

REMEDIATION OF PETROLEUM CONTAMINATED SOILS

Biological, Physical, and Chemical Processes

Eve Riser-Roberts

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REMEDICATION OF PETROLEUM CONTAMINATED SOILS

Biological, Physical, and Chemical Processes

PREFACE

This comprehensive technology survey describes and compares the many biological, chemical, and physical processes available for remediating soils contaminated by jet fuels, gasoline, bunker oil, hydraulic and lubricating oils, and related petroleum products. Many details have been collected from the literature and assembled under one cover to provide a convenient and informative reference source for those who must contend with the critical worldwide problem of environmental contamination by these compounds.

The survey was initially conducted for the Naval Civil Engineering Laboratory (NCEL), Port Hueneme, CA, which is now merged with other commands in the new Naval Facilities Engineering Service Center (NFESC). The survey was performed in connection with the installation restoration effort at Twenty-nine Palms, a marine corps base training and staging facility at Twenty-nine Palms, CA, on Purchase Order Number N62583/88 P 2085. It was later expanded and updated for this publication.

Bioremediation is emerging as an important tool for treating petroleum-contaminated soils, whether used as a stand-alone technology or in combination with other physical or chemical methods. Bioremediation was considered to be the desired primary approach for remediating the contaminated soil at Twenty-nine Palms, supplemented, as necessary, by other processes. Also, because of heightened world interest in the phenomenon of bioremediation and its appropriation as a viable treatment option, this book presents an in-depth coverage of its application for contaminated soils.

The results of current research are combined with essential background information to cover all aspects of *in situ* and *ex situ* bioremediation of petroleum-contaminated soils. This information elaborates on the numerous factors affecting biodegradation of petroleum hydrocarbons and describes how they can be enhanced to optimize bioremediation. The susceptibility of individual petroleum components to biodegradation by specific microorganisms is reported, as are the chemical reactions and metabolic pathways involved. All groups of microorganisms are considered for their potential contribution, and the effects of both aerobic and anaerobic conditions are discussed.

This survey also contains an extensive overview of current *in situ* and *ex situ* physical and chemical soil remediation processes for dealing with petroleum contamination, including many innovative approaches. It investigates means of controlling release of volatile organic compounds (VOCs) to the atmosphere and leachate that could migrate to the groundwater during remediation. Methods for collecting and treating VOCs and leachate are included to address these secondary waste streams generated during soil treatment, whether *in situ* or *ex situ*. The importance of selecting appropriate technologies for each contamination incident and the potential value of combining processes for maximum efficiency are discussed. The expansive coverage of these subjects will furnish the reader with a wide range of options for developing treatment strategies and for customizing remediation procedures to the specific site requirements.

Information for this report was obtained through API (American Petroleum Institute), NTIS (National Technical Information Service), DTIC (Defense Technical Information Center), and Dialogue searches, and by extensive use of the library facilities of the University of California at Santa Barbara, in Goleta, CA.

ABOUT THE AUTHOR



Eve Riser-Roberts, Ph.D., received her doctoral degree in microbiology from the University of London, England. She has over 30 years's experience in the life and physical sciences as a consultant, researcher, technical writer, copywriter, and editor. She has conducted and directed research and written for scientists, engineers, and the general public while working in England, Germany, and the United States.

Dr. Riser-Roberts compiled two major reports for the U.S. Navy on remediation of the environment contaminated by petroleum products. Her previous book, *Bioremediation of Petroleum-Contaminated Sites*, was published in 1992 by Lewis Publishers.

At the University of Arizona, Tucson, she wrote for the Lunar and Planetary Laboratory (LPL), Department of Planetary Sciences, Department of Physics, and the Department of Agriculture. She also conducted research in the university's Department of Geosciences, and coordinated the first microbiological research ever performed on hydroponic systems at the Environmental Research Laboratory. Prior to that she conducted medical research at the University Health Sciences Center at the University of Arizona; at the Royal Free and Middlesex Hospitals in London, England; at the Technical University in Munich, Germany; and at the University of Tübingen and Max Planck Institute in Tübingen, Germany.

