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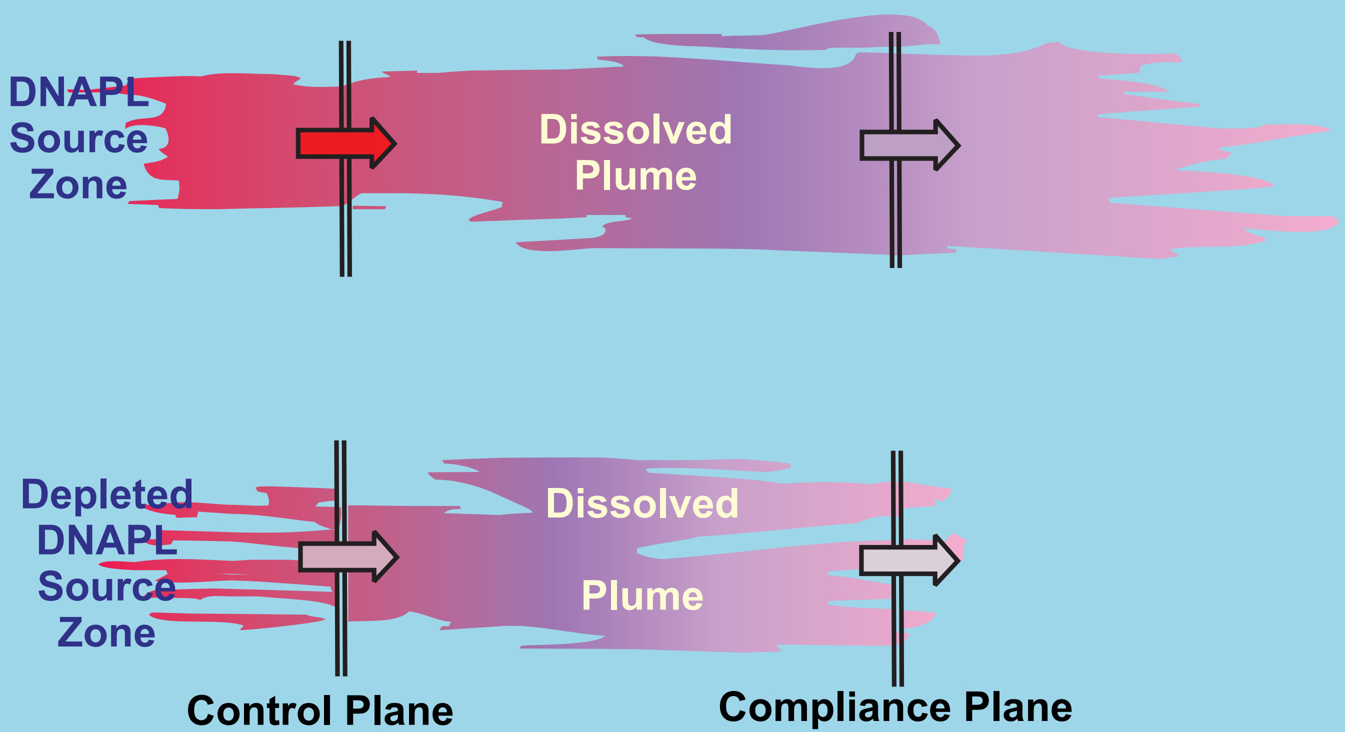
The DNAPL Remediation Challenge: Is There a Case for Source Depletion?



