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Article summaries

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U.S. EPA OUST has two excellent websites:

http://www.epa.gov/swerust1/states/index.htm
Contains state home pages for UST, LUST and Fund agencies

http://www.epa.gov/swerust1/mtbe/index.htm
Contains advisories, publications, and links on MTBE

MTBE vapor treatment in a biotrickling filter

Until recently, MTBE was thought to be biologically recalcitrant. This article describes an efficient and sustainable biological process for the treatment of MTBE vapors—a biotrickling filter. The process could offer a cost-effective alternative for the treatment of contaminated air from soil vapor extraction or air stripping operations *(Fortin and Deshusses 1999a)*.

How biotrickling filters work

"Biofilters work by passing a humid stream of contaminated air through a damp packing material—usually compost with bulking agents—on which pollutant-degrading bacteria are naturally immobilized. Biotrickling filtration is a variation of biofiltration where an inert support is used and a scrubbing solution is continuously or intermittently recycled over the packing to provide the process culture with the necessary moisture, nutrients and optimal conditions. While biotrickling filters are more complex and often more expensive to operate than biofilters, they often exhibit higher performance than biofilters. This is because they allow a better control of environmental conditions and because they rely on growing organisms, rather than on resting organisms, as in the case of biofilters" *(Fortin and Deshusses 1999a).*

Biotrickling filter setup

Researchers set up two laboratory-scale biotrickling filters to investigate the performance of MTBE removal from synthetic waste gas. Trickling filters consisted of clear PVC pipe with a packed bed height of 0.5 m. Total reactor height was 1.5 m, internal diameter was 0.153 m and bed volume was 9 L. "Reactor 1 was filled with 8.81 kg of wet lava rock (1-3 cm diameter, initial bed porosity of 50 percent) and reactor 2 was filled with 0.94 kg of 2.5 cm polypropylene Pall rings. The Pall rings had an initial porosity of 90 percent and a specific surface area of 206 m^2/m^3." Researchers supplied a metered flow of MTBE to reactor column tops at a rate of 0.65 to 0.85 gram MTBE per cubic meter of synthetic waste air. Reactor temperature was maintained between 19 and 21°C.

Researchers recirculated over the packed bed an aqueous mineral medium of potassium phosphate, ammonium chloride, calcium chloride and magnesium sulphate. The salts provide the process culture with mineral nutrients necessary for growth. Peat humic substances (PHS) were added at a concentration of 0.25 mg/L. A constant liquid volume of 3 L was maintained at the base of the reactors. Researchers found that adsorption/diffusion of MTBE through PVC pipe was negligible.

System performance and component analysis

Researchers defined system performance as the elimination capacity (EC), or removal efficiency (RE), functions of the inlet and outlet gas concentrations, as follows:

$$EC = (C_{g,in} - C_{g,out})/V \quad (g/m^3/h)$$
$$RE = (C_{g,in} - C_{g,out})\, 100/C_{g,in} \quad \text{(percentage)}$$
$$L = C_{g,in}\, Q/V \quad (g/m^3/h)$$

Where

C_g = gas concentration
Q = air flow rate
V = packed bed volume
L = pollutant loading

Carbon dioxide recovery was defined as:

$$CO_2 \text{ recovery} = C\text{-}CO_2 \text{ produced} / C\text{-MTBE degraded}$$

C-CO_2 or C-MTBE stands for carbon-carbon dioxide or carbon-MTBE.

The nature of the rate-limiting step was also evaluated by the effectiveness factor, which varies from 0 (when gas-liquid transfer is limiting) to 1, the limitation being in the biofilm *(Fortin and Deshusses, 1999b)*. In the biotrickling filter, the effectiveness factor will depend on

- operating conditions (gas and liquid flow rate, pollutant concentration)
- biodegradability, diffusivity and Henry's law constant of pollutant treated
- position in the reactor

Using a flame ionization detector, researchers monitored both MTBE and TBA from the biotrickling filter. They analyzed influent and effluent gas and liquid streams in triplicate once per day and weighed wet biomass accumulation.

Culture enrichment

Next, researchers added to each biofilter the ground-water samples and aquifer material from two long-term MTBE-contaminated sites. These samples were not analyzed to determine if they contained a successful MTBE-degrading consortium.

To shorten the startup phase, researchers added methanol (as a carbon source) to the system containing the Pall rings, but the methanol did not accelerate startup. Researchers found from previous studies that a potential co-substrate effect existed between methanol and MTBE, hence, they had expected enrichment in the presence of methanol. Researchers also caution that what is valid for one culture may not be valid for another. Even after six months of continuous operation, MTBE removal by biodegradation was less than 5 percent. "Its depletion coincided with the increase of an unknown metabolite, reported as methanol equivalent in Figure 1. While the retention time of the metabolite peak on the gas chromatograph coincided with both methanol and tert-butyl alcohol (TBA), a rapid calculation based on gas-liquid equilibrium showed that the concentrations measured in the gas phase were too high to be either of these two compounds. Researchers made no further attempts to identify the metabolite, since production ceased as reactor performance improved. It is probable that the metabolite was rapidly biodegraded as the process culture matured over time."

Comment: The metabolite was not TBA, because TBA is not volatile and the concentrations of the metabolite were relatively high. A simple calculation using TBA GC calibration and TBA Henry's coefficient showed that if it was TBA, the concentration would have been greater (in molar units) than MTBE, which is not possible.

"During the experiment, carbon dioxide concentration increased, but far more than the theoretical value calculated based on MTBE degradation. This indicated that a significant amount of secondary substrate was available in the biofilm.

Reviewer's comment: Was it due to the added impact of the unknown metabolite being degraded? Author's response: More CO_2 was actually produced than expected based on full conversion of MTBE to CO_2. Thus, there must be biodegradable material (secondary substrate) in the system. The nature of the secondary substrate is unknown.

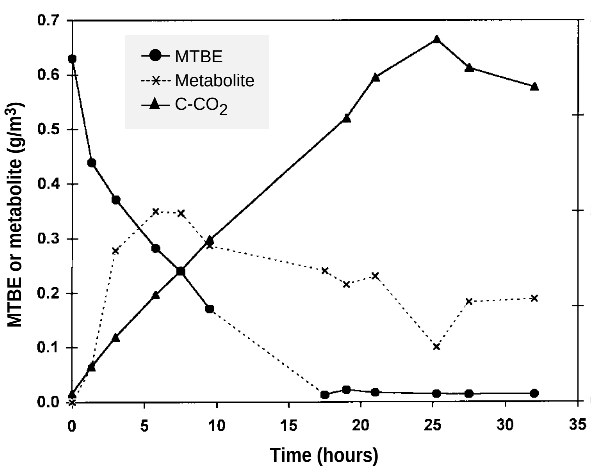

Figure 1. MTBE biodegradation, production of carbon dioxide and a metabolite in the Pall ring biotrickling filter. The reactor was closed at time zero, and MTBE depletion and carbon dioxide production were monitored (Fortin and Deshusses, 1999a).

Researchers took a biofilm sample from the reactors and cultured it in a liquid batch study. The consortium consisted of at least six gram positive and negative bacteria, bacilli and cocci, fungi, protozoa and rotifers. It formed a dense aggregate when grown on MTBE in liquid cultures and was eventually re-inoculated in the trickling filters, which proved successful.