ACKNOWLEDGMENT

Thanks must be given to all the practitioners and researchers in the many diverse areas related to remediation of soils contaminated by petroleum products. The information they contribute from their work and studies help facilitate restoration of our contaminated world.

DEDICATION

This book is dedicated to Richard M. (Mike) Roberts, my personal, in-house chemical and environmental consultant, whose help in so many ways made this book possible.

GLOSSARY

TERM/ACRONYM DESCRIPTION

- ABF:** Activated biofilters
- Abiotic reactions:** All reactions not biological in origin, including inorganic, photolytic, surface-catalyzed, sorptive, and transport processes
- Absorption:** Retention of the solute within the mass of the solid rather than on its surface
- Acclimation:** The lag time during which organisms acquire the ability to degrade novel compounds
- Acetogens:** Microorganisms that convert higher volatile acids to acetate and hydrogen
- ACGIH:** American Conference of Governmental Industrial Hygienists
- Acidophilic:** Favors acidic conditions
- Adaptation:** The modification of characteristics of organisms to improve ability to survive and reproduce in a particular environment
- Adsorption:** Retention of solutes in solution by the surfaces of the solid material
- Aerobic:** In the presence of oxygen
- AFCEE:** U.S. Air Force Center for Environmental Excellence
- AGP:** Attached growth ponds
- Alfonic 810-60:** A nonionic alcohol ethoxylate surfactant
- Alkalophilic:** Favors basic conditions
- Allochthonous:** Nonindigenous microorganisms
- Ambersorb 563:** Activated carbon
- Anaerobes:** Microorganisms that require anoxic conditions and oxidation-reduction potentials of less than -0.2 V
- Anaerobic:** The absence of oxygen
- Anisotropic:** Exhibiting properties with different values when measured along axes in different directions
- Anoxic:** Oxygen free
- Anthropogenic:** Of man-made origin
- AODC:** Acridine orange direct counting method
- API:** American Petroleum Institute
- Assimilatory:** Results in the reduction of nitrate to ammonia for denitrification cellular synthesis
- ATAB:** Autothermal aerobic bioreactor
- ATA MBR:** Autothermal aerobic membrane bioreactor
- ATF:** Automatic transmission fluid
- ATP:** Adenosine-5'-triphosphate
- Attenuation:** Mixing of contaminated soil with clean soil to reduce concentration of hazardous compounds
- ATTIC:** Alternative Treatment Technology Information Center (EPA database for technical information on innovative treatment technologies for hazardous waste and other contaminants)
- Autochthonous:** Indigenous or native bacteria found in soil in relatively constant numbers that do not change rapidly in response to the addition of specific nutrients
- Autotrophic:** The ability to use reduction of carbon dioxide as major source of organic compounds needed for growth
- Autotrophs:** Organisms that can survive autotrophically
- Axenic:** Free from other living organisms
- BAC:** Biological activated carbon
- BARR:** Bioanaerobic reduction and reoxidation; a remedial technique for *in situ* biodegradation in soil and groundwater
- BCP:** Bacterial chromosomal painting
- BDAT:** Best demonstrated available technology
- Bioaccumulation:** Accumulation of organic contaminants or metals by some microorganisms
- Bioaugmentation:** Supplementation of microorganisms to a contaminated site to enhance bioremediation; see Enhanced biodegradation
- BIOCELS:** Bioreclamation with Innovative On-Site Controlled Environment Landtreatment Systems

Biodegradation: Breakdown of organic substances by microorganisms by breaking intramolecular bonds; e.g., involving substituent functional group or mineralization. As a result, the microorganisms derive energy and may increase in biomass.

Bioemulsifier: An emulsifier produced by a microorganism

BIOFAST: Biological forced-air soil treatment for biopiles

Biofiltration: Treatment of off-gases using biological filters to remove VOCs

Biolog® system: Measures metabolic potentials to describe bacterial communities (Biolog, Inc.)

