

EPA/625/R-95/005

July, 1996

# **Pump-and-Treat Ground-Water Remediation**

## **A Guide for Decision Makers and Practitioners**

Prepared by  
Eastern Research Group, Inc.  
110 Hartwell Avenue  
Lexington, MA

U.S. Environmental Protection Agency  
Office of Research and Development  
National Risk Management Research Laboratory  
Center for Environmental Research Information  
Cincinnati, Ohio

## **Notice**

The information in this document has been funded wholly, or in part, by the U.S. Environmental Protection Agency (EPA). This document has been subjected to EPA's peer and administrative review and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

In September, 1995 the Office of Research and Development completed a reorganization of its Laboratories and Centers. The former Risk Reduction Engineering Laboratory located in Cincinnati, Ohio, the Robert S. Kerr Research Laboratory located in Ada, Oklahoma, the Air and Energy Research Laboratory, located in Research Triangle Park, North Carolina, and the Center for Environmental Research Information located in Cincinnati, Ohio, were merged into the National Risk Management Research Laboratory. No physical relocations were involved. The documents referenced in this guide were published prior to the reorganization: therefore former laboratory/center names are shown as they were at the time of publication.

## Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and ground water; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director  
National Risk Management Research Laboratory



## Contents

List of Figures .....	v
List of Tables .....	xi
Acronyms and Abbreviations .....	xii
Acknowledgments .....	xiii
1. Introduction to Pump-and-Treat Remediation .....	1
2. Appropriate Use of Pump-and-Treat Technology .....	3
3. Smart Pump-and-Treat Techniques .....	5
3.1. Contaminant Removal/Control .....	5
3.2. Thorough Site Characterization .....	5
3.3. Dynamic Management of the Well Extraction Field .....	7
3.4. Realistic Cleanup Goals .....	10
4. Anticipating Tailing and Rebound Problems .....	19
4.1. Effects of Tailing and Rebound on Remediation Efforts .....	19
4.2. Contributing Factors .....	19
4.2.1. Non-Aqueous Phase Liquids (NAPLs) .....	19
4.2.2. Contaminant Desorption .....	20
4.2.3. Precipitate Dissolution .....	23
4.2.4. Matrix Diffusion .....	24
4.2.5. Ground-Water Velocity Variation .....	24
4.3. Assessing the Significance of Tailing and Rebound at a Site .....	26

## Contents (continued)

5.	Effective Hydraulic Containment .....	28
5.1.	Ground-Water Barriers and Flow Control .....	28
5.1.1.	Horizontal and Vertical Capture Zones .....	28
5.1.2.	Pressure Ridge Systems .....	31
5.1.3.	Physical Barriers .....	31
5.2.	Hydraulic Containment: Other Special Considerations .....	32
5.2.1.	Effects of Anisotropy .....	32
5.2.2.	Drawdown Limitations .....	32
5.2.3.	Stagnation Zones .....	33
6.	Pump-and-Treat System Design and Operation .....	36
6.1.	Capture Zone Analysis and Optimization Modeling .....	36
6.2.	Efficient Pumping Operations .....	40
6.3.	Treating Contaminated Ground Water .....	42
6.4.	Monitoring Performance .....	43
6.4.1.	Hydraulic Head Monitoring for Containment .....	43
6.4.2.	Ground-Water Quality Monitoring for Containment.....	44
6.4.3.	Aquifer Restoration Monitoring .....	48
6.5.	Evaluating Restoration Success and Closure .....	50
7.	Variations and Alternatives to Conventional Pump-and-Treat Methods .....	53
7.1.	Alternative Methods for Fluid Delivery and Recovery .....	53
7.2.	Vadose Zone Source Control .....	54
7.3.	Physical and Chemical Enhancements .....	54
7.3.1.	Physical Enhancements .....	59
7.3.2.	Chemical Enhancements .....	59
7.4.	Biological Enhancements .....	59
7.5.	Alternatives to the Pump-and-Treat Approach .....	61
7.5.1.	Intrinsic Bioremediation .....	63
7.5.2.	<i>In Situ</i> Reactive Barriers .....	63

## Contents (continued)

8. References .....	66
9. EPA Publications Providing Further Information .....	70
List of Sidebars	
1 Changing Expectations for the Pump-and-Treat Approach .....	2
2 Major Types of Hydrogeologic Settings .....	11
3 Computer Graphics as a Site Characterization Tool .....	13
4 The Effect of NAPL Phases on Ground-Water Contamination .....	16
5 Computer Modeling of Well Patterns Versus Hydrogeologic Conditions .....	38