Obtaining a competent aerobic microbial consortium for MTBE degradation required a long acclimation and/or growth period, about six months. Thus, researchers hypothesize that the MTBE degrading consortium may require the specific environment of attached growth. "This may be because close cell proximity promotes genetic exchanges between species which are required for the establishment of proper genotypes(s) or because it stimulates metabolic complementation between the biofilm community members . . . For biofilms, such metabolic interdependency between community members has been investigated for dental plaque communities and little attention has been given to biofilter catabolic flora. Our experience tends to show that, in addition to phenotype and/or genotype changes, the structural integrity of the aggregate (in liquid culture) or of the biofilm (in the trickling filters) may be an important requirement for the MTBE catabolic activity to be expressed within the consortium" *(Fortin and Deshusses, 1999a).*

Figure 2 shows the inlet and outlet gas concentrations of MTBE and carbon dioxide production for the biotrickling filter 2 (Pall rings). Figure 3 shows MTBE loading, elimination capacity and percentage MTBE removed over time. Data for biotrickling filter 1 (wet lava rock) are similar. Figure 4 shows that reactors reach maximum elimination capacity at high loadings.

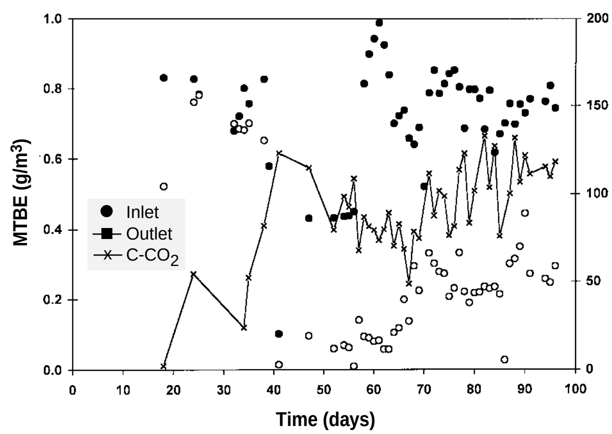

Figure 2. MTBE inlet and outlet gas concentrations and percentage recovery of the MTBE degraded as CO_2. Time 0 corresponds to re-inoculation of the filter with the competent mixed culture (Fortin and Deshusses, 1999a).

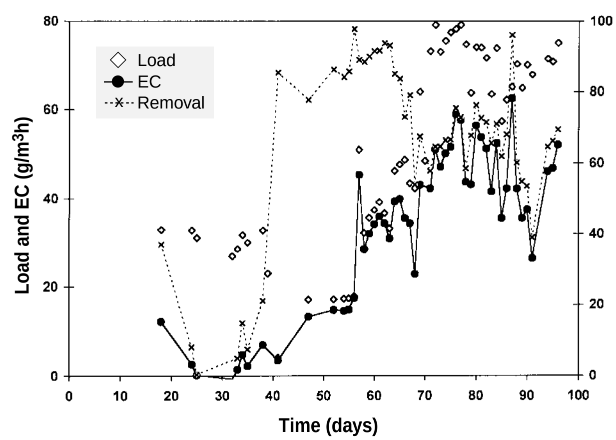

Figure 3. MTBE loading, elimination capacity and percentage removed over time (Fortin and Deshusses, 1999a).

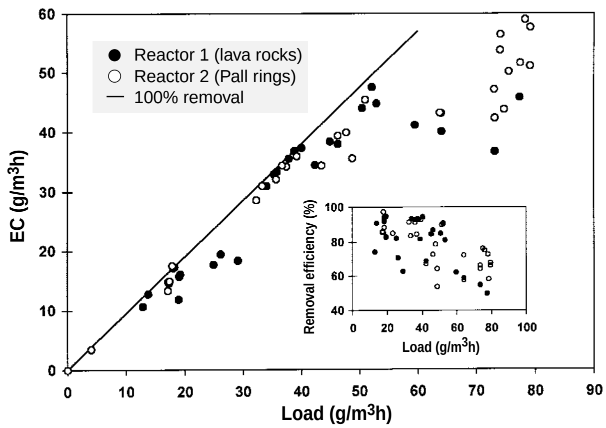

Figure 4. MTBE elimination capacity vs. MTBE loading: the inset shows removal percentage as a function of the loading (Fortin and Deshusses, 1999a).

Data from Figure 2 indicate a long acclimation phase, despite vigorous inoculation with competent microorganisms. "Bio-trickling filters are, in general, more difficult to start than biofilters because the process culture needs to attach to a carrier, form a biofilm to overcome wash-out, and is subject to shear stress. . . . it is likely that the real causes of slow startup were the difficulty to establish a thriving consortium (as discussed previously), the slow growth rate, and the low biomass yield of the process culture. . . The slow rate of biomass accumulation is consistent with the slow growth rate of the MTBE degraders and the high degree of MTBE mineralization (i.e. high CO_2 recovery) observed in the biotrickling filter, which was typically 20 to 40 percent higher than for toluene" (*Fortin and Deshusses, 1999a*). Toluene was also tested in a biotrickling filter.

To improve MTBE biodegradation, researchers began adding, on day 33, peat humic substances (PHS) to the scrubbing solution of both biotrickling filters. Slight differences in startup likely resulted from differences in the support materials' surface properties. "Peat humic substances were originally developed as a plant growth stimulant but have also been used as a stimulant for bacterial activity in various aqueous systems. The mechanisms by which PHS stimulate biological activity are not well understood, but the concentration at which PHS have an effect rule out any cometabolic process. A possible explanation is that humic acids form complexes with MTBE or any other growth-limiting substrate and improve their assimilation. Further experiments with PHS revealed that while humic substances had a pronounced effect at reactor startup, they had a marginal effect once an effective biofilm had been established, and effective MTBE removal could be obtained without PHS. This suggests that PHS helped in the initial colonization of the packing by competent cultures, rather than changing the intrinsic kinetics of MTBE biodegradation. Experiments performed in shake flasks confirmed that PHS stimulated the growth of the consortium. Clearly, the use of PHS for the biostimulation of environmental bioprocesses requires further investigation."

Conclusions

Researchers calculated that the specific activity, mass of MTBE degraded per gram of dry biomass in the biotrickling filter, was 5.5 x 10^{-3} and 11 x 10^{-3} g MTBE/g_{dw}/h for the two filters. This value gives a sense of how much MTBE a given mass of organisms can degrade. Difference in specific activity arises from high biomass content in the biotrickling filter. In general, researchers found

- reactors here were limited by the biological reaction rather than by mass transfer
- good performance could be obtained only after a proper density of a competent process culture was established; here, it was 15 to 20 kg of wet biomass per cubic meter of bioreactor
- buildup of the baseline biomass is usually fairly rapid, but with MTBE it is much slower because of the MTBE culture's low biomass yield coefficient and slow growth rate
- the greatest obstacle for industrial deployment of biotrickling filters is rapid clogging by growing biomass from degrading substances of high-yield coefficients; the present report of sustained MTBE elimination for more than 2 months with no noticeable accumulation of biomass shows that clogging will not occur if MTBE is the dominant pollutant treated
- no significant differences exist between the performance of the two biotrickling filters, although the packings were quite different
- a competent MTBE degrading culture can be very active in turning MTBE into carbon dioxide

A detailed study

Fortin and Deshusses *(1999b)* performed further detailed experiments of accurate reactor control and process optimization to determine the rate-limiting step. Another issue studied was transient operation, which is the rule rather than the exception for industrial biotrickling filters. Researchers analyzed the MTBE in the recycle liquid to determine the following:

- amount of carbon leaving the system via the liquid purge (to close the carbon balance)
- whether the liquid purge contained environmentally destructive metabolites
- whether mass transfer or biological reaction was the rate-limiting step of the process

"Various models exist to describe the mass transfer of a pollutant from the gas phase to the active biofilm. The simplest concept assumes that a liquid layer flows on top of the pollutant degrading biofilm and that the pollutant must fully penetrate the liquid layer before reaching the biofilm. Thus, it neglects direct gas-biofilm mass transfer." Fortin and Deshusses *(1999b)* discuss ways of looking at this phenomenon. They suggest that the rate-limiting step may well be "the gas-liquid transfer near the air inlet, that biology will control the rate in the middle of the reactor, and that the rate is controlled by diffusion in the biofilm near the outlet of the reactor."

