

API SOIL & GROUNDWATER RESEARCH BULLETIN

*A summary of research
results from API's
Soil and Groundwater
Technical Task Force.*

September 1996

SUMMARY OF PROCESSES, HUMAN EXPOSURES AND TECHNOLOGIES APPLICABLE TO LOW PERMEABILITY SOILS

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This paper summarizes a series of ten focus papers on the topic of light non-aqueous phase liquids (LNAPLs) in low permeability soils. Collectively, the papers address four key issues: (1) physical and chemical processes affecting the migration and removal of LNAPLs; (2) available models for predicting this behavior; (3) exposure potential posed by clay soil hydrocarbons via a soil, groundwater or air pathway; and (4) techniques presently available to remediate or enhance remediation. The goal is to provide guidance and understanding on the need and ability to remediate such soils *in-situ*. The emphasis is primarily on the vadose zone of contaminated petroleum sites. The focus papers are compiled in API Publication 4631, *Petroleum Contaminated Low Permeability Soil: Hydrocarbon Distribution, Exposure Pathways and In-Situ Remediation Technologies*, August 1995. (A list of the papers and ordering information are provided on page 7.)

SECTION 1 INTRODUCTION

Recognizing the limited options available to field practitioners charged with remediating sites with silty or clayey soils, the API initiated a three-year program beginning in 1992 to consolidate information on the topic and conduct research on technologies that show promise for removing or enhancing the removal of contaminants in this media. A multi-discipline group was assembled under the umbrella of the API to address the four phases of the problem. These individuals agreed to work as a team and write focus papers in their areas of expertise, which included topics in the process, modeling, exposure, and technology areas. Team members are listed below.

SECTION 2 PROCESS ISSUES

Low permeability soil refers to silts or clays whose saturated hydraulic conductivity is generally below 10^{-5} cm/s. These soils can be encountered in three distinct types of geologic settings. The first is a massive clay formation where the permeability is very limited and in fact dominated by secondary fractures normally the result of a desiccation or weathering process. The second is a layered or stratified formation where silt or clay layers are interspersed within sandy or higher permeability layers. The third can be considered a subset of the second and consists of silt or clay 'lenses' that tend to be discontinuous and of a lim-

<u>TOPIC</u>	<u>AUTHOR</u>	<u>AFFILIATION</u>
• Process Issues	David McWhorter	Colorado State University
• Modeling Issues	Marian Kemblowski	Utah State University
• Exposure Issues	Terry Walden	BP Oil
• Soil Vapor Extraction	Fred Payne	ETG, Inc.
• Bioventing	Robert Hinchee	Parsons Engineering Science
• Thermal Processes	Kent Udell	University of California at Berkeley
• <i>In-Situ</i> Soil Mixing	Robert Siegrist	Oak Ridge National Laboratory
• Hydraulic Fracturing	Larry Murdoch	University of Cincinnati
• Pneumatic Fracturing	John Schuring	New Jersey Institute of Technology
• Surfactant Flushing	Philip Gschwend	MIT

ited lateral and vertical extent within a sandy matrix. Fluid (including contaminant) migration is distinct in each setting and the remediation strategies differ accordingly for each medium.

In massive clay formations containing natural fractures in non-arid regions, the fractures a short distance above the water table are generally air-filled while the adjoining 'solid' matrix blocks between fractures are water-saturated due to capillary pressure forces. This means that, should a hydrocarbon spill occur, the LNAPLs will fill the fractures in the soil and bypass the matrix blocks, traveling downward until they encounter the capillary fringe (the area just above the water table), at which point they will spread laterally in cross-cutting fractures. The large entry pressures required to 'push' the LNAPL into the matrix will tend to keep these separate phase hydrocarbons in the fractures.

Although separate phase product (i.e., LNAPL) invasion into the water-saturated matrix will not occur to any great extent, its constituents will eventually appear in the matrix as a result of the process of diffusion, i.e., movement resulting from the existence of concentration gradients. This is an aqueous phase - not a separate phase - process. The soluble constituents in the LNAPL will dissolve and a concentration gradient will be established between the dissolved hydrocarbon components in the fracture and the uncontaminated pore water in the matrix. The more soluble components will partition out of the LNAPL phase first, and over a period of weeks to months, part or all of the LNAPL mass in the fractures will diffuse into the matrix, with equilibrium established when the matrix storage capacity (including both dissolved and adsorbed phases) is reached.

