LBNL-51386

SCFA LEAD LAB TECHNICAL ASSISTANCE AT LAWRENCE BERKELEY NATIONAL LABORATORY:

BASELINE REVIEW OF THREE GROUNDWATER PLUMES

SCFA Technical Assistance Request #114
Lawrence Berkeley National Laboratory
May 15-16, 2002

Disclaimer

TABLE OF CONTENTS

EXECUTIVE SUMMARY

On May 15-16, 2002, a technical assistance team from the U.S. Department of Energy (DOE) Subsurface Contaminants Focus Area (SCFA) met with the Lawrence Berkeley National Laboratory (LBNL) Environmental Restoration project leader and the DOE - Oakland (DOE-OAK) Project Manager to review the baseline remediation plans for three groundwater plumes at LBNL. The technical assistance request sought recommendations for cost-effective remediation, an evaluation of the adequacy of current plans, and suggestions for improving existing remediation plans. The three plumes of interest were identified as the highest priority plumes on the site: the tritium plume originating from the National Tritium Labeling Facility (NTLF), the Old Town Area Solvent Plume, and the Building 51/64 Volatile Organic Compound (VOC) Plume.

The technical assistance team was composed of leading technical experts from LBNL and other national labs and was assembled by SCFA's Lead Lab in response to a technical assistance request from Hemant Patel, Environmental Restoration Project Manager for LBNL at DOE-OAK (Technical Assistance Request #114, see Appendix A). A list of the technical assistance team members and names and contact information for all meeting participants are in Appendix B. Background information on the expertise of each technical assistance team member is in Appendix C. The technical assistance request is part of a voluntary effort by the LBNL Environmental Restoration Program to obtain support to optimize the baseline cleanup for three challenging LBNL groundwater plumes. Specifically, the goal was to identify potential technical enhancements to the program and to verify that selected remediation strategies are feasible and reasonable. Since the site is in the Corrective Measure Study phase of its Resource Conservation and Recovery Act permit, there is still an opportunity to select different technologies. In addition, the site is under pressure to close by 2006 and would like assistance in accelerating that schedule. At this site, closure means to build out the remediation systems and transfer long-term surveillance and maintenance to the DOE Office of Science.

Iraj Javandel, the lead for LBNL's Environmental Restoration Program, presented an overview and details about each plume to the technical assistance team. In the afternoon of the first day of the meeting, he led the team on a tour of the site, describing the source terms and distribution areas of the plumes, locations of the monitoring wells, and interim corrective measures the site is undertaking. Of particular interest was the proximity of wells with different detection levels; in some locations, wells only 10 feet apart produce vastly divergent measurements. On the tour and through presentations, he conveyed the complexity of the geological and hydrogeological conditions that lead to frequently perplexing results from the monitoring wells.

After the tour, Jens Birkholzer, LBNL, presented to the team the progress thus far on the LBNL site restoration model, the objectives of which are to predict the fate of contamination and evaluate different cleanup and containment strategies. The model incorporates three-dimensional finite volume, flow and geochemical transport, geologic layers, hydraulic features, and engineered structures. The model will be based on data

through 1996 and its accuracy will be verified by comparing its predictions to actual data from 1996-2002. The team also heard a presentation from Mark Conrad, LBNL, summarizing the stable isotope analysis that suggests naturally occurring biodegradation of specific VOCs at the Building 51/64 plume.

On the morning of the second day, the technical assistance team internally identified and discussed overall issues of critical concern, as well as issues for each of the three high priority plumes. The critical issues that the technical assistance team identified are listed below.

Overall Critical Issues

- Possibility of the presence of tritium underneath Buildings 6, 51, and B88, the legacy from high energy accelerators
- Waste designation for water containing perchloroethylene (PCE) and tritium at various concentration/activity levels; this definition has a large impact on management and treatment
- Setting cleanup goals as flux reduction instead of Maximum Contaminant Level (MCL); treating to MCLs (or lower) creates additional cost and remediation time with negligible effect on overall risk
- Geology – heterogeneity of the subsurface, difficulties in characterization, monitoring, modeling, and remediation
- Hydrology – multiple flow paths, range in hydraulic conductivity, difficulties in characterization, monitoring, modeling, prediction, and remediation
- Subsurface interferences from buildings, pipes, fill, etc.
- Characterization challenges – the combined synergistic effect of geology, hydrology, contaminants, interferences, and sampling accessibility increases the level of difficulty to complete characterization
- Public acceptability – the emphasis on no environmental degradation makes remediation and life-cycle costs technically impractical
- Institutional memory – the site needs more succession planning for the environmental restoration personnel
- Meeting the 2006 built-out schedule for DOE – Environmental Management closure

For each of the three plumes, the team identified critical and unresolved issues and evaluated all currently available remediation strategies, summarized in a matrix highlighting the various features of each strategy (see Appendix D). The team formulated specific recommendations for each groundwater plume as well as overall recommendations for the site. Figure 1 (on page 2) is a map showing the location of each plume on the LBNL site.

National Tritium Labeling Facility (NTLF) Plume

Critical Issues

- Definition of the activity of tritium to be used for controlling future actions
- Public acceptability of cleanup goals that are reasonable in terms of risk

Unresolved Issues

- Structural features controlling flow need additional characterization (Note: this is currently in progress)
- Chemical speciation of tritium, especially in regards to organically bound tritium

Recommendations

- Explore the possibility of ^{3}He/tritium dating for better definition of plume travel times.
- Confirm that the tritium near the NTLF is tritiated water to help plan future activities.
- If a recirculation strategy is used, conservative tracers should be utilized to estimate travel times and capture efficiency.
- Take advantage of structural features when designing remedial systems.

Old Town Plume

Critical Issues

- Residual source of VOCs
- Subsurface heterogeneity
- Interferences

Unresolved Issues

- Performance of thermal enhancements for soil vapor extraction
- Performance and value of current modeling effort
- Detection of trace levels of benzene in deep wells

Recommendations

- Continue to evaluate additional technologies for source removal.
- Continue to evaluate additional technologies for plume control.
- Continue modeling to assist in remedial design and communication.
- Develop a long-term strategy for managing the plume that includes phasing in more passive technologies for control and treatment and eventually monitored natural attenuation.

Building 51/64 Plume

Critical Issues

- Low permeability, geologically heterogeneous subsurface with slow rates of biodegradation of VOCs

Unresolved Issues

- Better definition of the vertical and horizontal extent of the plume to resolve uncertainties in the contaminant concentration gradients and document changes over time
- More feasibility studies on monitored natural attenuation as a treatment option

Recommendations

- Monitored natural attenuation is the most promising remediation strategy for this site, but it needs better documentation of shrinking plumes over time, biological activity, in situ biodegradation potential for contaminants of concern, and better documentation of production of daughter products and changes in carbon stable isotopic ratios that validate in situ biodegradation of the contaminants of concern.

- The 51/64 plume should be used as a template for negotiating cleanup efficacy standards for other VOC plumes at LBNL.
- Passive remediation strategies, such as passive bioremediation and chemical reactive barriers should be considered as a supplement to monitored natural attenuation since they could significantly decrease time and cost of the remediation of this plume.

On the afternoon of the second day of the meeting, the technical assistance team held a closeout session with project leaders from the site. The purpose was to inform the site of the team's recommendations and verify that the team had addressed all issues of concern to the site. Overall recommendations are listed below.

