
5.0 Conclusions and Recommendations

The DNAPL Expert Panel was charged with evaluating the following four key issues related to source remediation at DNAPL impacted sites:

- 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 response to this charge, the Panel generated seven questions to provide the technical basis for addressing each of these issues and to provide recommendations on strategies to address the overarching issue posed in the title of this Report, namely, can a case be made for undertaking DNAPL source-zone depletion at sites with contaminated groundwater? Based on the Panel's responses to those questions and other information presented in this Report, the Panel presents the following conclusions and recommendations.

5.1 Conclusions

a) Status of Technology Development and Deployment for DNAPL Source Remediation

1. Substantial progress in development and deployment of technologies for DNAPL source-zone characterization and mass depletion has been made in North America and Europe over the past two decades.
2. Available site characterization technologies are capable of bounding the locations of DNAPL sources in the subsurface in both the horizontal and vertical directions. The accuracy of DNAPL source-zone definition, however, is highly site-specific.
3. Even when a large effort is conducted for DNAPL source-zone site characterization using the best available technologies, uncertainties in the estimate of the total DNAPL mass present in the source zone will be large at many DNAPL-impacted sites because of the effects of geologic heterogeneity and the spatial heterogeneities in DNAPL distribution.
4. Even at those sites where DNAPL source zones have been delineated, and the initial mass of DNAPL present has been estimated within a factor of two to four, it is difficult to determine if the DNAPL mass has actually been depleted from the subsurface, degraded into other chemicals, or been moved or displaced to another subsurface location following source depletion. This problem has been clearly demonstrated from the results of highly controlled DNAPL release studies at the Borden and the Dover Air Force Base sites or the recent source depletion tests at the Cape Canaveral site as summarized in Appendix A.
5. Both conventional technologies (pump-and-treat, excavation) as well as innovative in-situ technologies are capable of partial DNAPL source-zone depletion. In a large number of pilot-scale studies of source-zone DNAPL removal as well as in numerous full-scale implementation projects, mass depletion greater than 90 percent has been claimed. However, the Panel cautions that reported mass depletion levels as a percentage of the initial mass are highly uncertain due to the uncertainty in estimating the initial mass of DNAPL prior to source depletion.
6. As far as the Panel is aware, there is no documented, peer-reviewed case study of DNAPL source-zone depletion beneath the water table where U.S. drinking water standards or MCLs have been achieved and sustained throughout the affected subsurface volume, regardless of the in-situ technology applied. Nonetheless, at a number of DNAPL-impacted sites, closure of the sites has been reported signifying achievement of RAOs.
7. Although numerous site trials have been conducted by both private and government entities for DNAPL source-mass depletion using innovative technologies over the past 15 years, comprehensive documen-

tation on the effectiveness of source-mass depletion and resultant effects on groundwater quality within the source zone and in the downgradient plume is available for only a few sites. Documentation on plume improvements following source containment is also lacking. Such documentation would provide important insights on the benefits that could be achieved even with partial DNAPL source depletion. Recent EPA publications (*U.S. EPA, 2003*) and a recent (2003) survey being conducted by the U.S. Navy may fill some of the gaps in this information base.

8. Results of more recent laboratory and theoretical analyses have indicated that partial source depletion of DNAPL in certain geologic settings using available in-situ technologies may provide quantifiable benefits including: 1) more rapid achievement of conditions conducive to monitored natural attenuation as the accepted remedy for the groundwater at the site, and 2) lower life cycle costs associated with treatment trains used to remediate both the source zone and the dissolved plume.