The process of diffusion has a rather significant impact on remediation strategy. Diffusion is a slow process, and a phrase that is commonly heard is that 'if it takes x amount of years to diffuse into the soil, it will take x amount of years to get out.' In fact, this is extremely optimistic. Simple diffusion calculations indicate that the time to achieve 85% mass recovery is nearly 10 times as long as the time the contaminant is in the ground before remediation begins. So if a spill were to occur 2 years before remediation (defined as an air or liquid flushing system which sweeps the fractures free of contamination), it may take 20 years to get 85% of the mass out, and 200 years to achieve 95% removal, under the conceptual assumptions that were made (in McWhorter, see list of focus paper on page 7). These long remediation periods are the result of disparate concentration gradients. High gradients drive the contaminants quickly out of the fractures, whereas only low gradients exist when the fractures are cleared, establishing a slow process of reverse diffusion out of the matrix. It is apparent that technologies relying strictly on diffusion-controlled fluid movement will take a long time to achieve success (if ever) and could therefore have high life cycle costs.

An important example of this concept is in the application of soil vapor extraction. The remediation literature has numerous exam-

ples where high vacuum systems (some approaching 25 inches of mercury or 0.8 atm) have been used for clay soils, presumably to improve the zone of influence of the induced air flow around the extraction wells. Air will likely, however, flow through the fractures in a massive clay formation, or the sandy layers in a stratified formation, and use of the term 'radius' - in implying uniform flow through the subsurface - is misleading in this regard. If the mass transfer of contaminants is diffusion-limited, the air flow rate through the fractures or high permeability layers is immaterial, and the vacuum system should be sized to the smallest unit that will simply keep the fractures swept clear, thereby minimizing operating costs.

SECTION 3 MODELING ISSUES

To define the exposure potential as well as the need for remediating hydrocarbons in low permeability media, a good understanding of the chemical composition of the LNAPL (e.g., crude oil or refined petroleum products), the geology and the subsurface processes affecting LNAPL behavior is needed. Regarding the first element, each key compound's vapor pressure, solubility and mole fraction in the LNAPL mixture are the critical parameters. The geologic factors that control exposure are subsurface permeability, the degree of stratification or fracturing, soil moisture content and distance of the source from the water table (for a groundwater pathway) or the receptor (for a vapor inhalation route of exposure). In order to assess exposure and the need or ability to remediate the site, the following geologic parameters should be measured in each of the three discussed settings:

Massive Clay

- Permeability and air-filled porosity of the fractures
- Average fracture spacing and connectivity

Stratified Soil

- Permeability over discrete intervals
- Air-filled porosity in low permeability layers
- Average fracture spacing and connectivity, if any

Clay 'Lenses'

- Diffusion coefficient of contaminants in clay
- Thickness and length scale of lenses

Tracer data may be used to estimate some of these parameters, such as air-filled porosity or average fracture spacing (which could be calculated from the tracer flow data after assuming or measuring an average aperture dimension). To determine the need for - or efficacy of - remediation, these data could be modeled to determine fate and transport of the contaminants, both with and without remediation. This is where the third element of the evaluation comes into focus - the subsurface process data. Partitioning, biodegradation and retardation effects need to be considered. Biodegradation in low permeability soils is particularly relevant because of the generally long residence times of dissolved or vapor phase product in the subsurface as it moves between a source and a receptor.

Given the varied subsurface conditions and contaminant compositions one might encounter and the data requirements for modeling

heterogeneity, the use of analytical models for screening purposes rather than numerical models for detailed prediction is considered the most practical approach at the present time. This approach would provide answers to questions such as whether a particular remedial action can be effective and what gross exposure threats are posed by leaving the soil untreated.

