase TEA comprised the largest fraction (90.2 percent) of TEA_T
- approximately 21 times (ESV~21) the TEA contained in the representative volume or 212 pore volumes of influent $TEA_{T,AQ}$ would be required to balance the TEA deficit for BTEX mineralization

Conclusions

Researchers concluded the following:

- "contaminant transformation rates are routinely estimated from monitoring well data using a regression method based on a steady-state analytical model; potential erroneous transformation rates may arise because of the defects of dispersion, developing plumes or too few data points"

- it may be incorrect to assume that reaction rates "responsible for the existing BTEX plume also extend many years into the future"
- "quantification of $TEA_{T,S}$ and $TEA_{R,LNAPL}$ and their roles in natural attenuation will lead to an improved understanding of the long-term sustainability of transformation rates, and associated remedial timeframes"
- the total TEA required for mineralization of BTEX in the LNAPL source area is predominantly attributed to $TEA_{R,LNAPL}$ (98 percent)
- a TEA deficit exists in the LNAPL source area; the large numbers of pore volumes ($PV > 200$ for this site) of influent aqueous-phase TEA, or the equivalent solid volumes (ESV about 21 for this site) required to balance the TEA deficit, suggests long-term persistence of the source
- $TEA_{R,Q}$ represents a minor fraction (< 0.3 percent) of the TEA required for mineralization
- solid-phase TEA is a major source of TEA used in the biochemical reactions, yet the aqueous-phase TEA and BTEX are the focus of many natural attenuation feasibility studies
- "studies that do not consider LNAPL and involve quantitative comparisons between upgradient $TEA_{T,AQ}$ and $TEA_{R,AQ}$ have limitations; for example, the $TEA_{T,S}$ contribution from iron is sometimes measured as the difference between upgradient and downgradient Fe(II) concentrations and is assumed infinite. This quantity is attributed to solid-phase dissolution of Fe(III), which is finite. Given sufficient time, it can become depleted, especially in a LNAPL source area. Depletion of $TEA_{T,S}$ in the source area may significantly affect the fate and transport of BTEX" (Huling and others, 2002).
- LNAPL recovery techniques can be used to remove

LNAPL and minimize the TEA deficit in source areas; such techniques include vacuum extraction, bioventing, skimming and dual-phase extraction

Reference

Huling, S.G., Pivetz, B. and R. Stransky, "Terminal Electron Acceptor Mass Balance: Light Nonaqueous Phase Liquids and Natural Attenuation," *Journal of Environmental Engineering*, March 2002; <http://www.pubs.asce.org/journals/ee>.



Research notes

Abandoned Underground Storage Tank Location Using Fluxgate Magnetic Surveying: A Case Study

Van Biersel, T.P., Bristoll, B.C., Taylor, R.W. and J. Rose, *Ground Water Monitoring and Remediation*, Winter 2002; <http://www.ngwa.org>.

This article describes the fluxgate magnetometer survey undertaken at a municipal garage in Sheboygan County, Wisconsin. According to Biersel and others (2002), "The fluxgate magnetometer was developed as an airborne submarine detector during World War II. It measures a single component (vertical) of the total magnetic field and is not affected by the horizontal component. This enables the geophysicist to use this equipment in the presence of manmade magnetic interference above the ground surface and to accurately measure magnetic field readings in the presence of steep magnetic gradients."

The non-intrusive survey, which used a 1.5 by 1.5 m sampling array, identified buried tanks within 3 m of buried structures. Field workers entered magnetic intensity readings into a database, corrected the data

for diurnal and instrumental variation, then analyzed and graphically displayed the data using contouring software.

Analytical Model to Quantify Crude Oil Spill Volume in Sandy Layered Aquifers

Al-Suwaiyan, M., Bashir, K., Aiban, S.A. and A.M. Ishaq, *Journal of Environmental Engineering*, April 2002; <http://www.pubs.asce.org/journals/ee>.

By comparing data from analytical and empirical models that estimate spill volumes in layered soils, researchers determined that most analyses will underestimate actual spill volume in soils. Results from the studies also indicated

- soil layering significantly affects the spill-volume/free-product relationship
- analytical prediction in homogeneous soils consistently underestimates the oil spill volume
- the degree to which the system is out of hydrostatic equilibrium has a major influence on analytical estimates
- factors that contribute to the unreliability of analytical model estimates include inaccurate hydraulic characterization of the soil, heterogeneity, spill time and history and water table fluctuations

Calibration of a Model for Volatile Organic Compound Mass Removal by Multiphase Extraction

Edwards, D.A., Little, J.W., Lanik, W. and P.A. Hajali, *Journal of Environmental Engineering*, May 2002; <http://www.pubs.asce.org/journals/ee>.