Biopiles: Mounds of excavated contaminated soil for controlled *ex situ* treatment

BIOPUR®: A patented, aerated, packed-bed, fixed-film reactor using PUR as a carrier material for microorganisms

BioPurgeSM: Technology using bioventing with a closed-loop concept to regulate soil moisture and release of nutrients, oxygen, and microorganisms into the vadose zone

Biorecalcitrance: Resistance of a compound to biological attack

Bioreclamation: A natural or managed process involving biodegradation of environmental contaminants

Bioremediation: A natural or managed process involving biodegradation of environmental contaminants

Biorestation: A natural or managed process involving biodegradation of environmental contaminants

BioSpargeTM: Technology using bioventing with a closed-loop concept to regulate soil moisture and release of nutrients, oxygen, and microorganisms below groundwater level

Biostim: Uses "Tysul" WW H_2O_2 to circulate oxygen in the soil (Biosystems, Inc.)

Biotic reactions: Reactions that are biological in origin

Biotransformation: Microbial or enzymatic alteration of the molecular structure of a chemical; i.e., microbial metabolism

Bioventing: Process of aerating subsurface soils to stimulate *in situ* bioremediation using SVE systems

Bio XL: Process employing stabilized solutions of H_2O_2 to increase level of oxygen in soil (Aquifer Remediation System)

BOD: Biochemical oxygen demand

Brij 30: A surfactant

BR: Butyl rubber, can be used as a liner

Brij 30: A surfactant

Brij 35: A surfactant

BSRR: Rotary reactor

BTEX: Benzene, toluene, ethylbenzene, and xylenes

BTX: Benzene, toluene, and xylenes

C8PE9.5, C9PE10.5: Nonionic alkylphenol ethoxylate surfactants

C12-E4: Nonionic alkylethoxylate surfactant

Catox: Catalytic/thermal oxidation units for controlling VOC emissions

Cedephos FA-600: Anionic surfactant mixture of mono- and diorganophosphate esters

CEQ: Council on Environmental Quality

CERCLA: Comprehensive Environmental Response, Compensation, and Liability Act (Superfund)

CFU: Microbial colony-forming unit

CGAs: Colloidal gas aphrons (foams); e.g. NaDBS

Chemoautotrophic: Derives energy from the respiration of inorganic electron donors

CO-601 carbons: Coal-based or coconut shell carbons for removal of hydrocarbons from gas streams with the DetoxifierTM

CoA: Coenzyme A

COD: Chemical oxygen demand

Commensalism: Sequential degradation of a compound by two or more microorganisms in a relationship that may benefit only one partner

Cometabolism or Cooxidation: The indirect metabolism of a recalcitrant substance; the process by which microorganisms, in the obligate presence of a growth substrate, transform a nongrowth substrate

Composting: A form of biodegradation involving mesophilic and thermophilic microorganisms

Conjugation: Reaction between a normal metabolite and a toxicant

Convective Transport: Passive transport of microorganisms through soil by transport addition of water or aqueous nutrient feed solution

Corexit 0600: A surfactant

CPE: Chlorinated polyethylene, can be used as a liner

CR: Neoprene, can be used as a liner

CREAM®: Video image analyzing system for reading ELISA plates (Kem-En-Tec A/S)

Critical micelle concentration: Lowest concentration at which micelles begin to form

CROW: Contained recovery of oily wastes process to recover DNAPLs

Cryo-SEM: Cryoscanning electron microscopy

CSPE: Chlorosulfonated polyethylene, can be used as a liner

Customblen: A slow-release fertilizer containing calcium phosphate, ammonium phosphate, and ammonium nitrate in a vegetable oil coating

Cy3, Cy5: Fluorochrome (fluorescing) DNA label

Cyanobacteria: Blue-green algae, which are actually bacteria; can be present in surface soil

DCE: 1,2-Dichloroethane

DEFT: Direct epifluorescence filtration technique for counting microorganisms

Dehalogenation: Enzymic removal of a halogen

DEHP: Di-2-ethylhexylphthalate

Denitrification: Also called dissimilatory nitrate reduction, where nitrate serves as the terminal electron acceptor in the oxidation of an organic substance, with production of N_2 and energy for the cell; begins when oxygen concentration goes below $10 \mu\text{mol/L}$

Denitrifying bacteria: Facultative bacteria that reduce nitrate using the oxygen of nitrate as a hydrogen acceptor; they (denitrifiers) have the ability to oxidize inorganic energy sources (e.g., hydrogen or sodium sulfide)

DETOXIFIER™: Technology/equipment potentially capable of implementing a range of *in situ* treatment methods; e.g., air/steam stripping, neutralization, solidification/stabilization, oxidation (Toxic Treatments U.S.A.)