Overall Recommendations

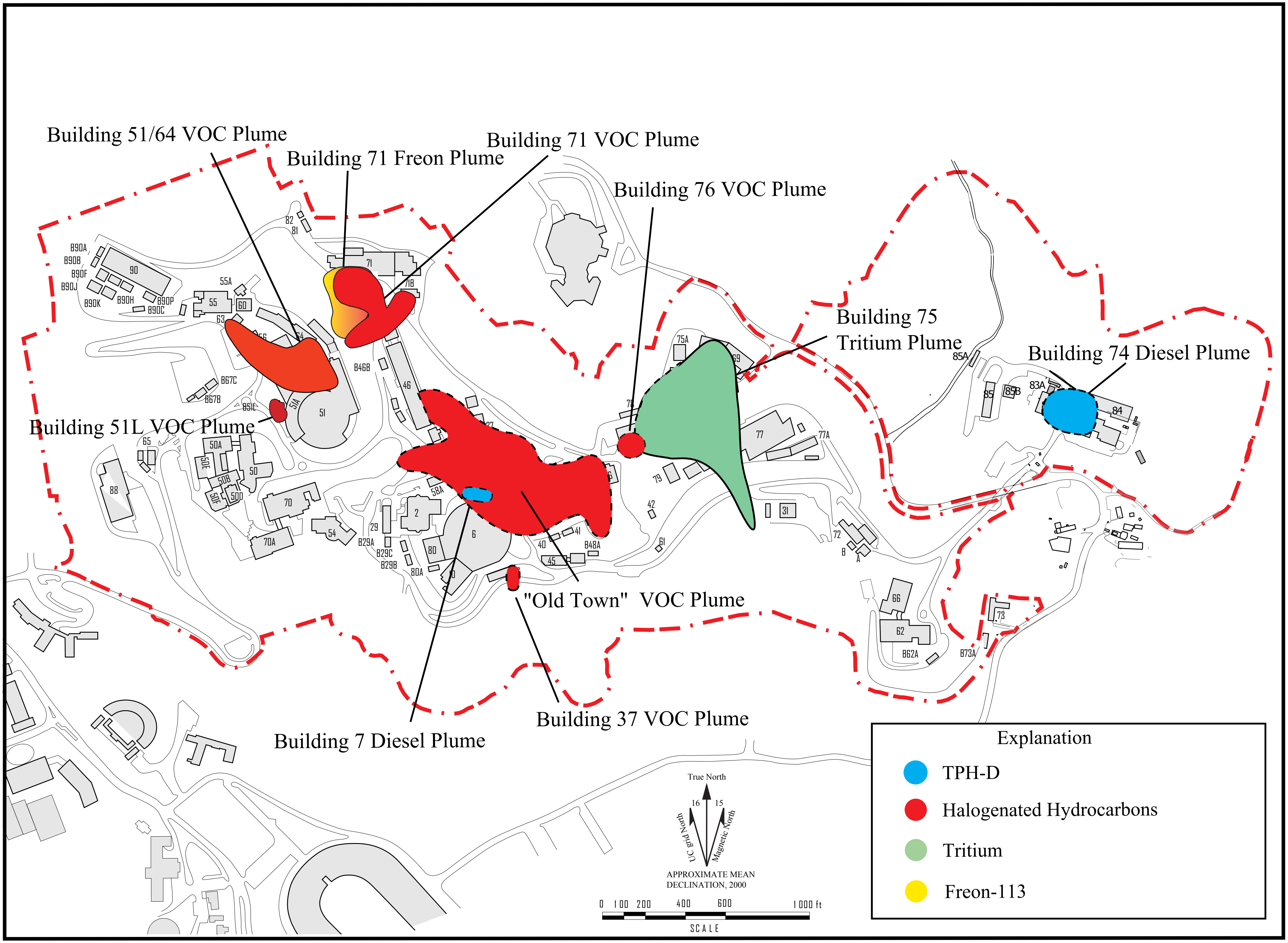
- The site has done a phenomenal job on characterization and identifying and removing source terms.
- Technologies selected to date are appropriate and high impact; e.g., collection trenches are an effective remedial strategy for the site's complicated geology. LBNL should continue using technology that is adapted to the site's unique geology.
- The site should consider developing cleanup criteria that are based on risk and the specific geology, hydrology and cultural influences for each site.
- Modeling to assist in remedial design and communication should continue.
- A plan to ensure institutional memory should be developed.
- The site should give high priority to removing the residual source of the Old Town plume and establishing the efficacy of remediation or monitored natural attenuation for the Building 51/64 plume.

The recommendations for each plume are discussed within the specific plume sections of this report.

1.0 ISSUE ANALYSIS

The technical assistance team identified issues critical to the successful and expedient remediation of the three groundwater plumes being considered in this baseline review. This section presents the critical issues and a brief overview of how these issues might impact restoration activities.

The technical assistance team met with key Environmental Restoration Program project staff on May 15, 2002. Lead scientist Iraj Javandel presented information on the groundwater plumes, including an overview of the program, description of the groundwater contamination, geologic and hydrologic features of the site, and remedial efforts either previously attempted or underway. The three plumes selected for the baseline review are the three plumes of highest priority to the site: the National Tritium Labeling Facility's tritium plume, which is a sensitive public issue; the Old Town Solvent plume, for which the site has already explored many remediation approaches; and the Building 51/64 Solvent plume. The locations of these plumes within the LBNL site are shown in Figure 1.



6_plumes.ai

Figure 1. Groundwater Contamination Plumes, First Quarter FY02

5/02

1.1 Overall Issues

The issues below apply to all three groundwater plumes.

Possibility of tritium underneath Buildings 6, 51, and B88

Building 6 is the site of the Advanced Light Source, Building 51 holds the Bevatron, and Building B88 houses the 88-inch cyclotron. As locations of accelerators, there is a possibility that tritium formed from beam energy interacting with the soil and soil water is present in the subsurface beneath the buildings. High energy accelerators often have tritium contamination associated with their beam stops (Susskind 1972; Gollon 1989; Lessard 1998). Since all three accelerators operated in an energy range sufficient to produce tritium by spallation reactions with materials used for beam stops, the potential for at least some contamination exists and should be recognized, particularly at such time as the facilities are abandoned and decommissioned. Few of the wells near all three buildings have been sampled for tritium and none have yet detected tritium. There are few wells near these buildings, and none directly underneath the buildings, where contamination is most likely. Complicating this issue is the fact that the buildings are quite large and there is no easy way to sample below them. In view of the low rate of groundwater migration seen on much of the site, lack of detection in monitoring wells outside the periphery of the buildings may be inconclusive. However, downgradient wells might also be expected to show at least some tritium by now since these facilities have all been in operation for decades. In any case, given the low permeability of the subsurface at LBNL and the lack of radionuclide detection in wells adjacent to these buildings, it is unlikely that the radionuclide contamination, if present, is extensive. However, the technical assistance team feels that it is an unknown that should be addressed. Various inexpensive and rapid sampling approaches may be utilized to evaluate this issue. Collection of water, or even humid soil gas, from beneath the building (via any available access) followed by cryogenic trapping and analysis of the moisture may help elucidate this program.

Mixed waste definition of PCE and tritium

Both tritium and PCE have been detected in a well located south of B71B, which has concerned the site because of the potential for the waste to be classified as mixed, even though the tritium concentrations are far below drinking water standards within the well in question. “Mixed waste” is a term used when waste is regulated both as hazardous under RCRA and radioactive under the Atomic Energy Act. RCRA drives the regulations for cleanup of VOCs such as PCE, but not radioactive isotopes, meaning the issue is to meet cleanup standards for tritium in groundwater. The MCL for tritium in drinking water is 20,000 pCi/L, established based on an ingestion scenario in which subjects drink 2 L/day of tritiated water and an inhalation scenario in which subjects inhale moist air contaminated with tritium. The Nuclear Regulatory Commission exemption limit for tritium concentrations is 30,000 pCi/L; at or below that level a license is not necessary for possession and the waste can be disposed at a hazardous-only landfill. EPA typically uses MCLs as the initial point of reference when evaluating a “no longer contained-in” interpretation (e.g., if the groundwater contained RCRA hazardous constituents at concentrations lower than the MCL, that would usually suffice as justification to no longer manage the waste as hazardous).

Set cleanup goal as flux reduction instead of MCL
Much of the tritium plume is at concentrations below tritium's MCL for drinking water (20,000 pCi/L), but there is still intense public demand to further reduce concentrations. LBNL would like to ensure that no tritium leaves the site. The technical assistance team is concerned that the site might agree to clean up the tritium to the detection limit (200 pCi/L). Such a cleanup goal would be unwise, since it is likely that tritium at concentrations higher than the detection limit (though still below the MCL) will still occur periodically, given the reservoir of tritium in the soil and tree detritus. Defining the tritium cleanup goal as flux reduction may provide a more defensible technical basis for demonstrating that cleanup results were achieved.

The difficulty in defining flux reduction in this case is that before promising a reduction, there must be a non-zero starting point. A flux reduction could be defined on-site before reaching the creek by choosing a compliance point. However, demonstrating a reduction in flux may prove challenging due to the limited data and episodic nature of the flow. It may be necessary to quantify flow over time versus instantaneous tritium concentration.

Although not exactly the same situation, there is precedence within DOE for setting a cleanup goal as flux reduction. Savannah River has an agreement with the State of South Carolina to reduce the tritium flux in the F Area plume to Fourmile branch (an on-site stream) by 70% in the next five years. However, this is a different situation as the tritium concentrations at Savannah River are far above the current drinking water standard. Ultimately, the State wants Savannah River to reduce tritium levels in the groundwater to the drinking water standards.

A flux reduction makes sense in that the regulators may be receptive to it and the site can show that it is improving over time. The technical assistance team did not have enough information to set a meaningful flux reduction, but suggests LBNL set a standard that is achievable and shows progress towards cleanup. It is better to promise a 50% reduction and achieve a 60% reduction than promise an 80% reduction and achieve a 70% reduction. Depending on the source and transport characteristics, a limit needs to be set by personnel that are extremely familiar with the site.

Another option is to pursue setting radionuclide levels based on risk. An EPA memorandum provides guidance for establishing protective cleanup levels at CERCLA sites (EPA 1997). However, 20,000 pCi/L appears to be a widely accepted standard for cleanup criteria at DOE facilities (see `http://c2d2.eml.doe.gov/index.cfm?target=ap.cfm&medium=groundwater&contami=tritium+%28hydrogen-3%29`).

Geology - heterogeneity of the subsurface
The geology underlying LBNL is highly heterogeneous, which poses a significant challenge for remediation of the groundwater plumes, as predicting plume movement becomes very difficult. The principle bedrock units underlying the site are Moraga formation volcanic rocks, Orinda formation sediments, and Great Valley Group sediments. Moraga formation, which is relatively permeable, overlies the low permeability Orinda. The surficial units are primarily artificial fill, colluvium, alluvium, and landslide deposits. Further complicating the geology is the lack of uniformity in the Orinda formation. Within the Orinda, there are small depressions filled with landslide material, at depths that vary from 2 to 80 feet. Sometimes the depressions are

connected to the Moraga formation, the mother rock. The Old Town plume exists primarily in the landslide material, while the tritium plume is inside the Orinda Formation. This complicated geology contributes to the difficulties in characterization, monitoring, modeling, and remediation of LBNL.