Edwards and others (2002) define multiphase extraction (MPE) as "simultaneous removal of contaminated liquids and vapors from soil or rock through wells subjected to a high vacuum. The high vacuum may be

applied at, near or below the static water table, with different implementations being referred to as 'bioslurping,' 'dual-phase extraction.'... The MPE process works by inducing steep hydraulic or pneumatic gradients in the saturated and unsaturated zones that tend to drive contaminated fluids to extraction wells. Contaminated fluids removed by MPE include light or dense nonaqueous-phase liquids (LNAPL or DNAPL), residual NAPL, groundwater, capillary-fringe water and soil or rock vapor. Extraction of capillary-fringe water by MPE removes a potential source of contamination not commonly remediated directly by other means."

In their paper, Edwards and others (2002) present a simple empirical model that can be used to approximate VOC mass removal by a MPE system. This model can be used for diagnosing operational problems, anticipating future rates of VOC mass recovery or planning for a system shutdown.

Diffusive Partitioning Tracer Test for Nonaqueous Phase Liquid (NAPL) Detection in the Vadose Zone

Werner, D. and P. Hohener, *Environmental Science & Technology*, Vol. 36, No. 7, 2002; <http://www.pubs.acs.org>.

Werner and Hohener (2002) developed a partitioning tracer test that detects nonaqueous phase liquid (NAPL) in the vadose zone. The procedure uses chlorofluorocarbons, which field workers inject into the vadose zone. Chlorofluorocarbons are used because they are volatile, non-toxic, non-biodegradable (under aerobic conditions) and have low detection limits (when analyzed by a gas chromatograph). Tracers diffuse away and small volumes of gas are withdrawn from the injection point. To quantify NAPL saturation, remediators compare the decline of tracers with various air-NAPL partitioning coefficients. This method was successfully

tested at a large-scale field lysimeter contaminated with artificial kerosene.

Werner and Hohener explain that this partitioning tracer test uses the same equipment used in soil surveys. The test is based on diffusion rather than advection, hence the name diffusive partitioning tracer test (DPTT). The procedure is as follows: "The tracer mixture is injected by a soil gas profiler and creates a point source. After the injection, the tracers diffuse into a larger spherical zone. Slower diffusion velocities of those tracers partitioning into NAPLs indicate the presence of an NAPL... Our approach includes two or more gaseous tracers with known partitioning behavior into the stationary phases. The objective of this study is to develop the theory underlying the DPTT and to test the new method in laboratory experiments and in a large-scale lysimeter study."

Researchers made several assumptions and observations:

- equilibrium will be reached after an initial stabilization period in the pore spaces filled with contaminants; equilibrium can be determined by plotting gas fractions as a function of time
- one equation neglects sorption to the solids and partitioning into the water phase
- diffusion in the gas phase is the only relevant process for tracer movement
- vadose zone isotropy and consequent diffusion of gas tracers in a homogeneous porous medium is a concern
- an instantaneous point source is assumed as an initial condition

Because the DPTT is so new, researchers have not yet completed extensive tests on how it compares with other methods such as the PITT (partitioning interwell tracer test), which is based on advective transport. The

DPTT is a rapid, relatively inexpensive test that does not disrupt the subsurface as soil coring does. Investigation of large soil volumes and determination of NAPL saturation with precision is possible. Researchers estimate that the test can be performed at five different locations (at least 3 m apart) within a working day and with about 25 GC (gas chromatograph) analyses.

Researchers believe that "The DPTT will be especially useful for applications in which the emphasis lies on the comparison of the NAPL saturation at different locations in a homogeneous soil, or on the observation of the evolution of NAPL saturation at a specific location... Such applications include source delineation and the monitoring of natural attenuation processes."

Electroremediation of Contaminated Soils

Page, M.M. and C.L. Page, *Journal of Environmental Engineering*, March 2002; <http://www.pubs.asce.org/journals/ee>.

Electroremediation of soils "involves passage through soil of direct current between appropriately distributed electrodes." Advantages of the experimental process include

- ability to be performed in-situ
- effective for fine-grained soils of low hydraulic permeability

In this paper, the reader will discover that most electroremediation work has been done in the laboratory using spiked synthetic soils, generally kaolinite. A current is passed through the soil, and this experiment lasts from a few to several months. During the experiment, current, voltage, fluid flow and chemical composition of the effluent may be continuously monitored. At the conclusion of an experiment, researchers usually measure moisture content, conductivity and pH of the pore solution, and contaminant distribution.