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The DNAPL Remediation Challenge:
Is There a Case for Source Depletion?

by

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Notice

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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 (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments, and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

At many hazardous waste sites contaminants reside in the subsurface as separate dense non-aqueous phase liquids (DNAPL). These DNAPL serve as persistent sources of dissolved phase contamination and are a major impediment to successful and cost-effective cleanup of sites. Commonly used pump-and-treat remediation systems have not been effective in removing DNAPL from these subsurface source areas or in restoring down-gradient contaminated groundwater to desired levels of cleanliness. However, field-scale research has demonstrated that a high percentage of the DNAPL mass can be removed by implementing aggressive *in-situ* technologies such as thermal or chemical flooding. These studies have shown that while a significant fraction of the DNAPL mass can be efficiently removed in a short period, the efficiency of DNAPL extraction often decays exponentially with increasing mass removal. As a result, there is currently no consensus in the academic, technical and regulatory communities on the ecological or environmental benefits of DNAPL source treatment or on the appropriate metrics for quantifying these benefits. To provide technical guidance regarding these critical environmental issues the US EPA convened a panel of national and international scientists and practitioners to conduct a critical, independent review of DNAPL remediation issues. This document contains the findings and recommendations of the panel. This report does not necessarily represent Agency views or policies and should not be interpreted as such. However, the information may be useful in developing appropriate research strategies and plans for solving this important environmental problem.

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Acknowledgments

This document was a joint effort of the Expert Panel on DNAPL Source Remediation consisting of the following members appointed by U.S. EPA.

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The Panel also wishes to acknowledge the thoughtful and constructive criticisms provided by reviewers selected by the U.S. EPA. While the Panel was commissioned and funded by the U.S. EPA, who also defined its general charge, the views expressed in this report reflect only the views of the Panel members, and not the official views of EPA or any other government agency, or Dynamac Corporation.

The Panel Co-Chairs extend their thanks to the Panel members for engaging in spirited debates about contentious issues, for providing insights based on their considerable experience and expertise, and for contribution and review of written material that formed the basis for the final report. The Panel Co-Chairs served as the editors for the final version, and made an attempt to represent divergent views on some topics when consensus could not be reached.

Executive Summary

Introduction

Releases of Dense Non-Aqueous Phase Liquids (DNAPLs) at a large number of public and private sector sites in the United States pose significant challenges in site remediation and long-term site management. Extensive contamination of groundwater occurs as a result of significant dissolved plumes generated from these DNAPL source zones that vary in size and complexity depending on site characteristics and DNAPL properties and distribution. Risk and liability management, consistent with regulatory compliance requirements, could involve remediation of the *source zone* as well as management of the dissolved plume. The *source zone* is defined here as the groundwater region (volume) in which DNAPL is present as a separate phase, either as randomly distributed sub-zones at residual saturations or "pools" of accumulation above confining units and includes the volume of the aquifer that has had contact with free-phase DNAPL at one time, but where all of the DNAPL mass is now present only in the dissolved or sorbed phases or diffused into the matrix in fractured systems. Over the past two decades, innovations in site characterization and remediation technologies have been developed and deployed at DNAPL sites. Several in-situ technologies are available which can achieve substantial DNAPL source depletion either by extraction or destruction. However, because of the risk of failure in achieving certain regulatory targets after implementing a source-depletion technology (e.g., MCLs in the source zone), combined with uncertainties in site characterization (i.e., the location and amount of DNAPL in groundwater at a site), in forecasting potential benefits and adverse impacts of partial source depletion, in prediction of life cycle costs, and uncertainties regarding the acceptability of alternative clean-up levels, many site owners have been reluctant to undertake aggressive source-depletion technologies. Thus, at the majority of DNAPL sites, containment of the source zone and/or management of the dissolved plume for cost-effective risk/liability reduction and regulatory compliance have been the dominant strategies of choice.