b) Assessment of Source Remediation Performance Goals and Metrics

1. Source remediation performance goals and metrics currently used to evaluate the “success” of source depletion technologies are limited in number. The dominant goal employed by the regulatory community for groundwater considered a potential source of drinking water is U.S. drinking water standards for all regulated chemicals. Thus, achieving MCLs in the source zone is the primary goal of DNAPL source depletion in the U.S., and verification of achieving that goal is defined by groundwater point samples collected from compliance monitoring wells.
2. Although the MCL goal may be consistent with prevailing state and federal laws, and easy to communicate to public stakeholders, this goal is not likely to be achieved at the vast majority of DNAPL sites in the source zones. Thus, the exclusive reliance on this goal inhibits the application of source depletion technologies because achieving this goal is generally beyond the capabilities of available in-situ technologies in most geologic settings. Changes in the regulatory climate based on increased knowledge of the technical impracticability of achieving MCLs in the source zone and knowledge of the potential benefits of partial DNAPL depletion should establish a context for increased consideration of DNAPL source-zone depletion technologies at sites with a containment remedy (e.g., pump-and-treat) in place as well as new sites with no remedy in place.
3. The use of the MCL goal as the single measurement of “success” does not account for other potential benefits of DNAPL source depletion. These may include a number of risk management benefits including: a) reduction of DNAPL mobility, b) reduced longevity of the plume source, c) reduction in mass flux and mass discharge from the source zone, and d) enhanced efficiency and effectiveness of complementary source-zone control technologies.
4. Although the Panel did not conduct a detailed review of regulatory requirements at DNAPL sites throughout the U.S., the Panel is aware of other goals that have sometimes been used at sites for remediation of DNAPL source zones. These have included: 1) mass removal goals, 2) removal of DNAPL “to the extent practicable,” and 3) removal or stabilization of “mobile” DNAPL. It also appears that regulatory agencies at the state and local level are proposing more flexible regulatory strategies for DNAPL source zones, which may result in a greater range of acceptable remedial action objectives for the source zone other than meeting MCLs throughout the contaminated zone. The Panel cannot confirm how widespread this new flexibility exists, but at the least, regulators are becoming fully aware of the need to consider benefits of partial source depletion other than meeting MCLs in the source zones.
5. Multiple metrics will provide a more comprehensive basis for performance assessment of DNAPL source-zone depletion technologies. Use of alternative metrics such as reduction in mass flux and mass discharge from the source area is conceptually and scientifically appealing, but use of this metric is still in a research mode. This metric has not yet been embraced by the regulatory community for various reasons including uncertainties in the reliability and accuracy of current measurement techniques. Recently, regulators have expressed increased interest in these metrics, and efforts are now underway to assess their applicability for compliance and performance assessment purposes.
6. For a few metrics, multiple measurement methods are available, but for others, including mass flux and mass discharge, the methods are not proven, and are currently under development.

c) Evaluation of Costs and Benefits of Source Remediation

1. DNAPL source-zone depletion can provide explicit and implicit risk management benefits. Explicit benefits include: a) mitigating the potential for human contact and exposure, and the potential for unacceptable ecological impacts, b) reducing the duration and cost of other technologies employed in conjunction with the source removal technology, and c) reducing the life-cycle cost of site cleanup. Implicit benefits may include: a) minimizing risks of failure of containment strategies, b) satisfying public stakeholders'

concerns, c) enhancing companies' "green image" as stewards of the environment, and d) minimizing future uncertain transaction costs associated with management of the site.

2. Information on the costs and benefits of source depletion is limited. Cost data for source depletion are available from governmental agencies and from technology vendors, but it is difficult to translate these costs from one site to another. In addition, it is not yet possible to estimate life-cycle costs following source depletion because of uncertainties in predicting the impact of source depletion on duration of the groundwater remedial action.
3. Few, if any, studies on source-zone depletion have evaluated all costs associated with source-zone remediation. Because few DNAPL-impacted sites have achieved site closure, information on capital and annual O&M costs for successful source-zone remediation is limited.
4. Cost data can be obtained from vendors for several of the source-zone depletion technologies, and these data allow for the economic comparison of alternative strategies for remediation of the source zone. A simple engineering economics analysis presented in this Report compares the costs of DNAPL (creosote) source removal at the Visalia site with the life cycle costs of the pump-and-treat system previously employed for source containment. The relative economic benefits of source depletion options are strongly dependent on the net discount rate assumed when considering the time value of money. In a low discount rate environment, source depletion may be cost-effective, but at interest rates above five percent, the life cycle costs of the containment option appear to be lower than the costs for source depletion. Use of this simple engineering economics approach is helpful in bounding the range of costs for source depletion technologies that would potentially be cost-effective compared to containment remedies. An assessment of economic benefits is only one of the potential benefits that should be evaluated when making a source remediation decision.
5. Risk management benefits are difficult to quantify because of inherent uncertainties in predictions related to the effectiveness of source-zone depletion and the impact of DNAPL source-zone depletion on overall site closure. Translation of implicit risk management benefits into monetary terms presents even greater challenges that have not yet been addressed.
6. Because of the limitations in available tools for predicting the effectiveness of source depletion technologies, estimating the monetary value of all explicit and implicit benefits, and estimating the overall cost impact of applying these source-zone depletion technologies, decision-making based on classic risk/benefit calculations is inherently limited. The degree of uncertainty in the costs and benefits of applying source depletion technologies is currently at levels that discourage widespread use of the available source depletion technologies at DNAPL sites.

5.2 Recommendations

The Panel provides the following recommendations to the U.S. EPA.

1. Fund research, demonstration projects, and technology transfer to address and reduce the uncertainties in quantifying the benefits from source-zone depletion.