Hydrology - multiple flow paths, magnitude range in hydraulic conductivity
Due to the presence of several streams, tributaries, and the extensive cut and fill operations needed to construct LBNL's facilities, there are multiple flow paths, both for surface and groundwater. Hydraulic conductivity is the primary physical characteristic that controls groundwater flow at the site. The Orinda formation has a hydraulic conductivity range between 10^{-7} to 10^{-12} m/s, while that of the Moraga formation is in the range of 10^{-4} to 10^{-6} m/s. The other geologic units exhibit hydraulic conductivity within these two extremes. Combined with the variety of flow paths and heterogeneity of the surficial and bedrock units, predicting contaminant plume movement both in time and space is very difficult.

Subsurface interferences
The subsurface is dominated by engineered structures, such as utility lines, sewers, pipes, manholes, cables, and other features. In addition to making groundwater flow more complicated to model, certain subsurface utilities affect the distribution of contamination. For example, heavy rainstorms frequently fill large manholes with rainwater that has become contaminated with tritium in the course of its runoff path. Cable traces and pipes from such manholes then act as conduits to distribute tritium through the underground utilities. In addition, some improperly constructed slope-stability wells have acted as a source of tritium distribution, although LBNL has resolved those problems.

Characterization challenges
There are many challenges involved in characterizing groundwater flow within the site: complex morphology with steep gradients, complex geological structures, vastly different hydraulic properties, transient seasonal behavior, small-scale heterogeneity, and a prevalence of subsurface utilities. The synergistic effect of all of these challenges makes characterization extremely difficult. Continued characterization is endorsed, as it is difficult to remediate the plumes when the contamination sources are not known. Characterization would also help specific remediation activities, such as optimizing placement of collection trenches. Data from soil borings reveal instances in which one borehole can be contaminated with multiple VOCs, while boreholes a few meters away reveal barely anything. Further complicating the characterization effort, use of traditional geophysical techniques has been ineffective and expensive.

Public acceptability
Public acceptance of the groundwater remediation plan is a challenge because public perceptions and values tend to favor complete destruction, which is not technically achievable or justified on a risk reduction basis. Of particular concern is the tritium plume, which is a public issue. Overall, flux is low and the tritium contamination does not mix with potable water. However, the public does not trust the government-established values for drinking water standards or radiological exposure.

Another public acceptability issue is that the public is often skeptical of natural attenuation, an approach frequently perceived as "doing nothing." LBNL should carefully configure any natural attenuation proposals based on documented detoxification mechanisms.

Institutional memory
Dr. Iraj Javandel, the senior scientist and lead for the Environmental Restoration Program at LBNL, has been working on cleaning up the site's contaminant plumes since 1989 and as such, represents a vast repository of information on all aspects of the cleanup efforts, plumes, sampling wells, and the unique challenges of the site. The technical assistance team was concerned whether that information is being captured in a team environment, and if the site has a strategic plan or succession plan that will adequately capture the vast, diverse, and irreplaceable knowledge, expertise, and leadership skills that Dr. Javandel possesses.

Meeting the 2006 built-out schedule for DOE – Environmental Management closure
The site has some unresolved issues, such as investigations under buildings, removal of residual sources, and better definition of plumes via modeling and characterization. The source removal at the Old Town plume and subsequent demonstration verification of the plume reduction strategies at all three plumes may impact the closure schedule. In addition, the length of time needed for permit review during the Resource Conservation and Recovery Act process from past experience at the site could also impact the schedule. The site is systematically and carefully dealing with issues, while increased investments might enable speeding up closure, it is doubtful that this would have a very significant impact. Since these are also active facilities with multi-million dollar research programs, characterization and remediation efforts that might only slightly decrease timelines could have major impacts on these on-going research programs.

2.0 NATIONAL TRITIUM LABELING FACILITY PLUME

The National Tritium Labeling Facility (NTLF) was established as a National Institutes of Health national resource center in 1982. The facility's role is to conduct research that assists biomedical researchers study cell metabolism and chemical reactions. Facility staff and visiting researchers "label" pharmaceuticals and other materials with tritium (replacing hydrogen atoms with tritium atoms). These labeled compounds are used to study chemical and biochemical processes.

The NTLF is located in LBNL Building 75. As part of routine operations, airborne discharges from Building 75 occurred through a 50-foot stack adjacent to and up-slope of the facility (see photo). These airborne discharges led to elevated tritium contamination in the soil and leaf litter (from trees growing in the area) in the immediate area around the stack. Over time, rainfall events have caused some of this contamination to enter the subsurface, eventually reaching the groundwater. In addition, liquids containing tritium were discharged through a sanitary sewer line. A break in the sanitary sewer line introduced a very small amount of contaminated water into the subsurface. This leak has been repaired. The highest concentration of tritium in the groundwater over the past few years has typically been around 25,000 pCi/L, which slightly exceeds the Federal Drinking Water Standard (DWS) and State of California Maximum Contaminant Level (MCL) of 20,000 pCi/L. The location of this concentration maximum appears at a monitoring well located close to the repaired sewer line break. Tritium is migrating away from that point and down slope from the stack, (Figure 2), at concentrations significantly below the DWS/MCL. The direction of flow is strongly influenced by subsurface geologic features. Movement of the plume is generally quite low because of the extremely low permeability of the Orinda Formation. Some enhanced movement to the south is apparent because of a subsurface erosional feature containing a sand lens with higher permeability than that of the underlying formation. At the leading edge of the plume, the full width is limited to less than a hundred feet. Even in the higher permeability zone, very low fluxes of water are moving downgradient.

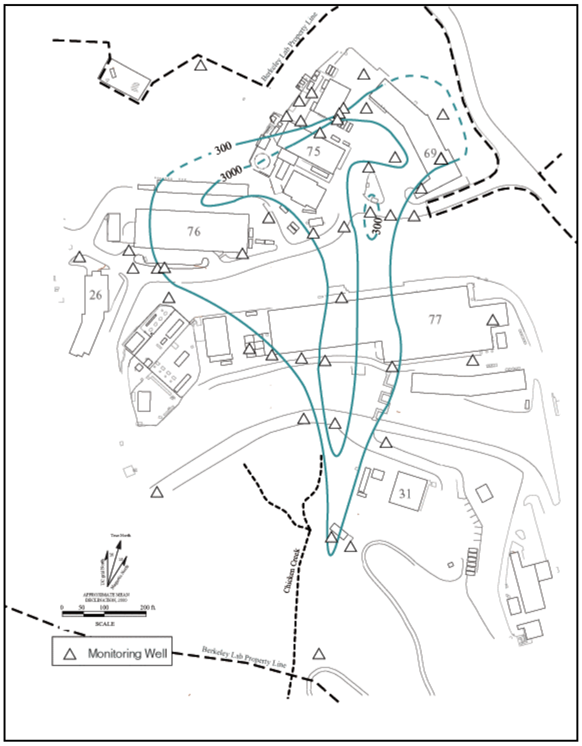


Figure 2. Tritium Plume Map at LBNL NTLF Site
(Source: LBNL Site Environmental Report for 2000, Chapter 6, found on LBNL website: http://www.lbl.gov/ehs/epg/html/env_protection.htm)

Critical and unresolved issues, an evaluation of remedial alternatives, and recommendations are discussed below.

2.1 Critical Issues

Definition of the concentration levels to be used for controlling the scope of future actions is critical. This will have a major impact on the duration and the amount of effort required for any control measures to be implemented in the future. For VOCs, the apparent goal for cleanup is the State of California MCL. However, this does not appear to be the case for tritium. All groundwater measurements of tritium are currently below the MCL, with the exception of one monitoring well, which is only slightly above the MCL. Since the associated sewer line leak has been repaired, it is likely that a combination of dispersion and radioactive decay (half-life or $t_{1/2}$ = 12.33 years) will reduce the level in that well to below the MCL also in a reasonable period of time. However, soil water measurements for tritium are much higher, so there may be a residual source of tritium in the soil that may require monitoring of groundwater for a longer period of time to ensure that no further tritium breakthrough will occur.

The local community is very concerned about the potential for releases of any quantities of tritium irrespective of amount. As a response to that situation, the current approach suggests managing the plume at levels below the widely accepted MCL. However, defining the action limit as background or as the analytical detection limit will lead to continual difficulties, as it will not be possible to have absolute control over tritium release. At this time, plume maps are drawn with an outer bound defined by the analytical detection limit of 300 pCi/L. Analytical detection limits are somewhat arbitrary quantities associated with the specific methodology employed and the details of its implementation (i.e., counting time, shielding, etc.). Significantly more sensitive techniques are available (i.e., gas counting or rare-gas mass spectrometry for the helium-3 daughter) that are capable of measuring tritium levels down to the cosmic ray induced natural background. In view of that, the currently used reporting limit does not have a clearly defensible basis.