Researchers found that "performance of both reactors was limited by the biofilm phenomena, i.e., either liquid-biofilm transfer, diffusion in the biofilm, or biodegradation in the biofilm. . . the effectiveness factor alone does not allow one to distinguish which one of the biofilm phenomena is rate-limiting. A detailed comparison of MTBE elimination data at different concentrations but at similar loadings reveals that the pollutant elimination was virtually unchanged by concentration changes, which indicates that biodegradation rather than mass transfer was the rate-limiting step in the biofilm, since both the diffusion rate and liquid-biofilm mass transfer are dependent on concentration. If diffusion or liquid-biofilm transfer was limiting, the concentration increases would have resulted in higher elimination capacities. The observation of a biological limitation is consistent with the relatively low biomass content in the reactors and the relatively slow rate of MTBE biodegradation compared to other VOCs."

Fortin and Deshusses *(1999b)* concluded the following:

- biotrickling filters operating under biological limitation are more difficult to operate than those limited by mass transfer because performance is susceptible to fluctuations in biological activities
- optimization of MTBE removal in biotrickling filters could include strategies to establish and maintain a high density and high specific activity of the process culture
- effective inoculation with MTBE degraders is warranted but may pose a challenge due to little information on MTBE degraders
- the biotrickling filter operation is transient and will depend on, for instance, the carbon sources available (biofilm polymers, dead cells, other nonvolatile dissolved carbon sources); alternatively, process cultures under stress caused, for instance, by an increase in MTBE concentration and necessity for adaptation, cause transient operation
- maintaining a stable and effective process requires a thorough control of the following (although fundamental knowledge is lacking):
  - cell density operating and environmental parameters such as nutrients, dissolved oxygen, pH, temperature, and inhibitory byproducts
  - ecology of the biofilm (culture composition and presence of predators such as protozoa or viruses)

For more information on MTBE biodegradation, see the website, http://engr.ucr.edu/˜mdeshuss/mtbe.html.

References

Fortin, N.Y. and M.A. Deshusses, "Treatment of Methyl *tert*-Butyl Ether Vapors in Biotrickling Filters, Part 1: Reactor Startup, Steady-State Performance, and Culture Characteristics," *Environmental Science and Technology*, Vol. 33, No. 17, pg. 2980-2986, 1999; http://www.pubs.acs.org.

Fortin, N.Y. and M.A. Deshusses, "Treatment of Methyl *tert*-Butyl Ether Vapors in Biotrickling Filters, Part 2: Analysis of the Rate-Limiting Step and Behavior Under Transient Conditions," *Environmental Science and Technology*, Vol. 33, No. 17, pgs. 2987-2991, 1999; http://www.pubs.acs.org.

UTTU thanks Marc Deshusses, Department of Chemical and Environmental Engineering, University of California, Riverside, CA, for his help on this article. Marc Deshusses can be reached at mdeshuss@engr.ucr.edu.

For other information on MTBE biodegradation, see the U.C. Davis website, http://www.tsrtp.uc.davis.edu/mtbe/ and the U.S. EPA OUST site, http://www.epa.gov/swerust1/mtbe/index.htm.

Horizontal wells

By Dr. Louis B. Fournier

Horizontal wells can deploy virtually any remediation technology used in vertical wells and/or trenches. These technologies include free product recovery, total fluids or groundwater extraction, air sparging, soil vapor extraction, biosparging, steam stripping, surfactant flushing, chemical or biological stabilization and water injection.

Well description and installation

Horizontal wells are generally installed by drilling from a remote point, descending into the subsurface at a gradual angle, leveling to horizontal, and then returning at a gradually changing angle back to the surface. The horizontal well thus, has a head and a tail. The "head" is the well section between the screen and the remediation equipment. The "tail" is the solid well section between the screen's distal end and the exit.

Materials successfully used for horizontal wells include fiberglass, mild and stainless steel, PVC, and various perforated, slotted, or fabricated products. The most widely used material appears to be the commercially available high density polyethylene (HDPE), and in particular, the custom-slotted four-inch-diameter SDR-11. Biodegradable polymers are used as drilling fluids.

Wells may be two-ended (continuous) or one-ended (blind). In general, installing blind wells is more difficult and costly, so continuous wells are preferred. Two-ended wells allow flexible well performance and well maintenance activities.

For two-ended wells, the most commonly utilized installation method is to drill the well, replace the drill head with a back-reamer, attach the well behind the back-reamer, and pull the well into the borehole as the drill string is being removed. Horizontal wells are typically drilled from some point on the site, down at a gradually changing angle to a horizontal orientation, and then back up to the surface at a remote exit point. The distance between the horizontal (usually screened) segment and the entrance and exit points is called the *set back* or *step back* distance. This distance can be three to five times the depth of the horizontal segment.

Once in place, the well has to be developed and the annular spaces on the ends grouted and cemented. A rigorous performance evaluation will ensure that all required installation steps have been properly conducted and that leaks do not exist. During the first year, wells should be properly maintained and system performance evaluated at least twice, then annually. Post-installation well development and performance testing is critical; unlike utility applications where the bore is the goal, horizontal wells must be functionally acceptable after installation.

Advantages of horizontal wells

Advantages of horizontal wells include the following:

- remediation equipment can be placed anywhere on- or off-site and can be remote to the actual treatment area
- drilling can be conducted under roadways, buildings, shallow water bodies and other surface features
- the horizontal well is generally connected directly to operational equipment (e.g., blowers, pumps), eliminating manifolding required for vertical wells
- depending on site logistics and plume area(s), a horizontal well may replace 20-50 vertical wells
- redundant remedial equipment is often replaced by a single equivalent unit; for biosparge wells, for example, 50 vertical wells might require 10 blowers, 10 power drops, and manifolding; this entire system can be replaced with a single horizontal well and blower with power drop and no manifolding
- operating expenses and difficulties of a single blower and well are far less than for multiple wells and blowers.