Charge to the Panel

As the continued annual costs and uncertainties associated with long-term management of DNAPL sites become more apparent, a reassessment of the factors controlling decisions on whether to implement DNAPL source depletion actions is needed. The long-term cost, reliability, and institutional requirements of the containment strategy for DNAPL source zones are thus topics of current scientific and policy debates, which provided the primary impetus for the U.S. Environmental Protection Agency (U.S. EPA) to establish an Expert Panel on these issues. In the summer of 2001, U.S. EPA formed an Expert Panel ("Panel") consisting of twelve recognized experts on DNAPL fate and transport and DNAPL site remediation to examine four specific issues regarding DNAPL source-zone treatment and management:

A. Status of technology development and deployment for DNAPL source remediation.

B. Assessment of source remediation performance goals and metrics.

C. Evaluation of costs and benefits of source remediation.

D. Research issues and needs.

In order to gather technical information and diverse views, the Panel participated in a two-day workshop involving Panel members and other invited experts (October 19 – 20, 2001; Dallas, TX), and then the Panel met for two days (February 2002; Orlando, FL) to deliberate. The Panel's discussions resulted in the identification of seven questions that cover three of the four issues for which EPA had sought guidance. Charge D, Research Issues and Needs, is addressed directly in Section 4.0 of this Report. These questions are as follows:

1. What are the potential benefits and the potential adverse impacts of DNAPL source depletion as a remediation strategy? (Charges A and C)
2. What are the appropriate performance metrics for assessment of DNAPL source depletion technologies? (Charge B)
3. Are available technologies adequate for DNAPL source characterization to select and evaluate depletion options? (Charges A and B)

4. What performance can be anticipated from source-zone mass depletion technologies? (Charge A)
5. Are currently available tools adequate to predict the performance of source depletion options? (Charges A and C)
6. What are the factors restricting the effective and appropriate application of source depletion technologies? (Charge A)
7. How should the decision be made whether to undertake source depletion? (Charge C)

Potential Benefits and Adverse Impacts of DNAPL Mass Depletion in the Source Zone

The potential benefits of DNAPL source depletion have been the subject of significant on-going technical and policy debates. Private site owners generally weigh remedies in terms of their risk management benefits and potential for reducing the total life-cycle cost to achieve site closure, assuming that the remedies under consideration meet all regulatory requirements for protection of human health and the environment. Government site owners, such as the Department of Defense (DOD), the Department of Energy (DOE), and EPA Superfund-lead sites generally follow a similar process, although the details of the remedy selection process may differ from decision processes at private sector sites, particularly with respect to assumptions regarding site institutional controls and the time value of money.

Regardless of the site owner, there is a range of benefits, from a risk management perspective, that may result from DNAPL source-zone depletion. These include explicit benefits such as: 1) mitigating the future potential for human contact and exposure through long-term reduction of volume, toxicity, and mobility of the DNAPL, 2) mitigating the future potential for unacceptable ecological impacts, 3) reducing the duration and cost of other technologies employed in conjunction with the source removal technology, and 4) reducing the life-cycle cost of site cleanup. These benefits can be achieved if the source depletion option can result in the following outcomes: 1) reduction of DNAPL mobility, if mobile DNAPL is present, 2) reduction in environmental risk to receptors; 3) reduced longevity of groundwater remediation, and 4) reduction of the rate of mass discharged from the DNAPL source zone. These outcomes could then lead to enhanced efficiency of complimentary technologies used for groundwater remediation as well as potential reduction in life-cycle costs. Implicit benefits of DNAPL source-zone depletion include: 1) minimizing risks of failure of long-term containment strategies, 2) mitigating public stakeholders' concerns, 3) enhancing a company's “green image” as stewards of the environment, and 4) minimizing future uncertain transaction costs associated with management of the site.

Adverse impacts of DNAPL source depletion could include: 1) expansion of the DNAPL source zone due to mobilization of the residual DNAPL, 2) undesirable changes in the DNAPL distribution (i.e., DNAPL architecture), and 3) undesirable changes in the physical, geochemical and microbial conditions that may cause long-term aquifer degradation, and/or may adversely impact subsequent remediation technologies. All of these adverse impacts could increase life-cycle costs of site cleanup.

Quantitative predictions of these potential benefits and adverse impacts to aid decision making on whether to implement DNAPL source depletion actions are highly uncertain. These uncertainties remain as significant barriers to more widespread use of source depletion options.