SECTION 4 EXPOSURE ISSUES

Human exposure to contaminated media can be the result of either direct or indirect contact with soil, groundwater or their vapor emissions. What distinguishes the potential for exposure in clay soils from other more permeable media is the unique soil structure. The small pores comprising the matrix blocks increase the capacity of the soil (relative to a more permeable media), to store and 'sequester' contaminants over time and to retain water in the matrix. The secondary or 'dual porosity-dual permeability' nature of the material, due to the presence of natural fractures, results in non-uniform distribution and transport of LNAPL, water and vapor phases throughout the subsurface. The low permeability of the bulk media affects the migration of contaminants in the vadose and groundwater zones.

SOIL CONTACT

The direct soil contact pathway is strongly influenced in clays by bioavailability of the compounds. Bioavailability is a concept which refers to the fact that contaminants which may be present in the matrix (in the sense they are extractable with a solvent) may no longer pose a toxicity risk because of the way they are retained or sequestered in the soil matrix. In simplest terms, the contaminants diffuse into the interior pores of the soil or into the humic fraction, and are increasingly slow in reappearing at the surface of the soil (where their toxicity can manifest itself) due to desorption rate limiting mechanisms. While this phenomenon applies to all soils, it is particularly relevant for clay because of its small pore structure. From an exposure standpoint, reduced bioavailability lessens the absorbed dose (and hence risk) of direct soil contact, either by ingestion or dermal contact. Identifying the suite of tests to demonstrate and quantify bioavailability is the subject of recent research led by the Gas Research Institute and the oil industry.

GROUNDWATER EXPOSURE

Exposure via the groundwater pathway is strongly a function of the type of fine-grained geologic setting. In massive clay soils, with no underlying sandy aquifer, there is little exposure threat because the low permeability limits contact in the source zone (because wells would be unproductive and, therefore, not used), and downgradient of the source (because of limited plume migration potential). However, for the case where a contaminated clay stratum containing fractures lies above or below an aquifer, mass transfer under two scenarios must be considered:

- If LNAPL is present in the fractures, rainfall or a fluctuating water table flowing through the fractures will release dissolved

phase components at their effective solubility limit (defined by Raoult's Law as the pure phase solubility multiplied by the mole fraction of the constituent in the mixture) into the aquifer. Dissolved phase concentrations of the BTEX compounds in excess of drinking water standards (e.g., their MCLs) could occur in the aquifer directly beneath the source.

- If the LNAPL has been depleted from the fractures (by some combination of the processes of volatilization, dissolution, biological degradation or diffusion into the matrix blocks), reverse diffusion of the dissolved phase contaminants from the matrix back into the fractures will occur. Unless the distance between fractures is on the order of meters, the resulting concentration in the fractures will essentially be equal to that of the water held in the matrix. For high matrix concentrations and limited mixing of the fracture leachate in the aquifer, dissolved phase concentrations of BTEX could also exceed their MCLs in the aquifer.

Both scenarios indicate that an exposure risk in the aquifer beneath the source area is possible. However, if the receptor well is down-gradient of the source, exposure will be mitigated by natural attenuation processes affecting the BTEX plume.

AIR EMISSIONS

Air emissions from low permeability soils are generally unlikely to pose an inhalation exposure threat from outdoor or indoor vapors. This is true even when the hydrocarbon source is directly adjacent to a basement, an excavated trench, or the soil surface. Diffusional transport is limited by the normally high moisture content of the clay soils, which limits the number and size of the air-filled passages through which the volatile organic vapors can migrate. The vapor plume is further attenuated by the processes of dissolved phase partitioning into the vadose zone pore water, adsorption onto the organic fraction, and biodecay.