Disadvantages of horizontal wells

Disadvantages of horizontal wells include the following:

- because of step-back distances, site logistics, and plume dimensions, horizontal wells may require higher mobilization/demobilization costs
- use of directionally drilled horizontal wells vs. vertical wells is generally not favored for sites of a few acres; even on large sites, they are generally prohibitively expensive if the water table depth or contaminated area is greater than about 100 feet below grade; for service stations and other small sites, horizontal sparge wells are rarely favored; however, a horizontal vapor extraction well may indeed be favored over vertical wells because they are not installed so deep below the ground surface and they do not interfere with site operations
- experienced and qualified drillers, appropriate equipment and engineering firms are limited; directional drill rigs install everything from cable television and fiber optic lines to sewers and tunnels; however, the community of drillers within the horizontal well industry is less than two dozen; thus, a lack of knowledge concerning engineering design requirements and operating characteristics of such wells is common
- directionally drilled horizontal wells typically cost $100-200/ft; this cost, however, is offset considerably by the large number of vertical wells required to equal the performance of a horizontal well system; for instance, at John F. Kennedy Airport remediators planned to install 600 vertical wells at $3,000 to $5,000 per well at a cost of $3,000,000, and 100 blowers ($10,000/blower), with a total cost of $4,000,000; instead, they installed 13 horizontal wells with 12 blowers for a total cost of $1,000,000.

System design

Appropriate well design is critical to success. For any remedial technology, well performance will vary with distance from the motive power system. For example, if a uniformly slotted horizontal well is used for air sparging, biosparging, or soil vapor extraction, the performance of the well will be greatest on the blower end of the well and decrease (non-uniformly) with distance down the length of the screened interval. If the percent open area of the well is too high, there will be severe distortion of well performance down the screen—perhaps resulting in no performance at all from some point along the screen to the distal end. This will occur even in a homogeneous formation placed at uniform depth below (or above for SVE) the water table. Performance is further compromised when formations are not homogeneous, when the water table fluctuates, and with wells with variable depth below water table (i.e., usually slanted wells).

To correct for performance problems, engineering/environmental firms use four general approaches, listed below. The first two are not appropriate.

1. Ignore differences between vertical and horizontal wells—not a good approach. Firms experienced only with vertical wells commonly fail to acknowledge the differences between vertical and hori-

zontal well design, only to find that the resulting horizontal wells do not function as expected.

2. The driller supplies the design for the well screen usually as part of procurement requirements. A holdover from vertical well procurement practices, this practice is inappropriate for horizontal well systems, yet the procurement officer often uses this contractual approach to assign the liability for unacceptable performance to the unsuspecting driller. This is a customary practice with inexperienced firms. It is technically infeasible to expect the driller to provide engineering designs for a highly complex, relatively new and innovative, and usually very expensive installation.
3. Assume that the subsurface is homogeneous and that the well will be at a constant depth below (or above for SVE) the water table. An engineering spreadsheet is used to calculate pressure drops along the well and to design a non-uniform well slotting pattern. In general, less open area is placed near the functional equipment with gradated increases in open area away from this equipment. This approach has been used with some success for water recovery wells especially if screen lengths are short, the formation is relatively homogeneous, and well depth below or above the water table is uniform. Failure occurs with air-based remediation technologies, in complex stratigraphies, and with fluctuation distances between the well screen and the water table.
4. Utilize the engineering design capabilities of a firm with a proven record of horizontal well design and system performance. A small number of firms meet this general description.

The most accurate methods for horizontal well and system designs are based on complex, reiterative, proprietary, computational computer software programs that consider:

- stratigraphic information
- variable well depth below the water table
- water table fluctuations
- contaminant plume distribution
- remedial system requirements

Output from these programs serve as the basis for defining customized well-slotting requirements, specifying equipment and operating conditions, and creating site remediation timetables. Reports that show the system design can be used to support negotiations with regulatory agencies and other concerned parties.

Modeling of expected well performance has shown that each particular remediation technology requires a unique well design. Thus, it is not usually acceptable to design a well for water recovery, for example, then use it for air sparging. The optimum designs for wells for these two technologies will be *very* different.

ROI and DOI

Horizontal well systems are often more cost-effective than vertical systems because of the large observed difference between the radius-of-influence (ROI) of vertical wells and the horizontal system's distance-of-influence (DOI). Typically the horizontal well's DOI will be three times the vertical well's ROI, assuming screens at approximately the same depth. This is based on data from more than 200 horizontal well projects. This estimate varies with site, soil type and determination of ROI and DOI. Usually, both are defined at the water table. For definition of ROI and/or DOI:

- air sparge and biosparge wells will typically use dissolved oxygen or helium tracer measurements
- SVE wells use pressure changes in surrounding wells (vertical only)
- water pumping wells use draw-down in neighboring wells (vertical only)

By industry convention, DOI as well as ROI are both measured at the water table surrounding the well. The measurement point may or may not be perpendicular to the axis of the well screen. For example, horizontal wells show DOIs pass the well screen in a circular arc around the end of the screen. It is important, however, to note that the measurement is, by definition, at the water table rather than at depth.

Comparison of performance

Vertical well design concepts developed within the environmental remediation industry may not be applicable to horizontal wells. In fact, a horizontal *well* should not even be considered as a well; more accurately, it is a *subsurface contaminant treatment device*. This distinction is important. Regulatory agencies may attempt to enforce vertical well design requirements that may be inappropriate and perhaps detrimental to system performance of horizontal wells. For example, it is virtually impossible to install a gravel pack or any over-wrap around the outside of a horizontal well. Such materials may pull apart during well pull-back.

One very successful approach has been to custom-slot HDPE with 0.010-inch or 0.020-inch slots, which allow silty well materials to enter the well. The silty materials can later be removed as part of the suggested well maintenance program. After one or two cleanings, a natural sand pack builds up around the outside of the well, prohibiting further infiltration. This is particularly effective with biosparge, air sparge, and soil vapor extraction systems, especially in sandy formations.

Another major difference between vertical and horizontal wells concerns treatment area. For air sparge wells, a vertical well has a very small ROI—a few inches or feet—at screen depth. Air leaves the screen and travels primarily up the side of the newly drilled well, following the path of greatest permeability. With newly installed vertical wells, this pathway is usually right up the annular space surrounding the disturbed formation next to the well. Near the water table, the sparge pattern flares or trumpets to the measured radius-of-influence at the water table. The effective ROI of a vertical air sparge well at depth below the water table is quite small; the line of treatment points produced by several vertical wells creates only small treatment areas.

Reviewer's comments: The industry literature may contradict some of the above statements; however, modeling, field and theoretical results have proven the statements to be true.

A horizontal air sparge well produces dramatically different treatment patterns. If the well is placed at right angles to the direction of groundwater and plume flow and positioned to treat the entire plume width, air from the well will move upward in an ever-increasing V-pattern and flare open as it reaches the water table. As with vertical wells, air will follow along the more permeable pathways to the water table. Lateral permeability, however, is usually about 10 times vertical permeability. In addition, the well installation method does not disturb the overlying soil formation; hence, a preferred vertical pathway is not created. This results in a much broader observed DOI than for the comparable vertical well system.

Both vertical wells and horizontal wells can be used in biosparging and air sparging applications. While both may work successfully at the water table, it is impossible to design a vertical well system that can intersect a dissolved plume at depth below the water table and prevent downgradient contaminant migration. With horizontal wells, a "line in the sand" can be drawn. A properly designed, installed, and operated horizontal sparge well can prevent the downgradient contaminant movement.

If free product is present, it is usually removed; then another technology (such as air sparging) treats dissolved contaminants as well as vadose zone contaminants sorbed to soil. A properly designed, installed, and operated horizontal well will supply sufficient air to treat free product, dissolved and sorbed contaminants simultaneously. Horizontal biosparge wells have biodegraded up to several feet of free product at several sites.