Potential enhancements to electroremediation can include the following:

- periodically reversing electrode polarity, which avoids excessive buildup of chemicals
- adding chemical conditioning agents at the electrodes such as water and sodium chloride to increase contaminant removal
- flushing of electrodes
- buffering the soil to control any existing pH gradient
- using acetic acid to depolarize cathodic reaction (used with soils contaminated by uranium salts and lead compounds)
- using an alkaline purge solution for organic contamination to increase electro-osmotic flow, or using surfactants for removing petroleum hydrocarbons
- using aggressive oxidizing agents, such as Fenton's reagent, to break up persistent organics

Hybrid processes include

- application of a hydraulic gradient (removed Zn, Mn and Pb from a sand/sludge)
- acoustic treatment (removed decane, Zn and Cd from clay soils)
- bioventing (removed gasoline)
- electro dialysis (removed Cu in part; removal of Pb, partially successful)
- bioremediation (useful for TNT, PCBs, pesticides, heavy tars), which can involve addition of terminal electron acceptors; application of electric fields can help move microorganisms because they have a negative charge
- phytoremediation; the electric field is applied so contaminants are transported and made available for uptake by plant roots

Researchers ascertain that future research in this field will probably focus on electroremediation as a hybrid technology with bioremediation.

Emissions of Aldehydes and Ketones from a Two-Stroke Engine Using Ethanol and Ethanol-Blended Gasoline as Fuel

Magnusson, R., Nilsson, C. and B. Anderson, *Environmental Science & Technology*, Vol. 36, No. 8, 2002; <http://www.pubs.acs.org>.

Researchers studied the carbonyl and regulated emissions from a two-stroke chain saw engine using ethanol, gasoline and ethanol-blended gasoline (0 percent, 15 percent, 50 percent, 85 percent and 100 percent ethanol). Results indicated that increasing the ethanol blending increased acetaldehyde level and reduced emissions of all other carbonyls except formaldehyde and acrolein. Reduced carbon monoxide and nitrogen emissions and increased hydrocarbon and nitrogen dioxide emissions were also noted.

Other papers of interests include the following:

"Analysis of Water Saturation, NAPL Content, Degradation Half-Life, and Lower Boundary Conditions on VOC Transport Modeling: Implications for Closure of Soil Venting Systems," DiGiulio, D.C. and R. Varadhan, *Ground Water Monitoring and Review*, Fall 2001; <http://www.ngwa.org>.

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"Common Myths, Misconceptions and Assumptions About MTBE: Where are we now?" Woodward, D. and D. Sloan, *Contaminated Soil Sediment and Water*, Spring 2001, <http://www.aehsmag.com>.

"Diffusive Transport of Permanganate During In-Situ Oxidation," Struse, A.M., Siegrist, R.L., Dawson, H.E. and M.A. Urynowicz, *Journal of Environmental Engineering*, April 2002; <http://www.pubs.asce.org/journals/ee>.

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"Environmental Impacts of PAH and Oil Release as a NAPL or as Contaminated Pore Water from the Construction of a 90-cm In-situ Isolation Cap," Herrenkohl, M.J., Lunz, J.D., Sheets, R.G. and J.S. Wakeman, *Environmental Science and Technology*, Vol. 35, No. 24, 2001; <http://www.pubs.acs.org>.

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"Experimental Investigation of the Interaction of Soil Air Permeability and Soil Vapor Extraction," Farhan, S.,

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"Field Measurement of Dissolved Oxygen: A Comparison of Methods," Wilkin, R.T., McNeil, M.S., Adair, C.J. and J.T. Wilson, *Ground Water Monitoring and Review*, Fall 2001; <http://www.ngwa.org>.

"Gaseous Transport of Volatile Organic Chemicals in Unsaturated Porous Media: Effect of Water-Partitioning and Air-Water Interfacial Adsorption," Kim, H., Annable, M.D. and P.S. Rao, *Environmental Science and Technology*, Vol. 35, No. 22, 2001; <http://www.pubs.acs.org>.

"Managing Uncertainty in Environmental Decisions," Crumbling, D.M., Groenjes, C., Lesnik, B., Lynch, K., Shockley, J., Van Ee, J., Howe, R., Keith, L. and J. McKenna, *Environmental Science and Technology*, Vol. 35, No. 19, 2001; <http://www.pubs.acs.org>.