Diauxie: The opposite of cometabolism; a sparing effect, when a compound is not degraded in the presence of another compound

Dissimilatory nitrate reduction: Nitrate serves as the terminal electron acceptor in the oxidation of an organic substance, producing N_2 and energy for the cells

Dissimilatory sulfate reduction: Strict anaerobes that utilize organic carbon as a source of carbon and energy and use reducible sulfur compounds (e.g., sulfate, thiosulfate) as terminal electron acceptors

DITS: Dual injected turbulent suspension

DNA: Deoxyribonucleic acid

DNAPLs: Dense nonaqueous-phase liquids

DNOC: 4,6-Dinitro-*o*-cresol

DO: Dissolved oxygen

Dobanols 91-5, 91-6, 91-8: Surfactants

DOC: Dissolved organic carbon

DOD: Department of Defense

Dowfax C10L: A sulfonated anionic surfactant

Dowfax 8390: A sulfonated anionic surfactant

DPA: Diphenylamine

EC: Elimination capacity

EDTA: Ethylenediaminetetraacetic acid

Eh: Redox potential

Electro-osmosis: Soil water is induced to flow toward a cathode during *in situ* or *ex situ* electrobioreclamation of low permeability, unsaturated soils

ELISA: Enzyme-linked immunosorbent assay; a monoclonal antibody immunoassay

ELPO: Elasticized polyolefin, can be used as a liner

END: Enhanced natural degradation; *in situ* process to increase amount of H_2O_2 in contaminated soil (Groundwater Technology)

Engineered bioremediation: Any modification or intervention in the bioremediation process

Enhanced biodegradation: Stimulation of microbial degradation of organic contaminants by addition of microorganisms, nutrients, or optimization of environmental factors on-site or *in situ*

Enrichment culturing: Addition of a specific hydrocarbon to a minimal medium to select for degraders of that compound

EO: Ethoxylate (surfactant)

E°: Standard reduction potential

EPA: Environmental Protection Agency

EPDM: Ethylene propylene rubber, can be used as a liner

EPS: Extracellular polymeric substances; exopolysaccharide; polysaccharide produced by microorganisms external to the cell

Eukaryotic: Nucleus is surrounded by a membrane, as in fungi and higher organisms

Ex Situ: Latin for not in its original place. *Ex situ* treatments could be on site or off site

F-1: Controlled-release, hydrophobic fertilizer; modified urea-formaldehyde polymer with N and P

F-400 GAC: Granular activated carbon

Facultative: The ability to adapt to the conditions specified with this term

Facultative anaerobes: Microorganisms that are metabolically active under aerobic or anaerobic conditions

FBR: Fluidized-bed reactor

FDA: Fluorescein diacetate-hydrolyzing activity assay for determining biological potential of pelleted fungi for bioaugmentation

FID: Flame ionization detector

Field capacity: Water-holding capacity of soil

FITC: Fluorescein isothiocyanate

Fluor-X: Fluorochrome (fluorescing) DNA label

F/M: Food-to-microorganism ratio

FyreZyme™: Bioremediation enhancing agent containing extracellular enzymes, microbial nutrients, and bioemulsifiers

GAC: Granular activated carbon

GAC FBR: Integrated biological granular activated carbon fluidized-bed reactor

GAS 3D: Three-dimensional gas flow model to aid in design of soil-venting systems

GC: Gas chromatography

GC/MS: Gas chromatography/mass spectroscopy

GLC: Gas-liquid chromatography

GPMS: Gas-permeable-membrane supported (reactor)

Gram-negative bacteria: Bacteria that do not possess a cell wall and thus do not retain the blue dye that stains cell walls; these cells are enclosed by a cell membrane that will absorb the red counter stain in the Gram stain technique