SECTION 5 TECHNOLOGY ISSUES

Seven technologies were judged to have some potential for the remediation of low permeability soils in the vadose zone. These technologies can be broadly segregated by the type of process they induce:

- Contaminant Removal
 - Soil vapor extraction (SVE)
 - Bioventing
- Mobility Enhancement
 - Thermal processes
 - Surfactant flushing
 - *In-situ* soil mixing
- Permeability Enhancement
 - Hydraulic fracturing
 - Pneumatic fracturing

To comparably evaluate each technology, an identical set of questions was posed to each of the seven technology paper authors. Generic questions included the effects on contaminant removal posed by high moisture content, the ability to access under buildings, the maximum depth to which the technology is appropriate, and the

capability to remediate petroleum products other than gasoline. The two major geologic settings of a naturally-fractured massive clay formation and a stratified formation were described, and in each case, the author was questioned on the technology's ability to remove free product, dissolved product, adsorbed product, and residual product trapped within pore throats. The papers conclude with a breakdown of the costs to close a hypothetical site; commercial availability; case histories; and a summary of the strengths, weaknesses and complementary technologies which could enhance remedial effectiveness.

The most salient points for each technology follow and are summarized in Table 1. A common set of cost data (e.g., well costs) has been used to derive comparable data for each technology as applied to the hypothetical site.

REMOVAL TECHNOLOGIES

In-situ technologies that actually remove, not simply enhance the removal of contaminants from the ground are limited to two air flushing techniques, which are very closely related.

Soil Vapor Extraction/Bioventing

Soil vapor extraction and bioventing refer to either the injection or extraction of air through a non-saturated medium. Both rely on the same principle for achieving success, i.e., the ability to sweep air through regions of contamination within the formation. In soil

vapor extraction, the air induces volatilization of the contaminants; in bioventing, the oxygen encourages biodegradation. The distinguishing feature between the two processes is the air flow rate, with bioventing requiring less flow because the biodegradation rate (and thus the oxygen demand) is relatively low.

In fine-grained soils, the air will preferentially flow through the fractures in a massive clay and the higher permeability layers in a stratified soil. Remediation of the matrix blocks or the clay layers/lenses will then be diffusion-limited. Although for vapor extraction, diffusion refers to the contaminants migrating into the swept fractures; while in bioventing, it refers to oxygen diffusing into the lower permeability regions. The success of both technologies depends on the diffusion path length, i.e., the distance between fractures or thickness of the clay layer.

The overall evaluation of these technologies is that they are reasonably effective, both from technical and cost perspectives. Stratified formations are somewhat problematic for soil vapor extraction because it is difficult to move the air anywhere other than the high permeability layers. In bioventing demonstrations, this was partially overcome by injecting air over narrow-screened intervals at close spacing in the clay layers. Both technologies may potentially be enhanced by dewatering and induced (pneumatic or hydraulic) fracturing, as long as the geometry and spacing of the fractures is well

Table 1 TECHNOLOGY COMPARISON MATRIX

	Soil Vapor Extraction	Bioventing	Thermal Techniques	Surfactant Flushing	Soil Mixing	Hydraulic Fracturing	Pneumatic Fracturing
Applicability	Volatile fractions	Middle distillates	Gasoline, diesel and crude oil	Diesel and crude oil	Volatiles & semi-volat.	Massive clay formations	Massive clay formations
Strengths	Proven technology	Low cost ^(f)	- Improved HC recovery	Residuals reduction	- Fast ^(f) - Enhanced mass trans.	Reduce diffusion path length	Reduce diffusion path length
Limitations	Low K layers in strat. soils	- Slow ^(f) - Low K layers	- Non-uniform heating - High cost ^(f)	- Emulsions - High cost ^(f) - Limited experience	- Large equipment - Boulders - High cost ^(f)	- Overconsolidated geology only - Surface heave	- Geology - Surface heave - Fractures close w/time
Costs (\$/yd ³) ^(a)	\$24 ^(b)	\$23 ^(b)	\$62 ^(c)	\$65 ^(d)	\$125	\$6 ^(e)	\$7 ^(e)
Time to Closure ^(a)	9 months	2 yrs	50 days	64 days	50 days	3 weeks (fracturing only)	3 weeks (fracturing only)
Availability	Widespread	Widespread	Sparse	Very limited	Sparse	Very limited	Very limited
Complementary Technologies	- Fracturing - Dewater	- Fracturing - Warming	- Fracturing - SVE	Fracturing	Heating	All fluid flush technologies	All fluid flush technologies

Notes:

- (a): Costs were calculated from information provided in the papers included in this report; closure refers to gasoline cleanup from 1000 to 200 ppm in stratified site, with 100 ft x 100 ft x 15 ft source dimension.
- (b): Includes \$15k for design, \$20k for a pilot study and \$20k for pre and post-soil sampling.
- (c): Assumes steam stripping.
- (d): Assumes 80% recycling of the surfactant.
- (e): Costs are for fracturing only, not subsequent remediation.
- (f): Relative to other technologies described in this report.

controlled. Soil warming could also enhance performance, although temperatures that would significantly improve vapor extraction (through pore water evaporation) would be at the expense of biological activity. Optimum temperatures for bioventing would be in the range of 20° to 30° C.

MOBILITY ENHANCEMENT TECHNOLOGIES

Mobility enhancement is broadly defined as a process which accelerates the movement of contaminant vapors or liquids to a subsurface collection system. Surfactant flushing is a typical example of this type of technology, but this definition also includes thermal techniques and soil mixing.

Thermal Processes

Soil can be heated through one of two ways: hot fluid injection (hot water, air or steam) or direct heating [electrical resistance (ER) or radio frequency (RF) heating]. In the former, the fluids are introduced through wells or trenches. In the latter, the heat is introduced through electrodes or antennae placed in the ground. In both cases, the key design goal is to spread the heat away from the source and maintain roughly uniform temperatures throughout the remedial area. These higher soil temperatures must be maintained near the extraction wells to avoid re-condensation or immobilization of the contaminants.

Thermal applications of water, air, and steam are different. Hot water would be used to improve mobile LNAPL recovery in water extraction wells by lowering the interfacial tension and contaminant viscosity. Hot air would primarily function to dewater the formation by vaporizing the pore water near the flow channels, thereby improving the performance of vapor extraction. The target for steam is removal of both residual and free phase hydrocarbons which are volatilized and recovered in the gaseous phase or as condensate. Like vapor extraction, hot fluid injection is compromised by the tendency of the fluid to flow through higher permeability layers in a stratified formation or the fractures in a massive clay formation. These preferential pathways make it difficult to uniformly heat the formation, limiting the remedial effectiveness of hot fluid injection as a stand-alone technology.

The ER and RF heating systems attempt to raise the vapor pressure of the contaminants to improve hydrocarbon recovery through vapor extraction wells. ER can heat the soil to close to the boiling point of water, while RF can heat significantly above the boiling point, providing the added benefit of drying the soil (but at higher cost). These technologies actually perform better in low permeability media since they depend on the water content of the soil to conduct energy (and capillary forces retain higher moisture levels in silts and clays as compared to sands and gravels). Still, sufficient permeability must exist to remove the vapors.

Undoubtedly, thermal technologies improve hydrocarbon recovery (especially of middle distillates) but the costs are high and field exper-

ience limited. In low permeability soils, a complementary technology such as fracturing may be needed to ensure more uniform heat distribution and a hydrocarbon removal pathway.

Surfactant Flushing

Injection of surfactants through wells can aid in hydrocarbon recovery in one of four ways. The surfactant can promote dissolution of an LNAPL by increasing its solubility in the flushing solution, or it can increase its mobility in the subsurface by lowering the water-LNAPL interfacial tension. Surfactants can also reduce sorption onto soil particles and, finally, may accelerate the release of soil colloids which may be carrying sorbed contaminants.

There are two principal drawbacks to the general use of surfactants. The first is their cost and the other is their tendency to form emulsions which are difficult to break. Unfortunately, in an attempt to overcome the first problem through recycling, the second problem of emulsions manifests itself. There are relatively few examples of surfactant usage in the literature, and the ones that do exist apply mostly to DNAPLs (dense non-aqueous phase liquids which are typically solvents) rather than petroleum hydrocarbons.

Low permeability media further complicate the effective use of surfactants. As with other fluid flushing approaches (air or liquid), the surfactant will bypass the lower permeability regions, relying on a diffusional process to reach the contaminants in the clay layers or matrix blocks. Induced fracturing of the soil could alleviate this problem to some extent, but when combined with the cost and emulsion issue, the feasibility of cost-effectively treating a silt or clay media with surfactants is doubtful. The technology appears to have limited potential at the present time.