Number of required horizontal wells

Remediators commonly use two methods to calculate the number of horizontal wells necessary for a site:

1. *Screen in the ground.* If a vertical well system has already been conceptualized, simply determine the total amount of screen in the ground in vertical wells; for the same SCFM/foot of screen, this total is the total length of horizontal well screen that will be required. For example, if the total length of the vertical screens will be 800 feet operating at 2 SCFM/ft screen, the total length of the horizontal screen will be 800/2 or 400 feet. If each vertical well will have 2 feet of screen and operate at 2 SCFM/ft screen, 100 vertical wells would be required for one 400-foot horizontal well; this is a back-of-the-envelope calculation.

2. *Water table treatment coverage*. If a vertical treatment well is determined to have an ROI of 15 feet at the water table, the area treated (at the water table) would be $3r^2$ or $675ft^2$. Assuming a loss of about 10 percent for overlapping coverage gives an effective treatment area of 636 ft^2. A horizontal well DOI here will be about 45 feet, three times the vertical well ROI. Thus, the area treated at the water table along the sides of the horizontal well will be 2 x 45 x 400 ft = 36,000 ft^2. In addition, the sparge pattern will treat an area past the screen ends. This can be approximated as a semi-circle with area equal to the DOI of the well. With two ends, the treatment area past the ends of the screen totals $3r^2$ where r is 45 feet, or 6,362 ft^2. Hence, the total area treated by the single horizontal well will be 36,000 + 6,362 or 42,362 ft^2. To determine the number of vertical wells required to treat the same area as the single horizontal well (assuming the SCFM/ft values are the same for each system), divide 42,362 by 636, which is 67. Sixty-seven wells are roughly comparable to the 100 obtained with the first calculation method. Sixty-seven wells with 6 wells per blower (for sparge wells, for example) would require 11 blowers, 11 power drops, and manifolding.

While each site is different and therefore requires a specific conceptual design, the above methods are handy for rough calculation purposes.

Co-metabolic biodegradation of chlorinated solvents

Directionally drilled horizontal wells can be deployed to treat chlorinated solvents using co-metabolic, aerobic bioremediation processes. At present, the most widely used process requires the addition of about 2 percent volume methane into an air stream introduced into the subsurface with horizontal air sparge or biosparge wells. Under aerobic conditions, methane addition supports microorganism growth, which degrades many chlorinated solvents without formation of vinyl chloride or other unacceptable daughter/end-products. Ethane, propane, butane, toluene and other materials, in addition to the methane, support this process, which can be advantageous at sites where hydrocarbon contaminants are co-mingled with chlorinated solvents.

Regulatory approval of the proposed system would obviously have to be obtained, and the percent of co-metabolite in the air stream would have to be below its lower explosive limit.

Biosparge vs. air sparge wells

Horizontal air sparge wells commonly operate at approximately 1.0 SCFM per foot of well screen. Their intent is to physically volatilize contaminants from the subsurface. For most horizontal air sparge projects performed to date, regulatory agencies have required that soil vapor extraction wells and a vapor treatment system also be installed.

Horizontal biosparge wells commonly operate at a reduced flow rate, approximately 0.5 SCFM per foot of well screen; they are intended to simply add oxygen to the subsurface to help biodegrade contaminants. Regulatory agencies have not yet required the installation of a companion soil vapor extraction system and air treatment system with biosparge wells. Thus, the total installation cost of a horizontal biosparge well system is typically about 40 percent of the total cost of a combination air sparge, soil vapor extraction and vapor treatment system.

Total remediation costs

While it is impossible to quantify total remediation costs for horizontal well projects vs. alternative approaches, it is still possible to provide general, conceptual cost comparisons for guidance purposes.

The total project cost of a horizontal well system used in place of a vertical well system for groundwater pump-and-treat technologies will commonly be slightly less than the vertical well system, perhaps a 20 percent savings. Exact costs will depend on deployment issues, whether or not buildings have paved areas and other factors.

Significantly greater project cost savings may result if the horizontal wells can be used for air-based remediation technologies. For example, a horizontal well air sparge and soil vapor extraction project can be as much as 50 percent less expensive than a vertical well pump-and-treat system. A horizontal biosparge well system may cost (typically) about 40 percent of the air sparge system or 20 percent of a vertical well groundwater pump-and-treat. Reduced costs result from

- elimination of wells—roughly half of the total wells in a combination HAS/HSVE (combination horizontal well air sparge and horizontal soil vapor extraction)
- elimination of air treatment equipment
- reduced operation and maintenance and analytical expenses

Conclusion

Horizontal well technology is geometrically increasing in the remediation field, aided by the development of equipment to accurately drill and install the wells. New reiterative computer modeling programs provide extremely accurate engineering design information for both wells and remedial equipment. Fueled by enormous cost-saving opportunities and growing recognition of entirely new concepts for site remediation, the use of directionally drilled horizontal wells will likely continue to increase.

For more information on horizontal wells, see http://www.angelfire.com/biz/horizontal wells.

UTTU thanks Dr. Louis B. Fournier, President, STAR Environmental, Inc., Chadds Ford, Pennsylvania, starcompany@erols.com, 610-558-2121, for contributing this article.

Research notes

A Heuristic Model of Aerobic Biodegradation of Dissolved Hydrocarbons in Aquifers

Ma, Y., Kemblowski, M.W. and G.E. Urroz, *Ground Water*, Vol. 37, No. 4, 1999; 800-332-2104; http://www.ngwa.org.

This article describes a conceptual and heuristic (using rules of thumb, empirical reasoning) model of mixing and aerobic biodegradation in heterogeneous porous media. The model is not predictive because the mixing coefficient must be calculated every time the model is used.

Important to the model is the spatial dispersion—spreading and mixing—of the mean concentration field. "The mixing process, which controls the biodegradation reaction, is concerned with the actual concentrations of oxygen and hydrocarbons." The mean-behavior model considers four mechanisms of hydrocarbon transport/transformation:

- mean advective transport, driven by effective pore water velocity
- macrodispersion, whose mechanism is the same as that for nonreactive species, and whose magnitude can be estimated using stochastic approaches
- mixing of mean hydrocarbon and oxygen concentration fields, controlled by the mixing coefficient (D_{mix} = infinity, corresponding to perfect and instantaneous mixing, $D_{mix} = 0$ for no mixing)
- Monod-kinetics, which drive biodegradation of mixed hydrocarbon and oxygen

These factors are discussed in some detail in the Ma, Kemblowski and Urroz article.

A Relative-Least-Squares Technique to Determine Unique Monod Kinetic Parameters of BTEX Compounds Using Batch Experiments

Schirmer, M., Butler, B.J., Roy, J.W., Frind, E.O. and J.F. Barker, *Journal of Contaminant Hydrology*, Vol. 37, 1999; http://www.elsevier.

Biodegradation studies often involve the use of a default first-order decay term to estimate biodegradation. In this study, researchers developed a method using batch experiments and computer modeling to derive first-order decay terms. A site-specific decay term would more accurately forecast an aquifer's intrinsic bioremedial capacity because the term would represent "the effects of complex biological processes such as adaptation, inhibition, preferential substrate utilization and growth of the population of degrader microorganisms."

Groundwater temperature and geochemistry, which also affect the decay term, "can be incorporated into derivatives of the Monod equation, and resultant kinetic equations may consider both substrate and biomass models, as interactions between these levels greatly affect the pattern of contaminant biodegradation."