Gram-positive bacteria: Bacteria that possess a cell wall, which retains the blue dye that stains cell walls in the Gram stain technique

H: Henry's law constant or Henry's coefficient

H₂O₂: Hydrogen peroxide, used to supply oxygen to the subsurface

Half-life: The time required to decrease original concentration by one half

Heterotrophic: The ability to derive energy and carbon for survival and growth from decomposition of organic materials

Hoechst 33342: Allows assessment of macromolecular composition for DNA

Homologous: Identical compounds except for number of repeating units

HPAH: High-molecular-weight PAH

HPCD: Hydroxypropyl-β-cyclodextrin

HRUBOUT®: Hot air injection process for soil flushing (Hrubetz Environmental Services)

HSWA: Hazardous and Solid Waste Amendments

Hydrocarbonoclastic: Ability to degrade and utilize hydrocarbons

Hydrolysis: Chemical reaction involving cleavage of a molecular bond by reaction with water

Hydrophilic: Water attracting

Hydrophobic: Water repelling

Hydrophobization: Conversion to a hydrophobic (water-repellent) state

Hydroxylation: Addition of OH to an aromatic or aliphatic molecule

ICB: Immobilized cell bioreactor (Allied Signal)

ICP/MS: Inductively coupled plasma/mass spectrometry

Igepal CA-720: A surfactant

Igepal CO-603: Nonionic ethoxylated alkylphenol surfactant

Indigenous microorganisms: Microorganisms occurring naturally in a particular region or environment; stable members of a community that have a selective, competitive advantage in that environment

Inipol EAP-22: An oleophilic fertilizer (Elf Aquitaine in France)

In situ bioreclamation: Biodegradation operations taking place in the contaminated soil or groundwater without excavation

INT Activity Test: A dye, 2-(*p*-iodophenyl)-3-(*p*-nitrophenyl)-5-phenyl-tetrazolium chloride; identifies bacteria active in electron transport

Intrinsic bioremediation: Lack of intervention in bioremediation process, or natural attenuation; the result of several natural processes (e.g., biodegradation, abiotic transformation, mechanical dispersion, sorption, and dilution) that reduce contaminant concentrations in the environment

Intrinsic remediation: Results from natural processes; e.g., biodegradation, abiotic transformation, mechanical dispersion, sorption, or dilution

In vitro: In a test tube

In vivo: In life

K: Soil adsorption constant; the measure of the tendency of a pollutant to be adsorbed and stay on soil; the greater the *K* value, the stronger the binding

KAX-50, KAX-100: Proprietary rubber particulates as stabilization additives

K_{oc} : This value reflects the impact of organic material to adsorb organic compounds out of solution

K_{ow} : Octanol/water partition coefficient; also *P*

K_p : The linear partition coefficient

***lacYZ*:** Gene for lactose utilization

Landfarming, Landtreatment: Controlled application of waste materials to soil for immobilization or for degradation or transformation by resident microorganisms

Leachate: Liquids generated by movement of liquids by gravity through a disposal site

LiP: Lignin peroxidase; extracellular fungal enzyme

Lipotin: Glycerophospholipids

Lithotrophic: The ability to obtain energy from oxidation of inorganic compounds

LNAPLs: Light nonaqueous-phase liquids

$\log K_{OH}^0$: The atmospheric reaction rate of a specific compound

$\log K_{ow}$, $\log P$: A measure of the tendency of a compound to dissolve in hydrocarbons, fats, or organic component of soil rather than in water

LPAH: Low-molecular-weight PAH

LPH: Liquid-phase hydrocarbon

***luxAB*:** Gene for bioluminescence

Macrofauna: Soil organisms, such as insects, protozoa, earthworms, and slugs that aid in decomposition of organic material

MARS: Membrane aerobic or anaerobic reactor system

MBR: Membrane biological reactor

MeOH: Methanol

Mesophilic: The ability to grow at temperatures from 10 to 45°C, with optimum growth around 20 to 40°C; most human pathogens grow best at 37°C

Methanogenic consortia: Groups of microorganisms that function under highly reducing conditions and produce methane from degradation of small or low-molecular-weight organic compounds