## Figures

1. Examples of hydraulic containment in a plan view and cross section using pump-and-treat technology: (a) pump well, (b) drain, and (c) well within a barrier wall system (after Cohen et al., 1994). ..... 4
2. Contaminant plumes as a function of density and miscibility with ground water: (a) light liquids (gasoline and methanol) create contaminant plumes that tend to flow in the upper portions of an aquifer; (b) dense liquids (perchloroethylene [PCE] and ethylene glycol) create a plume that contaminates the full thickness of an aquifer (adapted from Gorelick et al., 1993). ..... 6
3. This hollow-stem auger is fitted with a 5-foot sampling tube that collects a continuous core as the auger advances, allowing detailed and accurate observation of subsurface lithology. When drilling is completed, a monitoring well also can be installed. .... 8
4. Hydraulic or vibratory direct-push rigs can be installed on vans, small trucks, all-terrain vehicles, or trailers and allow collection of continuous soil cores and depth-specific ground-water samples for detailed subsurface mapping if contaminants are generally confined to depths of less than 15 meters. (Photo courtesy of Geoprobe Systems.) ..... 9
5. Conceptual diagram of Dense Non-Aqueous Phase Liquid (DNAPL) Trichloroethylene (TCE) based on soil and ground-water sampling in a heterogeneous sand and gravel aquifer. The extreme difficulty in cleaning up this site, which includes five distinct forms of TCE (vapors and residual product in the vadose zone; pooled, residual, and dissolved product in the ground water) led to modification of the pump-and-treat system for hydraulic containment rather than restoration (adapted from Clausen and Solomon, 1994). ..... 10

## Figures (continued)

6. GEOS computer screen showing organic contaminant plume in relation to subsurface stratigraphy. .... 12
7. EPA's SITE3D software, under development at the Ada, Oklahoma, laboratory, helps visualize in three dimensions a TCE contaminant plume at a Superfund Site. Yellows and reds indicate zone with highest concentrations of TCE in ground water. .... 14
8. Dark NAPL (Soltrol) and water in a homogenous micromodel after (a) the displacement of water by NAPL and then (b) the displacement of NAPL by water, with NAPL at residual saturation (Wilson et al., 1990). .... 17
9. Photomicrographs of (a) a single blob occupying one pore body, and (b) a doublet blob occupying two pore bodies and a pore throat (Wilson et al., 1990). .... 18
10. Concentration versus pumping duration or volume showing tailing and rebound effects (Cohen et al., 1994). .... 20
11. Contaminants are mobilized when ground water that is undersaturated with a contaminant comes in contact with a NAPL (a) or contaminant sorbed on an organic carbon or mineral surface (b). High ground-water velocities and short contact times will result in low contaminant concentrations, and low velocities and long contact times will result in high contaminant concentrations (c) (adapted from Gorelick et al., 1993). .... 21
12. Laboratory model of the transport of DNAPL contaminant through an aquifer with varying permeability; note the concentration of downward movement in fingers and the DNAPL pools above the low-permeability zones (the horizontal discs). (Source: U.S. EPA National Risk Management Research Laboratory.) .... 22
13. Dissolved contaminant concentration in ground water pumped from a recovery well versus time in a formation that contains a solid-phase contaminant precipitate (Palmer and Fish, 1992). .... 23

## Figures (continued)

14. Changes in average relative trichloroethene (TCE) concentrations in clay lenses of varying thickness as a function of time (NRC, 1994). ..... 24
15. Tailing resulting from ground-water velocity variations: (a) horizontal variations in the velocity of ground water moving toward a pumping well (Keely, 1989) lead to (b) tailing as higher concentrations of ground water in slower pathlines mix with lower concentrations in faster pathlines (Palmer and Fish, 1992); (c) in a stratified sand and gravel aquifer, tailing occurs at t1 when clean water from the upper gravel strata mixes with still-contaminated ground water in the lower sand strata (Cohen et al., 1994). ..... 25
16. Zone of residuals created in former cone of depression after cessation of LNAPL recovery system (Gorelick et al., 1993). ..... 27
17. Plan view of a mixed containment-restoration strategy. A pump-and-treat system is used with barrier walls to contain the ground-water contamination source areas (e.g., where NAPL or waste may be present) and then collect and treat the dissolved contaminant plume (Cohen et al., 1994). ..... 29
18. In an isotropic aquifer, ground-water flow lines (b) are perpendicular to hydraulic head contours (a). Pumping causes drawdowns and a new steady-state potentiometric surface within the well's zone of influence (c). Following the modified hydraulic gradients, ground water within the shaded capture zone flows to the pumping well (d). (Cohen et al., 1994, adapted from Gorelick et al., 1993). ..... 30
19. Cross section showing equipotential contours and the vertical capture zone associated with ground-water withdrawal from a partially penetrating well in isotropic media (Cohen et al., 1994). ..... 31
20. Effect of fracture anisotropy on the orientation of the zone of contribution (capture zone) to a pumping well (Bradbury et al., 1991). ..... 33