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"Monte Carlo Analysis of Uncertainty Attached to Microbial Pollutant Degradation Rates," Goovaerts, P., Semrau, J. and S. Lontoh, *Environmental Science and Technology*, Vol. 35, No. 19, 2001; <http://www.pubs.acs.org>.

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"Tracer Diffusion Coefficients in Sedimentary Rocks: Correlation to Porosity and Hydraulic Conductivity," Boving, T.B. and P. Grathwohl, *Journal of Contaminant Hydrology*, Vol. 53, 2001; <http://www.elsevier.com/locate/jconhyd>.



Information sources

U.S. EPA publications and information

Publications that can be downloaded from <http://clu-in.org/techpubs.htm> include

- Method 5035A: Closed-System Purge-and-Trap and Extraction for Volatile Organics in Soil and Waste Samples
- An Assessment of Protocols for Splitting Soil Samples

• Technology Trends and News (EPA 542-N-02-003)
Recent videos/presentations from CLU-IN studio (<http://clu-in.org/studio>) include

- ITRC Advanced Techniques on Installation of Iron Based Permeable Reactive Barriers and Non-Iron Based Barrier Treatment Material
- ITRC In-Situ Chemical Oxidation
- Modernizing Site Cleanup: Managing Decision Uncertainties Using the Triad Approach

Additional EPA information includes:

Dynamic Workplans and Field Analytics: The Keys to Cost-Effective Site Cleanup (EPA 542-C-02-003), CD-ROM, is available if you call 800-490-9198 or 513-489-8190 or send a fax to 513-489-8695.

FRTR Cost and Performance Remediation Case Studies and Related Information (EPA 542-C-02-004), CD-ROM, is available if you call 800-490-9198 or 513-489-8190 or send a fax to 513-489-8695.

Guidance for Optimizing Ground Water Response Actions at Department of Energy Sites, http://www.em.doe.gov/er/May2002gwguide1_508.pdf

Innovative Remediation Technologies: Field-Scale Demonstration Project Database and Report, <http://clu-in.org/products/nairt>

Innovative Technology Evaluation Report: EarthSoft, Inc., Environmental Quality Information System—Equis (EPA 540-R-02-503), <http://www.epa.gov/ORD/SITE/reports/540R02503.pdf>

Monitoring Well Comparison Study: An Evaluation of Direct-push Versus Conventional Monitoring Wells, <http://www.epa.gov/swrust1/cat/wellstdy.pdf>

Spill Prevention Control and Countermeasure Rule (40 CFR) http://www.access.gpo.gov/su_docs/fedreg/a020717c.html. For questions about this final rule, call 800-424-9346 or 703-412-9810.

Other documents and Web sites

California Fuel Cell Partnership, <http://fuelcellpartnership.org>

Critical Issues for Contaminated Sediment Management (MESO-0-TM-01), <http://meso.spawar.navy.mil/docs/MESO-02TM-01.pdf>

Fracturing Technologies to Enhance Site Remediation (TE-02-02), http://www.gwrtac.org/pdf/frac_e_2002.pdf

Gasoline and Other Fuel Additives, information on ordering, <http://www.freedoniagroup.com>

Health information on methanol can be found at <http://cerhr.niehs.nih.gov/news/>

New Federal Remediation Technologies Roundtable World Wide Web Site, <http://www.frtr.gov>

Report of the Nicole Workshop: Cost Effective Site Characterization Dealing with Uncertainties, Innovation, Legislation Constraints, <http://www.nicole.org/nicole2/news/ann212a.PDF>

Recent and updated publications from the Steel Tank Institute (<http://www.steeltank.com>) include

- Recommended Practice for Interstitial Tightness Testing of Existing Underground Double Wall Steel Tanks, RP012-02
- Recommended Practice for Anchoring of Steel Underground Storage Tanks, RP011-01
- Recommended Practice for the Addition of Supplemental Anodes to sti-P3^R USTs, RP972-01
- Specification for the AquaSweepTM Gravity Oil Water Separator, F021-02

- Standard for Aboveground Tanks Used as a Generator Base Tank, F011-01
- STI Technology Guide, Vol.3, No.1

United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) site on Life-Cycle Initiative, <http://www.uneptie.org/pc/cp7>

UTTU obtained this information from *Ground Water Monitoring and Review* (<http://www.ngwa.org>), *Environmental Science & Technology* (<http://www.pubs.acs.org/>), *Tank Talk* (<http://www.steeltank.com>) and *TechDirect* (<http://clu-in.org/techpubs.htm>). UTTU thanks the editors and writers for allowing us to reprint this information.