Methanogenesis: Conversion of short-chain organic compounds by anaerobic microorganisms to methane, carbon dioxide, and inorganic substances

Methanotroph: Microorganisms that break down methane

Methylation: Addition of a methyl group

MF: Microfiltration

Micelles: Surfactant molecules emulsify oily material into fine droplets that form aggregates 10 to 100 Å in diameter, called micelles

Microaerophilic: The ability to survive on very low levels of oxygen

Microbial consortia: Mixed population of interacting microorganisms

Microbial diffusion: Transport of microorganisms in soil as a result of (microbiological) life/death cycle and natural microbial movement; requires expenditure of energy

Mineralization: Complete biodegradation of organic molecules to mineral products; e.g., CO_2 , NO_3^- , SO_4^{2-} , PO_4^{3-} . A portion of the carbon from the organic molecule is usually incorporated into biomass

MLSS: Mixed liquor suspended solids

MLVSS: Mixed liquor-volatile suspended solids

MnP: Manganese-dependent peroxidase; extracellular fungal enzyme

MPN: Most-Probable-Number; method for estimating counts of viable microorganisms

MPP: Multiphasid *Pseudomonas putida*

MRI: Magnetic resonance imaging

mRNA: Messenger RNA

MS: Mass spectroscopy

MTBE: Methyl-*tert*-butyl ether, a gasoline additive

NaDBS: Sodium dodecyl benzenesulfonate; colloidal gas aphron foam

Na₅DTPA: Pentasodium salt of diethylenetriaminepentaacetic acid; most effective of the commercially available chelating agents for preventing contact between metals and H_2O_2

NAH plasmids: Naphthalene-degrading plasmids

NALS: Narrow angle light scatter at the cell surface reflects cell size

NAPLs: Nonaqueous-phase liquids (e.g., solvents and fuels); pollutants present in liquids that are immiscible with water

Natural attenuation: Unassisted biochemical degradation, evaporation, adsorption, metabolism, or transformation by microorganisms of subsurface contaminants

ndoB: Naphthalene degradation gene probes

Nitrogen demand: Amount of nitrogen required for degradation of a given amount of contaminant

Normal flora: Mixed population of microorganisms occurring in nature

Novel II 1412-56: A nonionic alcohol ethoxylate surfactant

NRV: Nitrogen requirement value; the amount of nitrogen required by organisms to decompose or degrade a particular organic chemical

NTA: Nitritotriacetic acid

NVOCs: Nonvolatile organic compounds

Obligate: Strict dependence upon the conditions specified with this term

Obligate anaerobes: Microorganisms that require the absence of oxygen

OCAs: Oil-core aphrons

ODR: Oxygen diffusion rate

Oligotrophic: The ability to survive on very low concentrations of nutrients

Oligotrophs: Organisms that can survive on low organic concentrations (<15 mg carbon/L)

OLR: Organic load rate

On-site bioreclamation: Biodegradation operations that occur above ground at the site of contamination

Operon: A DNA region that codes for several enzymes in a reaction pathway; it enables or prevents repression of structural gene function by controlling synthesis of mRNA by RNA polymerase enzyme

OR: Oxidation-reduction potential; Eh

Orange I: Azo dye; substrate for assaying for fungal manganese peroxidases

Orange II: Azo dye; substrate for assaying for fungal LiP

OTA: Congressional Office of Technology Assessment

P: Octanol/water partition coefficient; also K_{ow}

PAC: Powdered activated carbon

PAHs: Polycyclic aromatic hydrocarbons, also called polyaromatic hydrocarbons and PNAs

PB: Polybutylene, can be used as a liner

PCBs: Polychlorinated biphenyls

PCE: Tetrachloroethylene

PCPs: Polychlorinated phenols

PE: Polyethylene, can be used as a liner

PEL: Polyester elastomer, can be used as a liner

PHB: Poly-3-hydroxybutyrate, an intracellular storage polymer; improves eroding soil, enhances soil strength, reduces soil permeability

PHENOBAC® Mutant Bacterial Hydrocarbon Degradar: Mixture of mutant microorganisms (Polybac)