Appropriate Metrics for Performance Assessment

The Panel assessed the technical basis for using drinking water standards, such as Maximum Contaminant Levels (MCLs), as the single performance goal for successful DNAPL source-zone remediation and the use of chemical analyses in groundwater samples from monitoring wells as the primary metric by which to judge performance of groundwater remediation systems. Although an MCL goal may be consistent with prevailing state and federal laws for all groundwater considered a potential source of drinking water and is a goal that is easily comprehended by the public, this goal is not likely to be achieved within a reasonable time frame in source zones at the vast majority of DNAPL sites. Thus, the exclusive reliance on this goal inhibits the application of source depletion technologies because achieving MCLs in the source zone is beyond the capabilities of currently available in-situ technologies in most geologic settings.

In recent years, there has been a trend towards the adoption of a more pragmatic regulatory approach by some regulatory agencies that are considering alternate or intermediate performance goals and phased remedial action approaches for cleanup of contaminated sites. Such flexibility may result in implementing alternative strategies for groundwater cleanup, including: 1) establishment of management zones where cleanup goals other than drinking water standards may be applied, 2) groundwater classification schemes that permit alternative remedial action goals, and 3) other flexible regulatory approaches that do not impose non-degradation requirements or drinking water standards in DNAPL source zones. These new federal and state regulatory policies provide a more encouraging climate for implementation of innovative source-depletion technologies, in those situations where partial depletion of DNAPL sources is deemed an intermediate goal as a part of phased site cleanup.

In addition to alternative goals applied to DNAPL source zones, alternative metrics other than single-point measurements from groundwater monitoring wells should also be considered. One of the alternative metrics for judging the performance of source-mass depletion technologies is contaminant mass discharge, defined as the summation at a point in time of point values of contaminant mass flux (mass per time per area) across a vertical control plane encompassing the plume and perpendicular to the mean groundwater flow direction at a location downgradient of the DNAPL source zone. Both theoretical analyses and limited field data indicate that partial DNAPL mass depletion in the source zone reduces contaminant mass discharge. The magnitude and timing of such reduction are strongly governed by the site hydrogeology, the contaminant mass distribution (DNAPL and non-DNAPL masses), and the type and method of application of the source-depletion technology. Because a sufficient knowledge base does not yet exist to specify the level of mass discharge reduction needed to achieve site-specific benefits, such as risk reduction and reduction of the time lag between source remediation and mass discharge reduction, additional research will be necessary before this metric can be used to quantify the benefits of DNAPL source depletion.

Adequacy of Site Characterization Technologies

Site characterization tools are available to measure most of the performance metrics discussed. Because of the inherent complexities of DNAPL migration and distribution in subsurface environments, none of the available characterization tools is without limitations on suitability and accuracy. The current status of site characterization tools has been thoroughly reviewed in the literature, and several recent summaries provide adequate information for selection of the appropriate site characterization tools for the purposes of selection, design, and performance assessment of DNAPL source depletion technologies.

The Panel concluded that available technologies are adequate to locate and delineate the suspected DNAPL source zones. However, in practice, locating the DNAPL source zone and determining the actual mass and spatial distribution of the DNAPL mass is very difficult, and will only be possible with extensive sampling at the majority of sites. The cost and level of accuracy achievable by source-zone characterization tools can only be answered on a site-specific basis. Further investment by EPA and other governmental agencies in determining the level of accuracy required for source-zone characterization tools as a function of subsurface geologic conditions, DNAPL characteristics and distribution, and a specific DNAPL depletion technology is warranted.

New techniques for monitoring groundwater flow and contaminant mass flux and mass discharge rate have been developed, but to date, these methods have not been field tested at sufficiently diverse sites. Further guidance on the reliability, accuracy, and cost of mass flux and mass discharge rate monitoring techniques may be forthcoming based on research funded by DOD and other agencies.