The State of California has recently proposed revisions to the drinking water regulations to include a quantity referred to as the Detection Level for the Purpose of Reporting (DLR). For tritium, the proposed DLR is 1000 pCi/L. The new regulation, including the DLRs, is planned for full implementation on January 1, 2004 (California Department of Health Services 2002). The DLR might be an appropriate target to adopt as an alternate to the MCL. A simple calculation based solely on radioactive decay shows that the maximum tritium level in the groundwater on the site should drop below the DLR in approximately 60 years (Note: this is based on an assumption that the maximum tritium in the soil water is 30,000 pCi/L; there is uncertainty in this assumption). Efforts to define an action limit that is protective of public health and safety and agreeable to the regulators should proceed as a high priority. To the extent possible, agreement on an action level with other stakeholders should be obtained.

It is worth noting that even at the high rate of long-term consumption of 2 liters of water per day from a single source (i.e., the assumption used for risk assessments), a potentially exposed individual drinking groundwater from a well at the DLR level would only add an incremental dose of 0.05% of the national average natural background exposure rate. The risk level at the DLR is thus extremely small. Since the wells in question are incapable of being classified as drinking water sources due to their low flow, even that type of risk analysis is overly conservative. Nevertheless, in view of the high level of local concern, some resolution of the issue is imperative.

2.2 Unresolved Issues

Subsurface structural features that appear to be controlling groundwater flow south of Building 31 need additional characterization. The subsurface is extremely heterogeneous and complex. The distal lobe of the plume appears to be controlled by a relatively narrow, higher permeability channel. Definition of the location, width, and thickness of this channel may be needed to adequately design hydraulic control or other remedial alternatives, as well as for performance of a defensible risk assessment. It appears that the most promising technology for accurately defining the full extent of the higher permeability channel would be the use of the piezometric tool (i.e., electric cone) on a cone penetrometer with closely spaced multiple pushes across the region of the suspected erosional channel. The cone penetrometer has become a relatively mature technology, with numerous commercial vendors, such as Applied Research Associates (ARA), available to perform on-site geotechnical investigation using a range of tools. The piezometric tool, or as it is sometimes called, electric cone, uses a combination of strain gauges to log the ratio of cone-to-sleeve force during a continuous push at a fixed rate. That information can be used to determine soil type and degree of compaction. This technique has been used since 1948 and there is actually an American Standard for Testing and Materials standard for push rate. Other tools are also now available for cone penetrometer use, including soil gas probes, laser fluorimeters, and core collection tools. A wireline system recently developed by ARA facilitates change-out of tools down-hole. For more information on the technique, including implementation by DOE and the Department of Defense, see the following web reference: http://www.gnet.org/archive/4569.html#SUM. For commercial application, contact ARA directly (ARA contact: Jim Shinn, New England Division, 415 Waterman Road, South Royalton, VT 05068; (802) 763-8348 phone, (802) 763-8283 fax; e-mail jshinn@ara.com).

As its primary mission, NTLF produced organically bound tritium in a wide range of different chemical forms. Questions thus tend to arise with respect to the chemical speciation of tritium. Organically bound tritium was found in the leaf litter from vegetation near the facility exhaust stack. The tritium was likely either bound to the leaves directly by adsorption in the air or condensation from the air or through root uptake and the ensuing plant metabolic processes (the site believes the primary route is direct air adsoption; however, the technical assistance team did not have enough time to review all the data to make an accurate assessment). Since tritium is generally found to be highly labile, it will eventually be released as tritiated water, but the rate is hard to predict and organically bound forms can represent a long-term source of slow release not properly considered in modeling efforts. In addition to the tritium associated with the leaf litter, the materials released to the soil through the sewer leak may have contained organically bound tritium. If tritium is organically bound and water soluble to any significant degree, it will have different release and groundwater transport characteristics compared to tritiated water. Analytical methods for assay of organically bound tritium on soil have been explored and assays performed on selected soil samples at various depths in key areas of the contaminated region; however, the technical assistance team did not have time to review this data during the site visit.

2.3 Remedial Alternatives

Table 1 of Appendix D lists several remedial alternatives for the tritium plume originating near the NTLF. Each alternative is evaluated against the following criteria:

- Remediation strategy (containment, removal, in-situ treatment, ex-situ treatment)
- Effectiveness (likelihood of addressing the problem)
- Permitting risk (likelihood of obtaining regulatory permits)
- Implementability (ease of installing, operating, and maintaining remediation system)
- Health and safety risks (risks associated with installation, operation and maintenance of the remedial system)
- Cost
- Public acceptance (stakeholders)
- Long-term liability (is the contaminant removed or substantially reduced)
- Technical maturity (young technology that is under development or mature technology that has been extensively applied in the field)

Each category is qualitatively evaluated (e.g., high, medium, or low). An overall recommendation on the use of the technology is presented below.

Excavation

Excavation is a removal technology used for source control. It can be highly effective when a localized, well-defined, high concentration source region is found. However, at the NTLF site, due to the air deposition of tritium, a low concentration source is distributed over a large area. This would make excavation unacceptably intrusive on site operations, expensive, and generally inappropriate. Excavation would do more harm than good in risk reduction due to the added worker risk and accelerated rate of airborne release. Excavation is not recommended.

Water Control

Water control technologies attempt to prevent contaminated water from reaching certain regions of the aquifer or prevent clean water from contacting contaminated source regions. Water control technologies include control through extraction downgradient of the contaminant source region, or control through diversion or extraction upgradient of the source. Reinjection of extracted water from the downgradient portion of the plume in the flow path of the plume can be part of a water control technology. Upgradient water control could be applied along the hillside near the exhaust stack. This region has contaminated soil, so reducing run-off from the hillside could reduce the flux of tritium to the groundwater from the residual in the soil. However, the steep slopes and the possibility that the runoff is contaminated may reduce the overall effectiveness of this option. Downgradient water control at LBNL is generally performed by installing high permeability trenches intruding into the lower permeability subsurface geology. As water flows into the trench, it is pumped out. The water could be reinjected further upstream to form a closed loop, allowing more time for tritium to decay and mitigating the potential for any significant degree of off-site migration. Upgradient water control management would be low cost, low risk and easily implemented. It should be considered if additional source control is needed. Downgradient water control is a mature technology and is the best option to prevent further migration of the plume. Its implementation should be inexpensive and have low health and safety risks. Downgradient water control with reinjection may only have moderate public acceptability, as it relies on radioactive decay over decades rather than immediate removal to decrease concentrations. Both of these options will have moderate long-term risk, reflecting the duration over which these systems would need to be operated.

Pump and Treat

Pump and treat is an extension of water control in which the extracted water undergoes treatment to remove or destroy the contaminant. An extensive study of tritium treatment technologies performed by the Savannah River Laboratory concluded that there is no cost effective method to treat tritium at the contamination levels typical of those found at LBNL (Fulbright, et al. 1996). Evaporation technologies are the least expensive but simply change liquid tritiated water to gaseous tritiated water, which is released. Therefore, the total tritium release is unchanged and this may be unacceptable to the public.

Containment

Containment technologies include subsurface barriers (e.g., grouts, viscous liquids, etc.) that can be used to isolate the contaminated region from water flow. Containment technologies are typically used around a source region. The distributed source at NTLF makes this impractical. There may be strategic applications of containment technologies that would prove useful, for example isolating old pipelines or local highly permeable zones known to transmit tritium. The cost to perform containment would be moderate depending on the size needed to be contained, subsurface characteristics and accessibility. Public acceptance for this approach is likely to be low to moderate because the source is not removed. This also leads to moderate long-term liability.

Phytoremediation
Phytoremediation for tritium could be used in conjunction with extraction. Extracted water could be applied to the vegetation in the area, leading to evapotranspiration of a large fraction of the tritium, with the remaining fraction entering the subsurface environment and returning to the groundwater. Generally, the tritiated water is applied on lands that are above the existing groundwater plume to prevent spread of contamination to other parts of the aquifer. This approach has been successfully applied at the Savannah River Site for high tritium concentrations (> 10^6 pCi/L). It should also be noted that functionally, phytoremediation has the same net effect as pump and treat with evaporation in that the tritium is removed and diluted via the atmospheric release pathway. Due to the restricted land area available for irrigation, close proximity of offsite receptors, low public acceptability, and moderate long-term risk for this approach, it is not recommended.

Chemical/Bioremediation
A number of in situ chemical barriers and bioremediation approaches exist for removal of metals and destruction of volatile organic contaminants from the groundwater. None of these are appropriate for removal of tritium.

Monitored Natural Attenuation
Monitored natural attenuation is a viable approach to managing the tritium plume from NTLF. Concentrations are already below the MCL with the exception of one location. However, public concerns over tritium make exclusive use of this strategy unlikely. Monitored natural attenuation could be best used in conjunction with the hydraulic control and reinjection approach.

Metered Discharge to the Sanitary Sewers
Water extracted from the plume has a tritium concentration that is acceptable for discharge to the sanitary sewers. This approach would be inexpensive to implement, but it is not recommended. Public acceptability of this is likely to be extremely low. In addition, there is the chance that a pipe could break, leading to tritium contamination on other parts of the site. It would also make the tritium more accessible to the general public in a highly attenuated form. Although the population health risks from this are very small, it would involve less health risk to leave the tritium in its current location.