Photodegradation: Use of light for direct photodegradation or sensitized photo-oxidation to degrade organic compounds

Photolysis: Light-sensitized oxidation of resistant complex compounds

Photo-oxidation: UV light-induced oxidation for destruction of organic contaminants

Phototrophs: Organisms that derive energy from sunlight

PID: Photoionization detector

PISB: Passive *in situ* biotreatment

pKa: Dissociation constant indicates degree of acidity or basicity of a compound and thus the extent of adsorption and ease of desorption

Plasmids: Extra-chromosomal genetic material

Pleomorphs: Bacteria having multiple shapes

pMOL28 (163 kb): Microbial plasmids specifying nickel, mercury, chromate, cobalt, and thallium resistance

pMOL30 (240 kb): Microbial plasmids specifying zinc, cadmium, cobalt, mercury, copper, lead, and thallium resistance

pMOL85 (240 kb): Microbial plasmids specifying zinc, cadmium, cobalt, and copper resistance

PNAs: Polynuclear aromatic hydrocarbons, also called PAHs

Poly B-411: Polymeric dyes that serve as substrates for lignin degrading enzymes

Poly R-478: Polymeric dyes that serve as substrates for lignin degrading enzymes

Poly R-481: Polymeric dyes that serve as substrates for lignin degrading enzymes

Poly Y-606: Polymeric dyes that serve as substrates for lignin degrading enzymes

POLYBAC® E biodegradable emulsifier: Synthetic biodegradable emulsifier (Polybac)

POLYBAC® N biodegradable nutrients: Commercial fertilizer containing balanced nitrogen and phosphorus to enhance bioremediation by soil microorganisms (Polybac)

Pozzolanic: Materials such as Portland cement, fly ash, kiln dust

PP: Polypropylene, can be used as a liner

PRISM: Plasma remediation of *in situ* materials

Procaryotic "Nucleus": Single chromosome without a membrane, as in bacteria

Proppant: Material that props a fracture, as created in the subsurface by hydraulic/pneumatic fracturing

Protocooperation: Sequential metabolism of compounds by two or more microorganisms where both benefit

Pseudomonads: Bacteria belonging to the genus *Pseudomonas*

PSO: Petroleum sulfonate-oil surfactant; commercial Petronate

Psychrophilic: The ability to grow best at temperatures from -5 to 30°C, with optimum growth between 10 and 20°C

Psychrotrophs: Organisms growing optimally at lower temperatures (e.g., <20°C)

PUF: Porous polyurethane foam for immobilizing enzymes and living microorganisms

PUR: Reticulated polyurethane, a carrier material for microorganisms

PVC: Polyvinyl chloride, can be used as a liner

PWEs: Platinum wire electrodes

Q₁₀ effect: Decrease in microbial enzymatic activity as a result of low temperature

qO₂: Oxygen consumption rate

RAAS: Remedial action assessment system

RAPD: Randomly amplified polymorphic DNA to characterize bacteria in biodegradation

RAS: Return activated sludge

RBC: Rotating biological contactor

RCRA: Resource Conservation and Recovery Act of 1976

RE: Removal efficiency

Recalcitrant: Resistant to microbial degradation

RF: Radio frequency heating to desorb organic contaminants from soil; improves soil venting by increasing vapor pressure of contaminants

RESOL 30: Solution containing nonionic and anionic biodegradable surfactants for soil washing

Restore 375: Fertilizer with sodium triphosphate combined with orthophosphates

Rexophos 25/97: A phosphate ester blend weak-acid anionic surfactant

RF: Radiofrequency heating

Rhamnolipid R1: A glycosylated, anionic, amphipathic surfactant secreted by *Pseudomonas aeruginosa*