Performance of Source-Zone Mass Depletion Technologies

Over the past two decades, a large body of information has been developed on the performance of source-zone mass depletion technologies. Hundreds of pilot-scale site trials using innovative in-situ technologies have been conducted in DNAPL source zones, although a much smaller number of full-scale source depletion projects have been reported. In addition, various federal (EPA, DOE, DOD) and state agencies (e.g., Interstate Technology Regulatory Council, "ITRC") have compiled information on source depletion technologies and case studies of the application of DNAPL source depletion technologies, and this information is available on the respective web sites of these organizations. Additional information on the cost and effectiveness of source-zone depletion technologies is expected within the next year based on reported surveys conducted by the U.S. Navy (at over 170 sites) and the ITRC committee on DNAPL source remediation case studies.

Many of these studies report that substantial quantities of DNAPL mass have been removed from the subsurface. A few case studies are included in this Report where Panel members had first-hand knowledge. Based on this body of knowledge, the Panel concluded that several technologies are sufficiently developed and ready for deployment at DNAPL-impacted sites. These include thermal technologies, in-situ surfactant/cosolvent flushing, and in-situ chemical oxidation. In-situ biodegradation is the one technology evaluated that is still in an early developmental stage although even this technology has been implemented as a final remedy at several DNAPL sites. Combinations of different source depletion technologies have also not been widely tested or evaluated.

Although the Panel did not have the resources to evaluate this information on technology performance and costs in detail, it is clear that large quantities of DNAPL can be removed from source zones, with the magnitude of the removal highly dependent on site-specific and technology-specific factors. However, it is highly uncertain that MCLs can be achieved in source zones impacted with DNAPLs in most geologic settings. Nonetheless, a number of DNAPL sites have received no further action letters, indicating that regulators were satisfied that the remedial action objectives had been achieved in the source zone. It is clear that site closure of DNAPL-impacted sites may be possible depending upon site conditions, but such cases may be the exceptions rather than the rule at this time.

Source-zone containment has been a goal adopted at a large number of DNAPL sites, and groundwater pump-and-treat, cut-off walls, or permeable reactive barriers have been effectively implemented. In the long term, containment has the disadvantage of requiring continued maintenance of effectiveness and the associated perpetual financial burden. In addition, long-term effectiveness of the containment strategies is not assured. The Panel found only a few case studies where rigorous monitoring data have been used to assess the benefits of source containment for long-term plume management.

Although source depletion technologies are capable of removing substantial amounts of the DNAPL in source zones at sites with favorable hydrogeologic conditions (i.e., less heterogeneous and more permeable subsurface conditions), achievement of drinking water MCLs in these source zones as well as source zones in more challenging heterogeneous hydrogeologic conditions (e.g., bedrock, karst systems, multiple stratigraphic units) is unlikely. However, these technologies are capable of achieving partial DNAPL depletion, which may provide other performance benefits, including eliminating the mobility of the DNAPL, and reduction in the mass discharge rate of DNAPL constituents from the source zone, which may reduce environmental risks and life cycle costs.

Factors Limiting Application of Source Depletion Technologies

Several obstacles have prevented widespread application of source-zone depletion technologies. These include: 1) setting of remedial action objectives (such as achieving MCLs in the source zone) that are likely to be technically impractical within a reasonable time frame, 2) uncertainty of the long-term effectiveness and cost of source depletion and length of time before site closure, 3) the lack of well-documented case studies that could reduce the uncertainties regarding the effectiveness of source depletion technologies, 4) lack of availability of insurance to mitigate the risks of failure of source-zone remedial actions, and 5) the limited number of technology vendors, which adds to uncertainties of cost, risk of failure, and risk of bankruptcy by the vendor. An additional uncertainty at most sites is the fraction of the contaminant mass in the DNAPL source zone that may be present in diffusion-controlled, low-permeability zones. If the metric for successful remediation is achievement of MCLs, the source depletion goal must include depletion of the dissolved and sorbed phase mass in addition to the DNAPL mass. In-situ technologies for source-zone depletion are generally limited in their ability to remove contaminant mass from these low-permeability zones; however, thermal technologies may overcome this limitation at some sites. On the other hand, it is likely that continued release of contaminants from these low-permeability zones will be at mass discharge rates substantially lower than those prior to source depletion. Whether this reduction in source-zone mass discharge would be sufficient to warrant implementation of the source depletion technology is not currently predictable, and remains an important research topic.