2.4 Recommendations

In general, LBNL has done an excellent job in tracking the sources of tritium contamination, understanding flow in the complex geology of the site, and monitoring of the tritium plume. The following recommendations would be beneficial to improve understanding of flow dynamics (travel time) and flow paths:

1. Explore the possibility of using ^3He/tritium dating for better defining plume travel times. This approach could be used selectively to determine a realistic basis for assessment of the risk of offsite migration through the higher permeability channel. In order to perform reliable measurements, samples must be taken from groundwater wells screened below the water table and in a representative section of the geology (e.g., sand lens). Excellent expertise and equipment for performing this kind of measurement already exists at LBNL at the Center for Isotope Geochemistry

2. If a recirculation system is used as a water control option, consideration should be given to performing tracer tests at such time as the reinjection is initiated. Bromide, iodide, or other conservative tracers could be injected at the reinjection point used for contaminated water. With a proper monitoring program, data could be collected on samples taken downgradient from the injection point and at the collection trench to estimate travel times to those points. That information could be used to better define flow paths and improve understanding of system behavior, including providing a measure of water capture efficiency at the collection trench. This information will be useful in determining the effectiveness of the hydraulic control system.

3. Take advantage of structural features when designing remedial systems. Geological features appear to channel flow through certain small regions. Increased characterization to accurately define these regions should be pursued to assist in locating treatment systems such as trenches.

3.0 OLD TOWN PLUME

The Old Town Site is centrally located within LBNL and comprises a variety of active and historical scientific and support facilities. Some of these facilities, such as the Advanced Light Source, are valuable national scientific resources. Encompassing the area of Buildings 4–7, 14, 16, 25, 27, 52–53, and 58 and the slope west of Building 53, the Old Town VOC plume is the most extensive groundwater plume at LBNL. This plume is contaminated with several chemicals including: tetrachloroethylene (PCE), trichloroethylene (TCE), and lower concentrations of other halogenated hydrocarbons, such as 1,1-dichloroethylene (1,1-DCE), cis1,2-DCE, 1,1-dichloroethane (1,1-DCA), 1,2-DCA, 1,1,1-trichloroethane (1,1,1-TCA), 1,1,2-TCA, carbon tetrachloride, and vinyl chloride. Several of these are products of PCE/TCE or 1,1,1-TCA degradation. The maximum concentration of total halogenated hydrocarbons detected in groundwater samples collected from Old Town VOC plume wells has been measured at levels exceeding 100,000 µg/L. While the contaminant profile varies throughout the plume, two compounds, PCE and TCE, comprise over 95% of the VOCs in the highest concentration samples near the former and residual source areas. Figure 3 shows the aerial extent of VOCs in groundwater in the Old Town area.

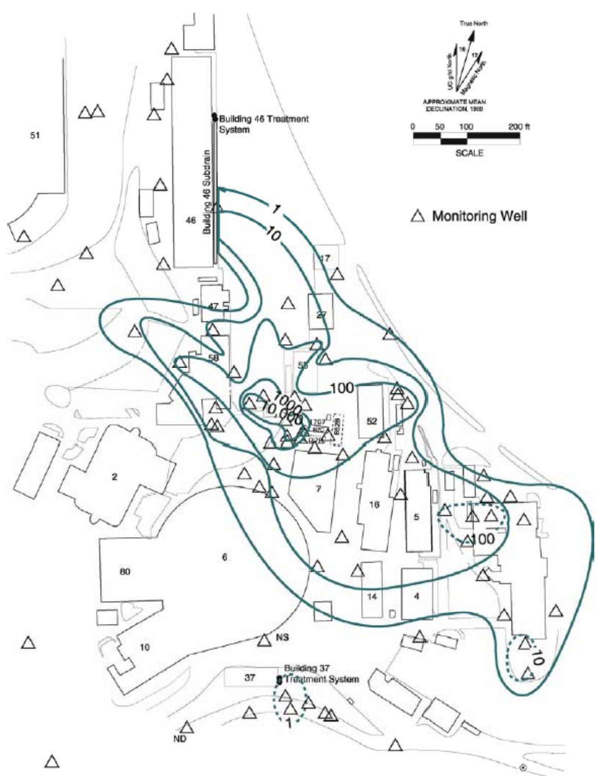


Figure 3. Groundwater Contamination (Total Halogenated Hydrocarbons in µg/L) in Old Town Area (September 2000)

The presence of the plume's maximum VOC concentrations north of Building 7 suggests that the primary source of the Old Town VOC plume was an abandoned sump located between Buildings 7 and 7B. The sump was discovered and its contents removed in 1992. The sump was removed in 1995 after underground utility lines that crossed the sump were relocated. Other less significant source areas for groundwater contamination are indicated by relatively high concentrations of halogenated hydrocarbons detected in groundwater samples from monitoring wells west of Building 16, east of Building 52, and west of Building 25A. The contaminated groundwater from these sources flows westward, where it intermixes with the main Old Town plume.

Interim corrective measures have been instituted to manage the Old Town VOC plume. These measures include:

- A groundwater collection trench was installed immediately downgradient from the former Building 7 sump to control the source of the groundwater contamination;
- A subdrain located east of Building 46 intercepts the northern lobe of the plume and prevents the discharge of contaminated groundwater to the storm drain;
- A groundwater collection trench was installed west of Building 58 to intercept the southern lobe of the plume and prevent its further migration;
- A groundwater collection trench was installed on the slope east of Building 58, in an area where high VOC concentrations had been detected in soil gas and groundwater.
- The primary VOC source underlying the former sump source was excavated (to the extent practical) leaving only residual source material that could not be safely removed by excavation.
- Enhanced removal of the residual VOC source using combined soil vapor extraction and groundwater extraction has been initiated. Several innovative technologies have been tested. Notably, the program has initiated use of standard conductive/convective heating at a pilot scale to enhance the soil vapor extraction removal of the residual VOC. Data from this test are being generated to allow future optimization or modification.

The environmental restoration effort in the Old Town area has been relatively effective and has been structured appropriately – focusing on source removal and plume control as the most productive early activities. The program for Old Town has a strong scientific basis and appears logical. The LBNL Environmental Restoration Program has exhibited creativity in selecting and implementing technologies, as well as appropriate flexibility in operating and optimizing the technologies. In particular, the use of interceptor trenches in this complex and heterogeneous hydrogeology is a robust and reasonable technique to collect water for treatment and/or control.

3.1 Critical Issues

The critical issues in the Old Town Area are the residual source, heterogeneity, and interferences.

The residual source needs to be addressed to stabilize the situation. Technology to triage and remove the residual source will facilitate reasonable and cost effective solutions for the primary and distal portions of the groundwater plume.

As with the rest of the LBNL site, areas of low permeability and a high degree of the heterogeneity (even over distances of < 1 m) dominate the contaminant plume structure and behavior. In a positive sense, this setting does generally limit plume growth and contaminant release. Unfortunately, this setting also severely hampers the efficiency of contaminant extraction or reagent injection systems and results in extended remedial time frames. Higher permeability intervals are more amenable to rapid cleanup (circa decades) while the lower permeability zones contribute contaminants to the active plume for a longer period of time (circa centuries). These effects are particularly significant in the Old Town area because of the patchy overlay of the more permeable Moraga Formation, consisting of ancient landslide deposits of clastic rocks with an overall hydraulic conductivity of 10^{-4} to 10^{-6} m/s, onto the less permeable Orinda Formation, containing fine grained siltstones and similar sediments with an overall hydraulic conductivity of 10^{-7} to 10^{-12} m/s. Even within the Moraga Formation, hydraulic conductivity can vary significantly both vertically and laterally, depending on the nature of the original landslide event(s). Effects of the heterogeneity have already been observed in the performance of the near source pump-treat-reinjection system. To date, concentrations in the most permeable material have been reduced several orders of magnitude, while contamination in lower permeability intervals has shown little or no change.

Interferences, including buildings, subsurface infrastructure, paving, hill slope stabilization systems, and safety/engineering issues, are critically important to the technology selection and implementation in Old Town.

These issues will be briefly addressed in the summary technology evaluations below.

3.2 Unresolved Issues

Three unresolved issues were identified:

- Performance of the thermal enhancements under a full time heating/extraction scenario
- Performance and value of the current subsurface hydrology, contaminant fate and transport modeling effort
- Detection of trace levels of benzene in deep wells

The technical assistance team anticipates resolution of the first two issues will be obtained through planned data collection and project completion efforts. The team did not examine enough detailed data to provide a definitive response about the potential source of the detected benzene and the relative likelihood of the alternative hypotheses. Nonetheless, a recent technical assistance report written to support the DOE Pantex Plant in Amarillo, Texas, addressed a similar issue – the unexpected presence of detected benzene in deep wells (Charbeneau, et al. 2002; SCFA Lead Lab 2001). In that case, the use of certain materials in well construction and sampling (e.g., nylon) led to the detections because benzene was shown to leach from the materials over extended time periods. Similar benzene detections were not observed in shallower Pantex systems because they were designed somewhat differently – samples were collected more quickly from the shallower wells and the wells were purged more effectively. In the case of the LBNL deep wells, early examinations might focus on the equipment and materials used to install the protective casings, and any differences in the sampling protocol between the shallow and deep wells.