The researchers' method involved analyzing aerobic m-xylene biodegradation in laboratory batch microcosms. The aquifer material and groundwater used in the study were from the Borden Aquifer, described in some detail in *UTTU* Vol. 13, No. 4, 1999. They used different initial substrate concentrations for their calculations. Also required was an estimate for microbial yield, Y, to determine kinetic parameters that were input into a modified version of the computer model BIO3D. This model then generated site-specific Monod kinetic parameters k_{max}, maximum utilization rate, and K_s, half-utilization constant, and the Haldane inhibition concentration, K_I. These values were "reasonable and comparable to literature values" and could be used to simulate plume behavior in the field.

Mycoremediation: a Method for Test- to Pilot-Scale Application

Thomas, S.A., Becker, P., Pinza, M.R., Sequim, J.Q. and P. Stamets, in *Phytoremediation and Innovative Strategies for Specialized Remedial Applications*, Vol. 5, No. 6, 1999, Battelle Press, 800-451-3543; http://www.battelle.org/conferences.

A pilot scale study of mycoremediation—remediation using fungi—was accomplished in Washington state by researchers at a marine sciences laboratory. Mycoremediation involves "field collection of higher fungi from a contaminated vicinity of interest or a comparable site, and includes the following steps: selection, culture, toxicity testing, screening, preconditioning, mesocosm-scale testing, and pilot-scale application. These steps result in development of proprietary fungal strains that are predisposed to remediate specific contaminants at increased efficiency under particular environmental regimes."

The advantage of mycoremediation is that contaminants break down to the relatively innocuous substances of water, carbon dioxide and other basic elements. The higher fungi can address compounds resistant to most microorganisms; they can, for instance, effectively degrade aromatic compounds.

Researchers used three soil types in their 4-month pilot-scale study:

- soil scraped from an earthen floor of a vehicle maintenance building
- a diesel-contaminated soil
- a gasoline-contaminated soil

Researchers created four 10 yd^3 mounds for each of the following treatment types:

- fungi treatment (oil-preconditioned)
- bioremediation
- enhanced bacterial treatment
- a control

The first mound, treated with the fungi, also contained alder sawdust. Researchers treated the second mound, the bioremedial mound, with 12-lb nitrogen fertilizer and turned the soil once a month. Enhanced bacterial treatment involved weekly to biweekly application of a liquid fertilizer and bacterial inoculum and soil turning every two to four weeks. The control was left alone.

The oil smell from the fungi-treated mounds soon disappeared, and after 12 weeks, secondary decomposer species of wild fungi had fruited. The bioremediated and bacterially treated soils, however, retained their "character of heavy clay composition, with an oil odor and visible pockets of oil."

Because the soils were not homogeneous, researchers could not determine "the specific ways in which the different treatments attacked the oils." Researchers concluded: "We would have expected from our prior studies that fungal mycelial activity would have broken down the higher-molecular-weight PAHs most effectively, and alkanes with nearly as high efficiency, but that perhaps as a consequence it could have contributed a temporary increase in lower-molecular-weight compounds during the early stages of the process. It is possible that the test should have been extended to a longer duration because of the scale of the treatment and the low winter temperatures at the site, which could have slowed the biological activity."

Toxicity tests using earthworms indicated "no statistically significant difference among the treatments or control for worm survival, although growth was slightly favored in the mycoremediated soils. Toxicity tests using Washington native plants used measures of plant growth and mortality to compare treatment effectiveness. Initial results were inconclusive; more controlled testing would be necessary to determine the value of treated soils for beneficial uses."

Researchers determined the cost of commercial application of mycoremediation to be under $50/$yd^3$.

The Relative Merits of Monitoring and Domestic Wells for Ground Water Quality Investigations

Jones, J.L. and L.M. Roberts, *Ground Water Monitoring and Remediation*, Summer 1999; http://www.ngwa.org.

A data quality and cost comparison study of domestic and monitoring wells was completed as part of the U.S. Geological Survey National Water Quality Assessment (NAWQA) program in eastern Washington state. "In both studies [domestic and monitoring wells] the methods—sampling, quality assurance, sample analyses—were identical: methods were also the same in land-use studies in other NAWQA study units so that the results may be compared and synthesized on local, regional and national scales."

Although the objective of this study was to "investigate the potential impacts on shallow groundwater quality from widespread use of agricultural chemicals," many of the conclusions could be applied to groundwater studies of petroleum-contaminated wells.

Researchers found that monitoring wells were more expensive to sample than domestic wells due to construction and development requirements. "Costs include materials, the time and cost of constructing and developing a monitoring well and the time to find landowners willing to allow drilling on their property. When applicable, the cost of abandonment should be included as well. In our study, about 15 percent (seven of 48) of the monitoring wells either were dry, went dry prior to sampling or failed to produce adequate amounts of water for sampling. About 10 percent (five of 53) of the domestic wells could not be sampled, but the costs incurred were comparatively small. . . The presence of existing pumps and plumbing made domestic wells easier to sample; however, because they produce much larger amounts of water than needed for sampling, it was sometimes difficult to keep the pump running continuously during the entire sampling period. Additionally, complex plumbing systems occasionally required lengthy study to find a suitable sampling point."

Jones and Roberts *(1999)* estimated that "Siting, installing, developing and sampling monitoring wells took about 12 person-days/well including expenses (such as the expense of constructing wells that had to be abandoned) compared to about three person-days for locating, inspecting and sampling domestic wells." Higher costs may be associated with drill rig employed, auger vs. air-rotary.

Researchers concluded that sampling monitoring wells was about four times more costly than sampling domestic wells. The data quality, in terms of what contaminants contaminate aquifers, is better from monitoring than domestic wells. Domestic wells are typically screened at deeper levels than monitoring wells, and the effect is evident in samples that indicate the effects of adsorption, degradation, dilution, or dispersion. Data from "monitoring wells might provide better early warning of potential ground water contamination and are a better indicator of current land-use practices."

Passive Volatilization Behavior of Gasoline in Unsaturated Soils

Gidda, T., Stiver, W.H. and G. Zytner, *Journal of Contaminant Hydrology*, Vol. 39, 1999; http://www.elsevier.

To gain better insight into gasoline behavior in the unsaturated zone, researchers devised a series of experiments to study passive volatilization of hydrocarbons. They created a synthetic gasoline (made up of 10 components) and tested three soils (sandy, silty and clayey) in a 250-mm-long column consisting of segments separated by gaskets. The segments could be removed from an outer sleeve and the soil analyzed for gasoline components. Conditions under which they ran the experiments included:

- at room temperature, and repeated at sub-zero temperatures
- with varying percentages of water (1 to 30 percent) and gasoline surrogate (1 to 19 percent)
- with soil samples analyzed at 0, 2, 6, 24, 72, 120, 240 and 336 hours; researchers initiated zero-hour column for each experiment to establish initial conditions and assess column preparation and handling loss

For this experiment, researchers assumed microbial degradation was negligible. Hexadecane was added as a non-volatile tracer to track immiscible phase movement. In the tests with water, water was added prior to gasoline.