In-Situ Soil Mixing

In-situ soil mixing refers to the process of physically disturbing the soil with the use of large diameter (up to 14 ft.) augers mounted on a drill rig. Overlapping columns of soil are augered down to depths as great as 25 ft. The technology requires that the site be relatively level and free of overhead obstructions; the subsurface must likewise be free of boulders or other large buried objects.

In the process of mixing the soil, treatment of the contaminants can take one of three forms. Grout can be injected down the hollow auger stem to solidify the soil; air can be injected to volatilize the contaminants (which are then collected under a shroud placed on the surface); or a chemical oxidant (e.g., peroxide) can be introduced for promoting contaminant removal through chemical transformation. All three treatments have been demonstrated in the field, although the long-term stability (leachability) of the grout has yet to be determined.

Soil mixing is an aggressive technology which causes significant site disturbance (the mixed soil has a volume at least 15% greater than the original volume). It is also very costly (relative to other tech-

nologies described in this summary), averaging as much as \$150/cu yd. Its advantages are that it is not very sensitive to the geologic conditions and that treatment is extremely fast, taking only on the order of hours for each soil column. The size of the equipment however makes it impractical for service-station-type settings. In summary, it is a 'niche' technology that may be uniquely suited to some applications but is not expected to see widespread usage.

PERMEABILITY ENHANCEMENT TECHNOLOGIES

Enhancing the permeability of low permeability media is possible with two techniques that involve artificially fracturing the soil: hydraulic and pneumatic fracturing.

The permeability of silts and clays can be significantly increased by induced fracturing of the soil. It is important however that the fracturing process be controlled, since random fracturing can create unwanted short circuits for a remedial fluid flushing solution, making it difficult to treat the bypassed area. The goal is to create a pattern of fractures that decrease treatment time by minimizing the distance over which the diffusional process is required to remediate the contaminated zone.

Controlled fractures can be created either hydraulically or pneumatically. Hydraulically, a fracture is nucleated through injection of a fluid, followed by a slurry of granular material and gel to 'prop open' the fracture, thus maintaining a permanent channel in the matrix. In pneumatic fracturing, high pressure air creates the channel, which is 'self-propped' and will tend to close over time. In stiff clays, the time to closure may be on the order of a year or more; it could, however be much less in soft saturated clays.

The key to successful fracturing is the ability to propagate the fractures in a horizontal plane. This will occur where the soil is 'over-consolidated', meaning that the horizontal compressive stresses exceed the vertical stresses. Under these conditions, both techniques are capable of initiating fractures to a radius of around 20 to 25 ft before they begin to rise toward the surface. Fractures can be created with a vertical spacing of 1 to 2 ft, thus providing a reasonably short diffusion path length for remediation. Creating fractures near building foundations must be carefully considered since surface displacements of up to 2 inches have been recorded.

Induced fracturing offers significant potential for remediating low permeability media by incorporating the technology with air flushing technologies or with thermal treatment. With air flushing, it may allow the amount of vacuum (and thus size of the equipment) to be reduced for moving comparable amounts of air through the subsurface. Both hydraulic and pneumatic fracturing have similar costs and installation requirements, but hydraulic fracturing has one distinct advantage. Sand-propped fractures are permanent and will not close over time - a characteristic making it less sensitive to moisture levels and the degree of stiffness in the clay.

SECTION 6 CONCLUSIONS

Distribution and migration of chemical compounds in low permeability soils are controlled primarily by fracture pathways and diffusional processes. If the clay contains natural desiccation fractures, transport of compounds will initially take place through the fractures, but diffusion into the matrix will quickly occur, until the storage capacity of the matrix is reached.

Human exposure can occur by contact with contaminated soil, groundwater or vapor emissions. The low air-filled porosity in typical clay soils severely limits the threat of vapor exposure. Direct soil contact exposure posed by dissolved or adsorbed contaminants that reside solely in the matrix blocks may be mitigated by reduced bioavailability of the compound(s). For groundwater, however, where a clay stratum is in contact with a sandy aquifer, mass transfer into the aquifer may readily occur, even if no separate phase product resides in the fractures. Treatment of the clay layer above or below this aquifer may therefore be needed, if a receptor well or compliance point is located in this source area.