3.3 Remedial Alternatives

Cleanup efforts at Old Town have been initiated based on the overall philosophy of interim corrective measures developed by LBNL and DOE in concurrence with the State of California regulators. The general principle is that interim corrective measures are used to remediate contaminated media or prevent movement of contamination, where the presence or movement of contamination poses a potential threat to human health or the environment. The general objectives of LBNL interim corrective measures are:

- Removing or controlling sources of contamination
- Stopping discharge of contaminated water to surface waters
- Eliminating potential pathways that could contaminate groundwater
- Preventing further migration of contaminated groundwater

These are scientifically appropriate interim corrective action goals that the technical assistance team fully endorses. These goals also may be used to help structure discussion of potential technologies and the technology matrix for this particular plume (see Table 2 in Appendix D).

A summary assessment of the various potential technologies is provided in the technology matrix and in the short discussion below. Technologies have been categorized into: source removal technologies and plume control and elimination technologies. Source control technologies discussed include physical removal (excavation), chemical extraction (e.g., surfactant or cosolvent flushing), physical containment, chemical destruction (e.g., chemical oxidants), energy based enhancements (e.g., various types of heating, electroosmosis, and sonic), and physical improvements to facilitate mass transfer (e.g., fracturing and soil mixing). Plume control and elimination technologies include water control, pump and treat, chemical reactive barrier, bioremediation, and monitored natural attenuation. An optimal solution will combine appropriate technologies from this list into an overall system that provides long-term and sustainable performance to meet LBNL's environmental stewardship objectives.

3.3.1 Source Control Technologies

Physical Removal

Excavation
This is the baseline and preferred technology for shallow accessible source zone contaminants. Extensive excavation activities beneath and adjacent to the most significant sump source have already been completed by LBNL. The source removal was not complete because of the limitations imposed by existing facilities, surface and underground infrastructure, and safety (slope and structural). For the remaining source, additional excavation remains an option, but only if specific focused solutions to these limitations are developed and alternative reasonable source removal approaches are not possible. Costs for additional excavation would tend to be very high because of the supporting need for complex engineering solutions and implementation of appropriate protective measures for the nearby affected facilities.

Soil Vapor Extraction (SVE) and Related Technologies such as "Dual Phase Extraction"
SVE is a baseline method that has been successfully used under a wide range of source zone conditions. The biggest limitation to use of SVE for the source material associated with the Old Town plume at LBNL is the low permeability of some of the source zone sediments and the high degree of heterogeneity. In this setting, the more permeable material is remediated quickly (circa years) while the less permeable material is remediated much more slowly (circa decades or centuries). Thus, while SVE is likely to be an important component of the cleanup of residual source solvent at this site, various enhancements should be considered as appropriate to improve mass transfer and removal rates. Related methods, such as dual media extraction, are being performed by a large number of companies (see EPA 1999; EPA 1995, Nyer et al. 1996; DOD 2002). These related technologies are based on removing as much water as possible by pumping and then cleaning up the sediment using the more efficient SVE approach (i.e., air is a more efficient VOC extraction medium than water). The water removal can be accomplished on a local scale by using a high vacuum suction tube in the SVE well or, on a slightly larger scale, by using intensive pumping of a small number of closely spaced wells. Dual media extraction is promising for small solvent source sites in relatively permeable and homogeneous geological conditions. Specific attributes that make dual media extraction promising include: 1) residual solvent present in the capillary fringe and shallow groundwater, 2) minimal solvent source deep in aquifer zone(s) beneath the water table, and 3) avoiding implementation at sites with either very high or very low permeability. At Old Town, this variant would be limited by the same heterogeneity challenges as standard SVE.

Chemical Extraction

Surfactant Flushing

This technology uses surfactant solutions to solubilize or mobilize source solvent. Because surfactant flushing requires delivery and capture of reagent and requires intimate contact of the reagent with the source solvents, it would have almost no applicability to the source area for the LBNL Old Town plume. This solvent source is in heterogeneous and, in some zones, low permeability sediments. In the appropriate setting, surfactant amendments allow solvents to be removed in a few pore volumes of flushing rather than the hundreds or thousands of pore volumes required if the solvent is dissolving into water. This technology has been studied for many years by various universities (State University of New York at Buffalo, University of Texas, University of Oklahoma, University of Florida, University of Waterloo, and others) and by Duke Engineering and Services Company. The process requires rigorous control on the injected and extracted fluids to assure that the source zone is swept by the injected reagent and to assure that the mobilized/solubilized dense non-aqueous phase liquid (DNAPL) is effectively captured. A key element to the success is optimizing the use of the relatively expensive surfactants by developing recycle systems, more efficient surfactants, or other strategies. This technology has been applied with limited success at sites with favorable source and geological conditions. Specific attributes that make this technology promising include: 1) relatively small and well defined solvent target in permeable material below the water table, 2) solvent present throughout the formation, and 3) competent confining zones to help control undesirable migration away from the treatment zone. Because it involves injection and extraction of reagent, this class of technology would have limited applicability above the water table and to clean up heterogeneous or fine-grained sediments. Recent research in this field is focused on surfactant recycle and reducing the buoyancy of mobilized DNAPL for more effective control and capture.

Co-solvent Flushing

This technology is very similar to surfactant flushing in theory and approach, except that co-solvents (e.g., alcohols and other such solvents) are used instead of aqueous surfactants. Because co-solvent flushing requires delivery and capture of reagent and requires intimate contact of the reagent with the source solvents, it would have almost no applicability to the source area for the LBNL Old Town plume, which is in heterogeneous and, in some zones, low permeability sediments. Co-solvent based remediation has been deployed by universities (e.g., Clemson University) with some success. In addition to research on reducing the buoyancy of the mobilized source solvent, co-solvent researchers are examining increasing the density of the reagent fluid to more effectively target “bottom-dwelling” dense solvent layers.

Sparging

This technique, based on injection of air below the water table, has limited applicability to most solvent source situations. A key exception is sites where small volumes of residual solvent are held up in the capillary fringe and sparge air can be directed up through the contaminated layer for collection by SVE. Because sparging requires well-understood and controlled delivery and spread of air and intimate contact of the air with the source solvents, it would have almost no applicability to the source area for the LBNL Old Town plume, which is in heterogeneous and, in some zones, low permeability sediments.

Physical Containment

Source Zone Isolation Methods

These methods include slurry walls, caps, sheet pile walls, grout injection/mixing, silica gel injection, and related geotechnical techniques. These methods attempt to stabilize and address solvents by removing them from the active transport pathways in the soil and groundwater system. Because of the low concentrations needed to meet regulatory goals (e.g., μg/L or ppb levels), isolation methods have not been successful to date. Thus, they are listed here for completeness and a commercial variant has not been identified. Even the carefully installed sealed sheet piles at the Borden site in Canada did not successfully eliminate the contamination of surrounding groundwater after source solvent was added inside the test cell in a controlled experiment. Based on the monitoring data, the VOC plume in the Old Town area of LBNL is not migrating rapidly and much of the residual source appears to be trapped in lower permeability sediments in this heterogeneous system. Despite these relatively favorable conditions for source zone isolation methods, the technical assistance team does not recommend these methods for the LBNL Old Town plume because of the type and degree of interferences and public/regulatory acceptability.

Chemical Destruction

In Situ Oxidation

This technology uses reagents to destroy DNAPLs in place. Because in situ oxidation requires delivery of reagent and requires intimate contact of the reagent with the source solvents, it would have almost no applicability to the source area for the LBNL Old Town plume, which is in heterogeneous and, in some zones, low permeability sediments. Typical reagents include Fenton's reagent (hydrogen peroxide and reduced iron) and permanganate solution. These reagents are strong oxidizers that "burn" the DNAPL in a saturated or vadose zone setting. As the reagent is added, it reacts vigorously and often induces bubbling and mixing – a process that may enhance contact of the reagent with the target DNAPL under some conditions. Several variants of in situ oxidation methods have been deployed commercially. A key element to the success is performing the work rapidly with a minimal volume of reagent. Sites with highly reduced conditions (conditions that would scavenge reagent away from the desired DNAPL destruction) would be poorly suited to this technology class. Specific attributes that make this technology promising include: 1) relatively small and well-defined DNAPL target in permeable material, 2) DNAPL present throughout the formation, and 3) competent confining zones to help control reagent delivery. Because it involves injection of reagent, this class of technology would have limited applicability to clean up heterogeneous fine-grained layers.

Energy Based Enhancements

Radiant/Conductive Heating

This is a straightforward technology that uses standard resistive heaters deployed in wells/boreholes to generate heat. Heat from this point source is distributed throughout the target volume by convection and conduction. A pilot test of this technology is ongoing in the Old

Town plume source area. The data, to date, appear promising – especially since the power of heaters was increased. Presently, the primary performance limitation appears to be efficient extraction of contaminant vapors after the target zone has been heated. A more aggressive extraction protocol was recently initiated and future data will suggest if this new protocol will overcome the problem of low extraction efficiency or if alternative approaches to improve extraction efficiency are needed. Historically, this technology has been deployed with variable success and the LBNL implementation is one of the best and most successful to date. The LBNL program has demonstrated creativity and appropriate flexibility during implementation. Based on the available data, the technical assistance team considers this to be the baseline heating technology for consideration at the site (i.e., reasonable performance, relatively safe and effective, low cost, etc.). Alternative heating technologies would have to provide unique advantages to displace this as the preferred method. The team recommends continued use of this technology for appropriate portions of the residual source if the extraction challenges can be overcome. This is a particular case where straightforward modeling (using TOUGH [**t**ransport **o**f **u**nsaturated **g**roundwater and **h**eat] or a similar tool) might assist in the design and operation of the remediation system.