Researchers concluded the following:

- an initial higher gasoline percentage (i.e., 14 vs. 5 percent) shows a faster surface flux or volatilization, which was unexpected given that higher gasoline percentages create reduced soil-air porosity; however, consideration of gasoline loss as a function of depth and behavior of individual components in the gasoline offers an explanation
- accumulation of hexadecane near the top of the column in contrast with the initial uniform distribution indicates considerable bulk phase movement (due to capillary action)—an immisible phase movement to the surface is known as *wicking*
- wicking significantly contributes to passive volatilization, and the effect is most significant at higher initial gasoline contents
- initial gasoline content (upon which wicking depends) has a greater effect on volatilization behavior than soil type does
- the top slice of the column in the experiments was comprised of 94 percent hexadecane and naphthalene; these two components likely exceed their solubility in the existing immiscible gasoline; at room temperatures, the naphthalene will solidify once it falls out of solution; at colder temperatures, both components will solidify, thus, phase separation maintains a lower liquid gasoline concentration at the surface even though total gasoline concentration is higher; this lower liquid concentration (caused by precipitation or freezing) preserves the driving force necessary for continued wicking, allowing evaporation of the more volatile components from the column top
- wicking will continue until about 5 percent of the gasoline remains; in other words, soil with about 5 percent gasoline is the approximate threshold level at which wicking ceases
- passive volatilization of higher-gasoline-content soils involves not only diffusion through the soil-air but also capillary action and solidification of the less volatile components of the gasoline mixture

- volatilization behavior from wet soils depends on soil type; soils with larger pores (vs. those with smaller pores) maintain interconnected pore structure more easily, hence, volatilization increases
- models that predict volatilization need to incorporate solidification at the atmosphere-soil interface, or at the edge of preferential flow paths; reliable measures of gasoline conductivities as a function of gasoline content in different soil types are needed
- the capillary action contribution to wicking is greatest for the clayey soil, likely because of the soil's smaller pores
- wicking is a non-linear function of water content, with some water helping the process, but too much water (25 percent or more) halts wicking; as water is increased beyond some threshold value, gasoline is forced into large enough pores where the capillary forces are too weak to promote wicking
- for larger-pore-structure soils, like the silt loam, even a modest increase in water content can hinder wicking
- volatilization rates from sub-zero temperature soils are always slower than above-zero temperature soils; thus, total fraction of gasoline lost is smaller in sub-zero temperature conditions and wet conditions
- capillary action is initiated as a result of volatilization, thus slower volatilization delays wicking; however, "there does not appear to be a significant difference in the importance of wicking in sub-zero temperatures"
- the presence of frozen water may influence volatilization in significant ways; air permeability of the clayey soil with 30 percent water content was 29 percent lower in the frozen soil, likely due to volume expansion of freezing water

Natural Attenuation of Hydrocarbons in the Vadose Zone: A Field Perspective

Hullman, A.S., Reisinger, H.J., Bartholomae, P.G. and L. Johnson, in *Bioreactor and Ex-Situ Biological Treatment Technologies,* Battelle Press, Columbus, Ohio, 1999; http://www.battelle.org.bookstore.

To better understand the parameters that affect vadose-zone hydrocarbon attenuation and vapor fate and transport, researchers studied five hydrocarbon-contaminated sites in New Jersey and Ohio. They wanted to generate data that might be used to evaluate vapor-phase exposure pathways in the risk-based corrective action process. They found:

- strong evidence of hydrocarbon attenuation exists in the vadose zone
- a significant change of oxygen, carbon dioxide and vapor-phase hydrocarbon concentrations occurs within a narrow and discrete zone; this is largely the result of biological degradation (as suggested by in-situ respirometry data)
- at most sites, or all, macronutrient concentrations (nitrogen, phosphorus and potassium) were sufficient to support biodegradation
- standard geotechnical sampling and analysis techniques are *insufficiently* precise to accurately estimate representative soil physical characteristics, particularly air-filled porosity
- in many cases, standard error and physical heterogeneity might preclude accurate determination of site-specific input parameters for RBCA evaluations and vapor-transport modeling
- one of the most important variables in the RBCA analysis is *air-filled porosity,* which requires that proper equipment and techniques be used to collect soil cores to determine bulk densities; bulk density values affect the calculated porosity values: total, water-filled and air-filled; "assuming constant values for moisture content and specific gravity, this analysis indicated that a change in dry bulk density of ±10 percent alone resulted in a change in the estimated air-filled porosity of ±88 percent"
- modeling of vapor-phase biodegradation in the vadose zone is complicated

Hydrogen Peroxide Treatment: The Good, The Bad, The Ugly

E. Nyer and D. Vance, *Ground Water Monitoring and Remediation*, Summer 1999; http://www.ngwa.org.

Hydrogen peroxide is a strong oxidant that "in sufficient quantities, can oxidize any organic in water or soil. The key to making it cost effective is to use a catalyst, usually iron, and perform the reactions at the correct pH. While hydrogen peroxide is a strong oxidant in and of itself, the iron catalyst allows the hydrogen peroxide to form hydroxyl radicals that are even stronger oxidizing agents. The combination of hydrogen peroxide and iron catalyst is usually referred to as Fenton's reagent."

Reviewer's comment: in most other applications, the key to making hydrogen peroxide cost effective is by not using a catalyst, but rather a stabilizer package which varies from application to application.

Nyer and Vance *(1999)* caution potential users of Fenton's reagent that the site's geological and geochemical environment must be understood. "Due to the presence of competing organics and mineral surfaces that are reactive to hydrogen peroxide, and to the less than optimal environmental conditions, dosage requirements may increase tenfold to accomplish the desired oxidation of organic chemicals . . . the macro and micro geologic conditions do not always allow for complete contact between the carrier and the organic chemicals present in the vadoze zone and aquifer. As with all liquid applications, great care must be taken to design a well system that will deliver the chemical oxidant to the maximum organic chemicals. The greatest benefit will be obtained using Fenton's reagent for the treatment of soils through which free product hydrocarbons have flowed or pooled."

For success stories, authors recommend reading "In-Situ Remediation Technology: In-Situ Chemical Oxidation" (EPA 542-R-98-008). Although treatment with Fenton's reagent can give good results, authors caution potential users that Fenton's reagent is an exothermic (heat producing) reaction that can be extremely dangerous if not used correctly. Given its dangerous nature, they emphasize employing only experienced consultants and vendors when applying Fenton's reagent.

For in-the-field comments on Fenton's reagent, visit the BioGroup website, http://biogroup.gzea.com. Go to Message Archive, then Message Arranged by Thread and search for messages with Fenton's reagent. In addition, *UTTU* Vol. 12, No. 4, 1998 published an article on Fenton's reagent, "Guidelines for using Fenton's reagent at remedial sites."

Information sources

Websites

Advanced Measurement and Controls, Inc.
http://advmnc.com/, for weather and hydrology sensors

American Institute of Chemical Engineers
http://www.aiche.org/

American Society of Civil Engineers, http://www.asce.org/

American Society of Mechanical Engineers
http://www.asme.org

Canadian Centre for Pollution Prevention, a clearinghouse for business projections, publications, names, numbers, listserve and email addresses of pollution prevention organizations, http://c2p2.sarnia.com/

Center for Environmental Information and Statistics contains maps, graphs and photos that depict air and water quality and potential chemical exposure at the state or county level
http://www.epa.gov/ceis

Campbell Scientific, for weather stations, data loggers and related equipment, http://www.campbellsci.com/

Chemical composition of petroleum products
http://www.etcentre.org/spills/

Code of Federal Regulations
http://www.access.gpo.gov/nara/cfr/cfr-table-search.html

Compliance Online
http://www.ieti.com/taylor/compliance.html

Department of Energy's screening model
http://www.sandia.gov/eesector/gs/gc/mnahome.html

Environmental Assessment Association
http://www.iami.org/eaa.html

Environmental Law Institute, http://www.eli.org/

Environmental Technology Center, for petroleum formulations from around the world, http://etcentre.org/spills/

Enviroene, http://es.epa.gov/index.html

Fedworld Information Network, http://www.fedworld.gov

Global Network of Environment and Technology
http://www.gnet.org/

Ground penetrating radar links
http://www.g-p-r.com/links.htm

Ground Water Remediation Technologies Analysis Center for information on heavy metals, their behavior and possible remediation methods, http://www.gwrtac.org/html/topics/metals.htm

Hydrogeology Journal, abstracts at http://link.springer.de/link/service/journals/10040/index.htm.