## Figures (continued)

21. Capture zone simulation of three pumping wells for an isotropic aquifer (a) and anisotropy ratio of 10:1 (b) using the EPA Well Head Protection Area (WHPA) code. ....	34
22. Examples of stagnation zones (shaded where ground-water velocity is less than 4 L/T): (a) single pumping well and (b) four extraction wells with an injection well in the center (Cohen et al., 1994). ....	35
23. Major types of pumping/injection well patterns (Satkin and Bedient, 1988). ....	39
24. Ground-water flow line in the vicinity of conceptual pumping centers at Lawrence Livermore National Laboratory superimposed on an isoconcentration contour map and showing areas of potential stagnation (Cohen et al., 1994, after Hoffman, 1993). ....	41
25. Effect of adaptive pumping on cleanup time at Lawrence Livermore National Laboratory Superfund site (Cohen et al., 1994, after Hoffman, 1993). ....	42
26. The pulsed pumping concept (Cohen et al., 1994, after Keely, 1989). ....	43
27. Nested piezometer hydrograph for 1992 at the Chem-Dyne Superfund site (Cohen et al., 1994, after Papadopulos & Associates, 1993). ....	46
28. Ground-water flow between and beyond the extraction wells, resulting even though hydraulic heads throughout the mapped aquifer are higher than the pumping level (Cohen et al., 1994). ....	47
29. Example display of ground-water flow directions and hydraulic gradients determined between three observation wells (Cohen et al., 1994). ....	48
30. Influent and effluent VOC concentrations (mg/L) at the Chem-Dyne treatment plant from 1987 to 1992 (Cohen et al., 1994, after Papadopulos & Associates, 1993). ....	49
31. Cumulative mass of VOCs removed from the aquifer at the Chem-Dyne site from 1987 to 1992 (Cohen et al., 1994, after Papadopulos & Associates, 1993). ....	50

## Figures (continued)

32. Determining the success and/or timeliness of closure of a pump-and-treat system (Cohen et al., 1994). .....	51
33. Stages of remediation in relation to example contaminant concentrations in a well at a pump-and-treat site (U.S. EPA, 1992). .....	52
34. Some applications of horizontal wells: (a) intersecting flat-lying layers, (b) intercepting plume elongated by regional gradient, (c) intersecting vertical fractures, and (d) access beneath structures (U.S. EPA, 1994). .....	55
35. Two approaches using trenches or horizontal wells to intercept contaminant plumes (U.S. EPA, 1994). .....	58
36. Process diagram for air sparging with (a) vertical wells, and (b) horizontal wells [after National Research Council (NRC), 1994]. .....	60
37. Schematic of chemical enhancement of a pump-and-treat system. Key areas of concern are shown in boxes. In some cases, the reactive agent will be recovered and reused (Palmer and Fish, 1992). .....	61
38. Two types of aerobic <i>in situ</i> bioremediation systems: (a) injection well with sparger, (b) infiltration gallery (Sims et al., 1992, after Thomas and Ward, 1989). .....	62
39. Alternative ground-water plume management options: (a) pump-and-treat system, (b) intrinsic bioremediation, (c) <i>in situ</i> reaction curtain, (d) funnel-and-gate system (adapted from Starr and Cherry, 1994). .....	64
40. Funnel-and-gate configurations (Starr and Cherry, 1994). .....	65

## Tables

1. Categories of Sites for Technical Infeasibility Determinations (NRC, 1994) .....	15
2. Data Requirements for Pump-and-Treat Systems (Adapted from U.S. EPA, 1991) .....	37
3. Applicability of Treatment Technologies to Contaminated Ground Water (U.S. EPA, 1991) .....	45
4. Issues Affecting Application of Alternative Methods for Delivery or Recovery (U.S. EPA, 1994) .....	56

## Acronyms and Abbreviations

ACL	Alternate concentration limit
CZAEM	Capture Zone Analytic Element Model
DNAPL	Dense non-aqueous phase liquid
DOD/ETTC	Department of Defense Environmental Technology Transfer Committee
EPA	Environmental Protection Agency
GAEP	Geographic Analytic Element Preprocessor
LNAPL	Light non-aqueous phase liquid
LLNL	Lawrence Livermore National Laboratory
MCL	Maximum contaminant level
MCLG	Maximum contaminant level goal
NAPL	Non-aqueous phase liquid
NRC	National Research Council
NTIS	National Technical Information Service
ORD	Office of Research and Development
OSWER	Office of Solid Waste and Emergency Response
PCB	Polychlorinated biphenyl
PCE	Perchloroethylene
RCRA	Resource Conservation and Recovery Act
SVE	Soil vapor extraction
TCE	Trichloroethylene
TI	Technical impracticality
VOC	Volatile organic compound
WHPA	Well Head Protection Area

## **Acknowledgments**

This document was prepared under Contract No. 68-C3-0315, Work Assignment No. 1-33, by Eastern Research Group, Inc. (ERG), and under the sponsorship of the U.S. Environmental Protection Agency.