Remedial technologies that perform mostly by clearing the fractures of contaminants will be slow in reducing concentrations because reverse diffusion from the matrix into the fractures is much slower than diffusion in the other direction, due to a marked difference in concentration gradients. Because most remedial technologies rely on moving a fluid (air, steam, water or a surfactant) through the media, flow through the fractures, or a sandy layer adjacent to a clay stratum, is inevitable. Acknowledging this constraint, the best approach to remediating silty or clayey soils may be to ensure that the diffusional path length between adjacent fluid channels is minimized. Combining fluid flushing technologies with artificial fracturing (either hydraulically or pneumatically) at minimal vertical intervals may potentially offer the best approach for reducing contaminant concentrations at a reasonable rate. However, the degree to which this mass removal (which will likely be limited) reduces the potential for human exposure should be considered before applying these technologies.

ABOUT THE AUTHOR...

Terry Walden is an internal soil and groundwater consultant for BP Oil Europe, overseeing remediation and risk-based corrective action issues. Mr. Walden is the technical and administrative manager of the consultants that contribute to API's Low Permeability Soil Remediation Program. He has been a member of API's Soil and Groundwater Technical Task Force since 1991.

**FOCUS PAPERS CONTAINED IN
PETROLEUM CONTAMINATED LOW
PERMEABILITY SOIL: HYDROCARBON
DISTRIBUTION, EXPOSURE PATHWAYS AND IN-SITU
REMEDIAATION TECHNOLOGIES
AUGUST 1995**

Summary of Processes, Human Exposures and
Technologies Applicable to Low Permeability Soils

*Terry Walden, BP Oil Europe
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Relevant Processes Concerning Hydrocarbon
Contamination in Low Permeability Soils

*David B. McWhorter, Colorado State University
Fort Collins, Colorado*

Assessment of Human Exposure Posed by LNAPLs
in Low Permeability Soils

*Terry Walden, BP Oil Europe
Brussels, Belgium
David B. McWhorter, Colorado State University
Fort Collins, Colorado*

Soil Vapor Extraction in Low Permeability Soils

*Frederick C. Payne, ETG Environmental Inc.
Lansing, Michigan*

Bioventing in Low Permeability Soils

*Robert Hinchee, Parsons Engineering Science
Columbus, Ohio*

Hydraulic and Impulse Fracturing for Low
Permeability Soils

*Larry Murdoch, University of Cincinnati
Cincinnati, Ohio*

Pneumatic Fracturing for Low Permeability Soils

*John R. Schuring, New Jersey Institute of Technology
Newark, New Jersey*

Thermal Technologies in Low Permeability Soils

*Kent S. Udell
University of California at Berkeley
Berkeley, California*

Surfactant-Enhanced Soil Flushing in Low
Permeability Media

*Thomas M. Ravens
Philip M. Gschwend
Massachusetts Institute of Technology
Cambridge, Massachusetts*

Mixed Region Vapor Stripping and Chemical
Oxidation for *In-Situ* Treatment Of NAPLs in Low
Permeability Media

*R. L. Siegrist, O. R. West, and D. D. Gates
Oak Ridge National Laboratory
Oak Ridge, Tennessee*

Modeling Issues Associated with Fractured Media

*Marian W. Kemblowski, HydroGaia Inc.
Logan, Utah*

**ABOUT API'S SOIL & GROUNDWATER
TECHNICAL TASK FORCE...**

API's Soil and Groundwater Technical Task Force provides an expert, multidisciplinary technical focal point within API to address soil and groundwater issues. The Task Force identifies and defines emerging technical issues related to soil and groundwater contamination/protection, and develops research programs to address these issues. API-sponsored research yields practical tools and basic science for risk-based, cost-effective solutions to the petroleum industry's soil and groundwater problems. The Task Force disseminates information and research results through publications, presentations, and interaction with industry clients and regulatory agencies.

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