Institute of Professional Environmental Practice (IPEP)
http://www.ipep.org/

International Institute for Sustainable Development for data on international environmental negotiations and other international environmental issues such as climate change, chemical management, forest and ocean policy and sustainable development, http://www.iisd.ca

International Organization for Standardization
http://www.iso.ch/welcome.html

Internet Software Guide for Engineers, a non-commercial site with free software and shareware, covers issues such as coastal engineering, hydraulics, hydrology, water resources and the environment, http://www.geocities.com/CapeCanaveral/Launchpad/9631/software.html

Journal of Environmental Law, http://www.oup.co.uk/envlaw/

Laser Induced Fluorometry/Cone Penetrometer
http://www.epa.gov.etv/02/frwextoc.htm

National Association of Environmental Professionals
http://www.naep.org/

National Library for the Environment for information such as the 500-plus Congressional Research Service reports
http://www.cnie.org

Occupational Safety and Health Administration
http://www.osha.gov/

Phytoremediation of Petroleum Hydrocarbons in Soil, Field Study Protocol, http://www.RTDF.org/public/phyto/protocol/protocol99.htm

Practical statistics for scientists, http://www.practicalstats.com

Publicly accessible listserve groups, http://www.NeoSoft.com:80/internet/paml/

Right-to-Know Network website for a Windows-based program that creates detailed street maps, EPA-regulated sites and demographic and economic information; also data from the U.S. Geological Survey, the Nuclear Regulatory Commission, the Department of Transportation and the Federal Emergency Management Agency, http://www.census.gov/apsd/pp98/pp.html

Risk Assessment & Policy Association
http://www.FPLC.edu/tfield/rapa.htm

Sediments Research Website, an EPA site, for technical papers and reports, http://www.sediments.org.

Science and Environment, http://www.cais.net/publish/

Society of Environmental Toxicology and Chemistry (SETAC), http://www.setac.org

Storage and Preservation of Soil Samples for Volatile Compound Analysis (Special Report 99-5), which evaluated methods to minimize VOC losses during sample collection and storage, http://www.crrel.usace.army.mil/techpub/CRREL_Reports_web/

The Pace Virtual Environmental Law Library
http://joshua.law.pace.edu/env/vell6.html

The Western Environmental Law Center
http://www.welc.org/

TPH Working Group, http://www.aehs.com/asp/publications/tphbooks.htm, contains information for ordering the following documents:

- *Petroleum Hydrocarbon Analysis of Soil and Water in the Environment*
- *Composition of Fuel Mixtures*
- *Selection of Representative TPH Fractions Based on Fate and Transport Considerations*
- *Development of Fraction Specific Reference Doses (RfDs) and Reference Concentrations (FDCs) for Total Petroleum Hydrocarbons*
- *Implementation of the Working Group Approach*

U.S. Army Corps of Engineers Topographic Engineering Center, http://www.tec.army.mil/tecsite.html, has a geographic data coordinate conversion program for Windows that can convert both spatial and elevation data between latitude/longitude and Universal Transverse Mercator.

U.S. Army Corp of Engineers, http://www.usace.army.mil/inet/usace-docs/eng-manuals/em.htm, has these manuals:

- *Multi-Phase Extraction*, EM 1110-1-4010
- *Soil Vapor Extraction and Bioventing*, EM 1110-1-4001
- *In-Situ Air Sparging*, EM 1110-1-4005

U.S. EPA Government Printing Office
http://www.epa.gov/docs/GPO.html

U.S. EPA's page of Laws & Regulations
http://www.epa.gov/epahome/rules.html

U.S. EPA RCRA Corrective Action Program: a model of hazardous waste migration in the subsurface and critiques of remedial techniques for DNAPL. The agency is also soliciting comments on the site's information: http://www.epa.gov/epaoswer/hazwaste/ca/naplweb1/.

U.S. Geological Survey bibliographies/reports/information on groundwater and surface water, http://www.usgs.gov

U.S. Geological Survey National Weather Conditions site: a color-coded map of current flow conditions around the country, http://water.usgs.gov/dwc/national_map.html

Software

Sources for groundwater modeling software (some free):

- The International Groundwater Modeling Center, http://magma.Mines.EDU/igwmc/zipfiles/
- the Institute for Groundwater Studies, South Africa, http://www.uovs.ac.za/igs/software.htm
- the U.S. Geological Survey
  - http://water.usgs.gov/software/ground_water.html
  - http://water.usgs.gov/software/geochemical.html
  - http://h2o.usgs.gov/software/
  - http://water.usgs.gov/software/water_quality.html
- EPA, http://www.epa.gov/epa_ceam/wwwhtml/minteq.htm
- U.S.D.A., http://www.ussl.ars.usda.gov/MODELS/models.htm
- SCISOFTWARE, http://www.scisoftware.com/products/prod_alpha/prod_alpha.html
- DOS models, http://www.hydroweb.com

BUGS Scratchpad is free from Bugbytes Inc. at http://www.bugbytes.com, although there is a fee for setup diskettes and hardcopy documentation. The program simulates one- or two-dimensional steady-state flow and advection or advection-dispersion of multiple interacting solutes. A description of the program appears in *Ground Water,* Vol. 37, No. 4, 1999.

ADEPT (A Program for Aquifer Data Evaluation) contains pump and slug test analysis routines and is available from C.H.E.S.S., http://www.us.net/adept; 301-493-9114 for a fee in the $100 to $325 range. An evaluation appears in *Ground Water*, Vol. 37, No. 5., 1999.

U.S.G.S., for ground water modeling source and executable codes: http://water.usgs.gov/nrp/gwsoftware

A list of state environmental agencies and environmental newsletters and associated URLs: 1998 issue (Vol. 17, No. 2; http://www/aiche.org/; 800-AIChemE) of *Environmental Progress*, "The Environmental Professionals' World Wide Web Non-Technical Directory." For websites related to air pollution control instrumentation, "A Review of World Wide Web Sites for Air Pollution Instrumentation" (Vol. 18, No. 2).

Discussion groups and new bulletin boards

To join the Environmental Forensics discussion group, send a blank note to mailto:env_forensics-subscribe@listbot.com or register at http://www.elmengineering.com or http://www.environmentalforensics.com

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UTTU obtained many of these sites and other information from the Groundwater Mailing List (http://groundwater.com), the Bioremediation Discussion Group (http://biogroup.gzea.com) and TechDirect (http://clu-in.com/techdrct.htm). UTTU thanks the moderators/editors from these groups—Ken Bannister of Groundwater, Richard Schaffner of Biogroup and Jeff Heimerman from U.S. EPA's TechDirect. UTTU also obtained information from Ground Water (http://www.ngwa.org) and Environmental Progress (http://www/aiche.org/)

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