Uncertainties in quantifying the economic benefits of DNAPL source-zone depletion are a major barrier to the use of source remediation technologies. The research needs identified in Section 4.0 should be part of EPA's program to address these uncertainties. To determine the appropriate level of funding, EPA should conduct an inventory of DNAPL sites throughout the U.S. to confirm the magnitude of the problem and to assess the potential reduction in life-cycle costs from increased application of source depletion technologies compared to containment strategies. EPA should build on the results of the recent survey conducted by the U.S. Navy on the use of DNAPL source depletion technologies at over 175 sites.

2. EPA, in cooperation with other agencies and private industry, should continue support of demonstration efforts to develop, test, and validate the most promising technologies for DNAPL source-zone characterization and mass depletion.

Cost-effective and reliable technologies are needed to improve the accuracy of locating DNAPL sources, estimating the magnitude of the DNAPL source, and quantifying the distribution of the DNAPL. Current techniques show promise but are limited in accuracy and/or are costly. All of the in-situ source depletion technologies have advantages and disadvantages, depending on the site-specific conditions. Knowledge of the effectiveness and cost of thermal technologies, surfactant and co-solvent technologies, and ISCO is most advanced for DNAPL source depletion. However, uncertainties persist, and additional demonstration projects that are fully documented are needed. There is a particular need for performance and cost data for DNAPL source-zone depletion technologies in fractured systems.

3. EPA should provide 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.

Given the sparse use of the TI waiver policy at DNAPL sites, and the limited number of source removal actions that have been undertaken, a new guidance document should be prepared for use by decision-makers to determine if source depletion technologies should be implemented given site conditions and the institutional setting. This document should build on the large amount of information compiled by various federal agencies, state agencies, universities, and private sector initiatives on the cost and effectiveness of DNAPL source depletion technologies. The document should include detailed guidance on how to conduct technology demonstrations in a credible manner. EPA should develop protocols to permit a quantitative assessment of the appropriate potential remediation category in which to assign a DNAPL site. As part of this protocol development, EPA should review a representative sample of DNAPL sites in the U.S. to determine the estimated proportion of sites that would be considered for three categories, namely: a) strong candidate for DNAPL source depletion, b) potential candidate for DNAPL source depletion, and c) not suitable for application of DNAPL source depletion technologies. The guidance document should also discuss the use of alternative remedial action goals other than achievement of target cleanup levels in the source zone and the value in using alternative performance assessment metrics.

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 a multiple of metrics.

The need for well-documented case studies of remedial technology application and performance in a variety of geologic and DNAPL distribution scenarios is apparent. The currently available documentation on these studies is substantial, but limitations in the performance evaluation and accuracy of cost estimates contribute to the reluctance by decision-makers to implement source depletion technologies at many DNAPL sites. There is also a critical need for the validation of process-based model performance predictions at the field scale. Without these models, the long-term benefits of source depletion cannot be quantified in any meaningful way. This effort should include the development of parameter estimation guidance, guidance on scale-up of pilot scale studies, and more simplified modeling tools that can reliably predict remedial aggregate performance and its associated uncertainty under diverse geologic and chemical conditions.

5. Develop and validate technologies for cost-effective and accurate measurement of mass flux and mass discharge from DNAPL sources zones.

Measurements of the distribution of mass flux and the mass discharge from a source zone may provide new metrics for assessing the performance of source-zone depletion technologies. Research into technologies to measure these metrics accurately has only recently begun. Field experiments are needed to verify theoretical predictions that DNAPL removal from the more permeable zones in an aquifer may substantially reduce mass discharge from source zones. Furthermore, the benefits of this reduction as they relate to risk reduction must be quantified. EPA should support the development and validation of these technologies, building on research efforts currently funded by the Department of Defense through the Strategic Environmental Research and Development Program (SERDP).

6. Evaluate impacts of source depletion technologies on long-term aquifer water quality.

Demonstration projects conducted over the past decade have focused primarily on the effectiveness of DNAPL mass removal by candidate source depletion technologies. Few projects have considered the long-term water quality impacts of source depletion technologies. EPA should conduct necessary post-remediation studies to verify that long-term impacts of source depletion technologies will not be deleterious to future beneficial uses of the groundwater.

7. Develop and assess the suitability of cost-minimization and net-benefit maximization decision models for evaluating the complete spectrum of costs and benefits of source depletion technologies.

Current economic and financial models, used to make decisions on whether source depletion should be undertaken, have a number of limitations as discussed in this Report. The development and validation of a much more comprehensive economic model such as a cost-minimization or net-benefit maximization approach may provide important insights into the current tradeoffs between DNAPL source containment and long-term institutional controls compared to the generally significant capital cost of source depletion technologies. The practical benefits of this approach should be assessed by EPA, and if found to be feasible, such a model should be further developed, validated, and made available for practitioners and regulators.

6.0 List of References and Bibliography

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