Joule Heating

This technology directly "injects" AC power into the subsurface to heat the soil through self-resistive ("Joule") heating. Through resistance to the flow of electricity in the bulk soil/groundwater, heat is generated. Thus, the ground itself acts in a manner analogous to the heating element in a small radiant home or office heater. The geological conditions in the source area of the Old Town plume are suited to Joule heating, so it remains a viable method. Nonetheless, implementation would be very difficult and expensive because of cultural interferences. Locally this technology was tried at a south San Francisco bay site and the electrodes melted due to lack of moisture close to the electrodes, so additional water might be necessary and, given the low permeability, the technique might be even more difficult than a first glance would indicate. Also, collection of the contaminant vapors from the heated zone remains a challenge and the method is not demonstrably superior to the existing pilot technology – convective/conductive heating. As a result, this approach is not strongly recommend as a general source cleanup tool in the Old Town area and might only be applicable to highly targeted niche implementation.

Joule heating normally requires some moisture to be maintained in the heated zone. Since the area immediately adjacent to the electrodes heats faster than the overall treatment zone, injection of small amounts of water or electrolyte solution is often required to allow the ground to be heated to temperatures near 100° C. A relatively successful commercial variant is called six-phase heating. Dividing the power into six phases (rather than the traditional three phases of line power) helps avoid problems because the power density near each electrode is reduced and the overall power pattern is more uniform. An advantage of six-phase heating for vadose zone contamination is that power and heat are preferentially directed into fine grained or clayey layers. These layers tend to be more moist and they have been shown to be the long-term solvent reservoir in many layered geological systems such as A/M Area at Savannah River. Six-phase heating was developed by the Pacific Northwest National Laboratory and has been licensed for commercial implementation. This process was originally funded and developed by the DOE Office of Technology Development. The first field test of six-phase heating was performed at the Savannah River Site in South Carolina. This test successfully heated a shallow contaminated clay zone underlying the former process sewer line leading to the M Area Settling Basin. Six-phase heating is potentially applicable to similar solvent source targets as steam but with less robustness to heat below the water table and the possible need for closer borehole spacing to install electrodes. Six-phase heating is likely to be more robust than steam for low permeability conditions. Recent developments related to this technology include use of a higher power density to generate an in situ corona to stimulate in situ destruction in addition to mobilization. This particular enhancement has been observed in the laboratory and may not be suitable for initial field-testing at a large contaminated site.

Electroosmosis

This technology exploits electrokinetic phenomena in which ions in the diffuse double layer near soil particles move in response to a DC electric field and induced water movement. Electro-osmosis in porous media, such as clays, is possible because of the structured electrical double layer of negative and positive ions formed at typical solid-liquid interfaces. For soil particles, the double layer consists of a fixed layer of negative charges associated with the solid phase and a diffuse aqueous layer of positive ions. Application of an electric potential on the double layer results in a driving force for displacement of the two layers toward the respective electrodes; i.e., the positively charged layer to the cathode and the negatively charged layer to the anode. Since the particles in the soils are immobile, the fixed layer of the negative ions is unable to move. However, the positive ions can move within the diffuse layer and drag water toward the cathode (EPA, 1990). While the basics of this technology are well established from industrial applications in dewatering and clay consolidation, reliable performance for remediation applications has yet to be established. DOE has invested significant resources in the development of this technology, with some limited success documented for organic contaminants (e.g., the Lasagna consortium tests at Paducah and similar pilot studies at Lawrence Livermore National Laboratory), as well as limited success in direct extraction of metals and radionuclides (“electrokinetics”). In general, this technology is potentially well suited to the LBNL Old Town plume source conditions and the planned “small” pilot test is appropriate. Site-specific challenges associated with potential interferences and geologic heterogeneity may limit performance of the technology. A well-designed pilot test would address the issue of applicability and performance at a minimal cost.

In saturated or nearly saturated sediments, the electroosmotic conductivity is directly proportional to the permitivity of the pore water solution, the zeta potential of the soil, and inversely proportional to the viscosity of the fluid. Importantly, electroosmotic conductivity is essentially independent of hydraulic conductivity. For typical fine-grained sediments with a hydraulic conductivity of 10^{-7} to 10^{-12} m/s, electroosmotic conductivities range from 10^{-4} to 10^{-5} cm^2/volt/s. Therefore, reasonable induced voltage gradients on the order of V/cm will increase water flow velocities by several orders of magnitude (assuming typical hydraulic gradients of 0.1 and below).

There have been many problems with electroosmosis systems. Water electrolysis at the electrodes can generate large excursions of pH. This, in turn, can result in unstable operation and/or metals dissolution and precipitation. Also, for organics, the method is limited to the soluble fraction and will not remove residual nonaqueous phase solvents in the system. The technology is most applicable to saturated or near saturated sediments with low permeability (e.g., < 10^{-5} m/s hydraulic conductivity). Within this bound, the method has low power consumption and will induce a relatively uniform flow that is "independent" of heterogeneity. Because it extracts the dissolved phase only, the method has limited applicability in source zones with solvent trapped in pools or isolated pores (unless combined with another technology). Recently, various claims have been made for a related technology that uses even lower current densities and "induced polarization" resulting in "discharges in the soil" causing in situ destruction of contaminants. To date, the data for this new Electro Geooxidation Process are anecdotal from both Europe (P2 Soil Remediation Inc.) and the U.S. (Weiss and Associates) and there is little support for the process in terms of mechanistic descriptions and understanding. Nonetheless, the technology, if successful, would be inexpensive and simple to implement. Thus, LBNL may want to keep up with developments to determine if a small field test is warranted.

Steam Flushing

This technology uses steam to sweep residual solvent from the subsurface and to deliver heat. Because steam flushing requires delivery of a fluid and general contact of the fluid or its energy with the source solvents, it would have limited applicability to the heterogeneous and low permeability sediments in the source area for the LBNL Old Town plume. Steam flushing is a crossover method originally developed and studied for enhanced oil removal to increase the productivity of oil wells and oil fields. In fact, early development work related to this technology was performed at LBNL. The primary mechanism of oil/solvent removal is concentration of the contaminant phase along the expanding steam front and collection at strategic locations. Typically, steam based remediation systems use a set of wells to deliver steam and move the contaminant phase towards "interior" collection wells to minimize the potential for spreading. In addition to the primary mode of action, steam provides heat energy to increase the mass transfer of contaminants from fine-grained materials and increases contaminant vapor pressure and solubility. A final benefit of steam and other in situ heating methods is that a fraction of the organic phase will break down in the subsurface in the presence of heat and oxygen. Steam is an extremely effective fluid for cleaning soil and groundwater. It delivers its energy efficiently in a minimal condensed volume (much of the energy is released as the steam front condenses). Steam is less dense than water. Thus, it will tend to be most effective and efficient in the vadose zone and in areas below the water table where the entire aquifer is contaminated, rather than just a thin layer at the bottom of the treatment zone. Natural layering of sediments and careful design and operation will also limit the tendency of the steam to override the water table. Collection of the contaminant vapors from the heated zone will also be challenging at this site due to the many cultural interferences.

There are a few commercial variants of steam heating. The most successful and widely used are by licensees of the Lawrence Livermore National Laboratory steam remediation processes. These particular processes are known as Dynamic Underground Stripping (DUS) and Hydrous Pyrolysis Oxidation (HPO) for the steam sweep and the abiotic oxidation process, respectively. The steam variant of "DUS with HPO" was developed with the support of the DOE Office of Technology Development. In virtually all variants of in situ steam treatment, the steam is injected at high pressures and spreads rapidly through the formation. Heat is transferred to the formation and the steam front expands as the treatment zone reaches target temperatures near the boiling point of water. The rapid expansion of the steam zone reduces the required number of access points compared to many alternative technologies such as six-phase heating or the reagent-based destruction/mobilization/solubilization methods.

Radio Frequency (RF) Heating and Similar Methods
RF heating is an electromagnetic technique that is similar to microwave heating. The geological conditions in the source area of the Old Town plume are suited to RF heating so it could be a viable method. Nonetheless, implementation would be very difficult and expensive because of cultural interferences. Also, collection of the contaminant vapors from the heated zone remains a challenge and the method is not demonstrably superior to the existing pilot technology – convective/conductive heating. As a result, this approach is not strongly recommended as a general source cleanup tool in the Old Town area and might only be applicable to highly targeted niche implementation.

Heating occurs internally through a dielectric mechanism in which molecular dipoles interact with the electromagnetic wave. The induced molecular distortion and/or motion is translated from mechanical to thermal energy. The effectiveness of the dipole coupling and the power absorbed is a function of the frequency and amplitude of the RF field and the dielectric properties of the sediments. These properties, in turn, are a function of soil composition, moisture content, and temperature. RF heating works initially through interaction with the pore water and water of hydration, but is capable of continued heating to temperatures above 100 degrees C by interaction with the minerals. Typical frequencies applicable to soils are in the range of 1 to 100 MHz. The frequency band has been set aside by the Federal Communications Commission for industrial, scientific and medical use with expedited approval in this range and, as a result, the technology has been studied for enhanced oil recovery and successfully deployed for pilot solvent source cleanup (Jarosch et al., 1994). Different applicator configurations are possible. The two most common are a dipole for application in a borehole, and a “triplate array” for treatment of a fixed volume block. RF heating was developed primarily by researchers from the Illinois Institute of Technology Research Institute.