Rhodamine 123: A bacterial stain to demonstrate viability

RNA: Ribonucleic acid

RREL: Risk Reduction Engineering Laboratory (EPA)

rRNA: Ribosomal RNA

RT-PCR: Reverse transcription-coupled-PCR

SARA: Superfund Amendments and Reauthorization Act

SBR: Sequencing batch reactor

SCF: Self-cycling fermenter

SCF: Supercritical fluid oxidation

SDS: Sodium dodecyl sulfate, an anionic surfactant used for soil flushing

Serqua 710: A surfactant

SITE: Superfund Innovative Technology Evaluation Program

SITE ETP: SITE Emerging Technologies Program

SLB: Signature microbial lipid biomarker indicates viable biomass

MMO: Soluble form of methane monooxygenase from the methanotroph, *Methylosinus trichosporium* OB3b

Sorption: Refers to both “adsorption”, the retention of solutes in solution by the surfaces of the solid material and “absorption”, retention of the solute within the mass of the solid

SPR: Single particle reactor

SSM: Shallow soil mixing; can be combined with SVE to extract VOCs from soil

Sulfate-reducing bacteria: Strict anaerobic bacteria that use sulfate as a terminal electron acceptor, converting sulfate to sulfide

Sulfidogens: Organic acids are used as electron donors

Superbugs: Strains of microorganisms developed in the laboratory with the potential of biodegrading a range of contaminants

Superfund: See CERCLA

Surfactants: Surface active agents that promote the wetting, solubilization, and emulsification of organic chemicals

SVE: Soil vapor extraction; also called soil vacuum extraction, soil venting, and soil vapor stripping; reduces vapor pressure in soil and increases volatilization of contaminants, which are then withdrawn by the vacuum

SVOCs: Semivolatile organic compounds

Synergism: Sequential metabolism of compounds by two or more microorganisms where both benefit

Syntrophism: One organism supplying a missing nutritional requirement of another

TAD: Thermophilic aerobic digestion

TAH: Total aliphatic hydrocarbons

TBA: Tertiary butyl alcohol

TCLP: Toxicity characteristic leaching procedure

TEA: See terminal electron acceptor

TEL: Tetra-ethyl lead

Tergitol 15-S-9: An ethoxylated nonionic surfactant

Tergitol NP-10: A surfactant

Tergitol NPX: A surfactant

Terminal electron acceptor (TEA): Chemicals necessary for transfer during metabolic processes while microorganisms biodegrade contaminants; aerobic biodegradation of petroleum hydrocarbons requires the TEA, oxygen; anaerobic biodegradation requires the TEAs iron, sulfate, or nitrate

TESVE: Thermally enhanced soil vapor extraction

Tetren: Tetraethylenepentamine, a chelator

Thermophilic: The ability to grow at temperatures from 25 to 80°C, with optimum growth at 50 to 60°C

TLD-FID: Thin-layer chromatography-flame ionization detection

TLV: Threshold limit value

TOL plasmid: Toluene-degrading plasmid in bacteria

TPH: Total petroleum hydrocarbons

Treatment trains: Use of more than one technology or process, in series or in parallel, to remediate a contaminated site; these will be site and incident specific

Triton N101: A surfactant

Triton X-100: An ethoxylated nonionic surfactant

Triton X-114: A surfactant

TSDFs: Treatment storage and disposal facilities

Turnover time: The amount of time required to remove the concentration of substrate present

Tween-20-80: A surfactant

Tween-80: A surfactant

Tysul WW: H_2O_2 from du Pont, used in Biostim to provide oxygen to the soil

UASB: Upflow anaerobic sludge blanket

UST: Underground storage tank

UTCHEM: Multiphase, multicompositional simulator to model migration and surfactant-enhanced remediation of an NAPL

UV: Ultraviolet

Vadose zone: Unsaturated soil above water table

VES: Vapor extraction system; also called soil vacuum extraction, soil venting, and soil vapor stripping; *in situ* technique for removing VOCs from soil

VOCs: Volatile organic compounds

WALS: Wide angle light scatter reflects internal cell structure as refractility

WIGEs: Wax-impregnated graphite electrodes

Xenobiotic: Compounds that are man-made or are unique in nature; also refers to compounds released in the environment by the action of humans and, thereby, occur in a concentration that is higher than natural

xylE: Toluene, xylene degradation gene probes

Zymogenous: Soil bacteria that increase rapidly when furnished with certain nutrients and then diminish in numbers when the material is exhausted