Adequacy of Tools to Predict Performance

Reliable (validated) modeling codes and decision tools along with associated data are not currently available to: 1) predict the performance of DNAPL source-zone remediation technologies, 2) predict the beneficial and adverse impacts after the remediation is attempted, and 3) guide the decision process for selecting technologies or end points. The Panel concluded that quantification of explicit benefits, such as the reduction of risks and cost liabilities after partial source depletion, is an exceptionally difficult task and that much of the difficulty results from the inherent uncertainty in determining the magnitude and distribution of the DNAPL source zone mass prior to remediation.

Uncertainties in predicting remedial performance, life cycle costs, and benefits confound both economic and technical analyses and comparison of technical options for DNAPL source-zone depletion. A strategy for achieving benefits from partial source mass depletion would be to reduce contaminant mass discharge to a level less than the natural attenuation capacity within the dissolved plume. Under such conditions, the contaminant mass discharge for the DNAPL constituents becomes less than the rate of contaminant degradation in the plume and, as a result, the plume gradually shrinks until a new, smaller steady state plume is achieved. Such a strategy is most likely to be beneficial for small DNAPL source zones at sites that are inactive. However, at many chlorinated solvent sites, natural attenuation by microbial degradation is ineffective because of inadequate microbial and geochemical conditions in the plume, and modifications of these conditions will be necessary to achieve acceptable degradation rates or dispersion to be protective of potential receptors.

On Making the Decision to Undertake Source Depletion

The Panel recognizes that the decision to implement source-zone depletion technologies for DNAPL site remediation is based on highly site-specific conditions and criteria, and that numerous regulatory, technology, and stakeholder factors must be considered. The current decision process, as practiced in the U.S., has generally resulted in selection of containment over source depletion. The Panel concluded that new approaches to this decision process are needed. Therefore, the Panel considered two distinct options for developing an improved decision analysis framework: one based on a qualitative, semi-empirical analysis, and the other based on a quantitative model-based analysis. The Panel recognizes that neither of these options has been formally used at DNAPL sites for decisions on whether to implement source-depletion technologies, but the Panel urges EPA to consider the utility of qualitative approaches as a screening level tool for evaluating the appropriateness of source depletion compared to containment, and to assess the feasibility of developing a quantitative model that can account for a broad range of potential costs, benefits, and negative impacts from implementing DNAPL source-depletion technologies.

Knowledge Gaps and Research Needs

The Panel found that although much information on DNAPL source depletion has been developed, knowledge gaps still exist regarding the effectiveness and cost of these technologies for DNAPL source removal in a wide range of hydrogeologic settings. Research is needed on the following topics: 1) development, verification, and comparison of alternative technologies for measuring mass flux and mass discharge from DNAPL source areas before and after source depletion, 2) development of improved predictive tools to estimate the benefits and adverse effects of partial source depletion for a range of DNAPL treatment technologies and DNAPL distribution and geologic scenarios, 3) continued field testing of DNAPL source-depletion technologies incorporating more than one technology (e.g., thermal, in-situ flushing, or in-situ chemical oxidation combined with biodegradation), 4) development of guidance on the conditions in which source depletion is not likely to be an effective strategy, 5) assessment of the long-term water quality impacts of source-depletion technologies, and 6) development of quantitative decision analysis tools that will permit an accounting of all potential costs, benefits, and adverse impacts of partial DNAPL source depletion.

A key knowledge gap is estimating the fraction of the total universe of DNAPL-impacted sites that would benefit from partial DNAPL depletion from the source zone. The Panel consensus was that partial DNAPL source depletion will have benefits at a portion of DNAPL-impacted sites, but the Panel did not have sufficient information to reach consensus, and was not willing to speculate. Resolution of this knowledge gap is a major research need and would provide the necessary foundation for expanded support of research and development programs on the issues raised in this Report. In the meantime, market forces and regulatory mandates will likely determine the extent to which DNAPL source-zone depletion technologies will be applied.

In the past decade, major advances have been made in technologies for characterization and performance assessment of remedial actions of DNAPL source zones, but there is need for additional advances. Part of the cost of applying an innovative technology for source mass depletion includes the cost of additional site characterization needed for technology selection and remedial design based on the choice of performance metrics. A major challenge is the identification of the degree of characterization and post-remediation monitoring necessary for effective application of each of the in-situ source depletion technologies. Research is needed to establish guidance for practical source-zone characterization keyed to the available technologies.

Conclusions

In the final analysis, the Panel concluded that partial mass depletion from DNAPL source zones has been a viable remediation strategy at certain sites and is likely to provide benefits at a number of additional sites. However, barriers to more widespread use of DNAPL source-zone technologies persist. Additional theoretical analysis and assessment tools (performance prediction tools; cost-benefit assessment tools; technology failure analysis; reliability of long-term management), improved monitoring techniques (site characterization; performance assessment), and field scale demonstrations that elucidate benefits of partial source depletion are needed to provide a more informed basis for decision-making on whether to undertake DNAPL source-zone depletion at both sites with a containment remedy in place and at new DNAPL sites. This information will also provide a basis to estimate the proportion of DNAPL-impacted sites that would be candidates for implementation of source-depletion technologies. At some DNAPL sites, containment may be the only viable remedial action, and at such sites, containment may be considered a “presumptive remedy” eliminating the need for costly additional studies. The Panel urges EPA to provide appropriate guidance for defining the conditions under which DNAPL source remediation would be a viable option for site cleanup compared to a containment-only option using the broader definition of benefits of this strategy as discussed in this Report.

The current strategy of source-zone containment has generally proven reliable for limiting routes of human and ecological exposure to chemical contaminants emanating from DNAPL-impacted sites, provided that the containment system (e.g., pump-and-treat, or permeable barriers) has been properly designed and maintained. However, this strategy poses long-term risks, transfers the burden of site management to future generations, and requires long-term financial stability of the responsible parties. Furthermore, these long-term risks are generally difficult or impossible to quantify accurately. It is thus imperative that sufficient resources be devoted to resolving the many uncertainties that this Panel has identified in DNAPL source-zone characterization and depletion technologies to ensure that source depletion at DNAPL sites is implemented to the maximum extent practicable.

Recommendations

The Panel’s specific recommendations to EPA are as follows:

1. Expand the existing EPA program for research, demonstration projects, and technology transfer to address and reduce the uncertainties in predicting and verifying the benefits and undesirable impacts from application of DNAPL source-zone depletion technologies.

2. Continue to support demonstration efforts to develop, test, and validate the most promising innovative and emerging technologies for DNAPL source-zone characterization and mass depletion.
3. Develop a new guidance document for source-zone response actions at DNAPL sites that provides a road map for decision makers to determine if implementation of source depletion technologies is appropriate.
4. Conduct a thorough and independent review of a selected number of DNAPL sites where sufficient documentation is available to assess the performance of source depletion using multiple metrics.
5. Develop and validate technologies for cost-effective and accurate measurement of mass flux and mass discharge from DNAPL source zones, and determine how these measurements relate to risk management decisions.
6. Evaluate impacts of source depletion technologies on long-term aquifer water quality.
7. Develop and validate cost-minimization and net benefit-maximization decision models suitable for evaluating the complete spectrum of costs, benefits, and negative impacts of source-depletion technologies.