Because of the cost of the RF generator and matching network, and poor efficiency with respect to the original power source (<70%), RF heating has not had as much commercial success as Joule heating. The potential applicability of either technology to the source area at the Old Town plume would be similar. Related technologies such as in situ microwave heating have also been proposed in the past. Unfortunately, as discussed above, microwave frequencies are too high for effective volumetric heating and these systems only heat a thin layer immediately adjacent to the applicator.

Sonic Enhancement
This technology uses low frequency sonic energy to improve mass transfer and enhance recovery in pump and treat systems such as soil vapor extraction. As with several of the energy techniques, this method was originally studied to support enhanced oil recovery and has recently been proposed for enhancing environmental cleanup of organic contaminants. Researchers have actively studied this technology in Europe (e.g., University of Delft in the Netherlands) and in the United States (e.g., Weiss and Associates and more recently P. Kearl at the Grand Junction Office). DOE invested significantly in commercial development. There are several

hypothesized mechanisms for the increased mass transfer, including vibration of contaminants in and out of pore throats, vibration of the matrix itself, generation of thermal energy, and others. None of these has been clearly demonstrated or quantitatively confirmed. Further, tests to date show that the effectiveness of the method tapers off rapidly and much of the residual solvent in a system (circa 80%) does not respond to this enhancement. Thus, the technique has shown limited success to date and would likely have limited effectiveness at this site. Properly implemented, this method is very inexpensive, however, and LBNL may want to keep up with developments to determine if a small field test is warranted (see EPA 1990, and project reports by Weiss and Associates available from the DOE Small Business Innovative Research program).

Physical Improvements to Facilitate Mass Transfer

Fracturing

Fracturing involves using air or water to generate controlled fractures in the subsurface, improve mass transfer and enhance recovery in pump and treat systems. Fracturing technologies are subject to problems in the presence of significant cultural interferences, significant heterogeneity, slope stability concerns, and the need to deliver large amounts of propping solids to keep the fracture open. Since all of these “negative” conditions are present for the Old Town source area, fracturing does not appear to be a significant viable technology for this site.

Soil Mixing

This is a standard commercial technology used for foundation stabilization when grout is injected during the mixing. The method has also received significant use for environmental cleanup by using chemical reagents (e.g., oxidants), rather than grout to destroy contaminants, or chemical reagents combined with grouts to stabilize contaminants. Such standard implementations might be applicable to niche portions of the Old Town plume source. An unusual application envisioned by the technical team for the area of the Old Town source that has a higher permeability layer on top of a lower permeability layer is to simply mix the layers without amendment to increase the permeability of the lower layer. This would allow release and flushing of the contaminant with the current capture and recycle system or any other removal technique. This would have to be performed carefully to avoid slope stability problems and would still represent only a niche application to the overall plume source target.

3.3.2 Plume control and elimination technologies

Water Capture and Reinjection (no treatment)

This is a hydraulic control technology that provides hold up time for contaminant degradation or decay and, in the case of a contaminant that is currently being released, this approach reduces and levels the flux and exposure. Based on the available data, the Old Town plume is not being significantly released through normal groundwater flow processes, so the primary objective of this technique would be to provide time for degradation. Further, treatment of VOCs at the surface once the water has been collected is straightforward, so there is no compelling reason to reinject the water without treating it. Thus, water control alone is not applicable to this site, although water control in combination with other methods is always important to successful environmental remediation.

Pump and Treat

This is a baseline that provides good performance for dissolved contaminants that can be efficiently collected using wells or trenches. LBNL has appropriately selected trenches for water collection at the Old Town plume. Pump and treat in this setting, however, is limited by the continued presence of a residual source and the high degree of heterogeneity. Thus, the technical assistance team recommends continued capture and treatment with the several current and planned collection trenches and completion of the source removal. Also, a plan for turning off the system in the extended future and the approach for defining the distal edge of the plume requiring action needs to be developed in cooperation between the regulators and stakeholders. Pump/collect and treat is applicable to this site. Continued use of collector trenches supplemented by hot spot wells is recommended. Selected reinjection of water, as was done in early work near the source, may be beneficial in speeding the cleanup of the most permeable layers. If contaminated intervals of highly different permeability are present at a location, LBNL may want to consider separate screens in the different materials. This would allow more control on the process by providing more driving force on the less permeable material and minimize pumping from the permeable zone after it has already been cleaned up.

Chemical Reactive Barrier

This technology utilizes a treatment material in a permeable trench or structure. The intercepted water is treated as it flows through the system and “clean” water is discharged. Chemical reactive barriers have been the subject of active research throughout the world with investment by universities (Waterloo and others), companies (e.g., EnviroMetal Technologies, Inc. and others), and all relevant federal agencies. The most common treatment material for VOCs is granular iron (“zero-valent iron”), amended granular iron, sorbents derived from industrial byproducts, or waste organic material for redox control. In the case of iron, the barrier provides an environment that dehalogenates chlorinated VOCs as they pass through because of the high energy of the surface corrosion reaction and the high surface area. The primary problems with this technology relate to the chemistry of the water exiting the barrier, which often has a high pH (>10) and no dissolved oxygen. Other problems include low treatment flow rate, especially in low permeability materials, sometimes-expensive installation, and unknown lifetime of the barrier materials. While this technology is not a panacea for the Old Town plume, LBNL may want to consider niche uses and opportunistic uses. Specific examples include use of permeable treatment materials in some of the collection trenches that are being constructed and use of a permeable treatment system in the distal portion of the plume. Distal installation would provide plume release protection in this unique setting that has a low water yield and does not justify active pumping and treatment. Distal installations would not be required if the plume is shown to be contained and not spreading and monitored natural attenuation is actively occurring.

Bioremediation

Bioremediation is a mature in situ treatment technology routinely applicable to organic contaminants. Unfortunately, the heterogeneous and low permeability nature of the subsurface media at LBNL suggests that the delivery of nutrients would be extremely difficult, making the effectiveness of aggressive bioremediation approaches low to suspect. Bioremediation exhibits low health and safety risks, few permitting hurdles and has high social acceptability. The down side at this location is the extremely poor ability to deliver nutrients. Classical bioremediation schemes are aggressive and involve the timely addition of electron donors, electron acceptors and nutrients being flushed through the contaminant plume, resulting in toxicant degradation within months to years. If aggressive bioremediation is implemented at LBNL, the costs would be quite high due to the close spacing of circulation wells and the cost of said infrastructure.

However, if nutrients were delivered in a manner such that time was not of the essence, then less aggressive bioremediation activities could, over time, complement plume abatement and add considerable value in terms of contaminant reduction per dollar spent. Though not as widely implemented, passive bioremediation is worthy of consideration at the Old Town plume. In contrast to aggressive bioremediation that would be highly intrusive, passive bioremediation resembles an enhanced natural attenuation scheme. Nutrients could be added at discrete points and times, likely with other planned site operations. Dispersion of nutrients and amendments would subsequently be accomplished via passive transport, i.e., simple infiltration and diffusion rather than injection. Native microorganisms growing in the area may then degrade the contaminants over an extended period of time. An example of passive bioremediation could include adding biostimulating amendments whenever borehole or drive point technologies are operational in the plume area. Accordingly, rather than backfilling boreholes with gravel or grout, one could include additions of zero-valent iron, which produces hydrogen, although it also raises the groundwater pH, or other amendments (see above). A recommended treatment would include the addition of slow-release hydrogen compounds, such as lactate or polylactate, that biostimulate resident microorganisms. Other additions, such as carbohydrates or nitrogen and phosphorous containing nutrients, could also be considered. Over the longer term (years to decades), such additions would contribute to bioremedial contaminant degradation at little additional cost. Implementation of passive bioremediation would be straightforward if accomplished during further plume characterization or monitoring activity. In other words, if well borehole infrastructure is used in the area of the plume, then passive bioremediation could likely be implemented with low costs and risks; and positive impacts realized would represent supplemental low risk and high dividend contaminant reduction.

Monitored Natural Attenuation

Monitored natural attenuation (MNA) is the stabilization and long-term shrinking of a contaminant plume (as defined by the isoconcentration contours) by natural processes such as microbial degradation. In general, MNA is considered applicable only to dissolved plumes. This technology has been the subject of active research throughout the world, with investment by universities, companies, and all relevant federal agencies. The Department of Defense, Environmental Protection Agency, United States Geological Survey and DOE, in particular, have invested in the study of MNA for hydrocarbon contaminants. More recently, MNA has been studied for chlorinated solvents. The data suggest that MNA can play a role in a long-term strategy for responsible environmental cleanup for these more challenging contaminants at appropriate sites (i.e., sites with the potential for anaerobic dehalogenation or aerobic co-metabolism).

Until the source term has been effectively removed, MNA is not appropriate for the Old Town plume. Though MNA is the easiest technology to implement, is low cost and exhibits few health and safety risks, it is inappropriate with the source term in place. Migration of the plume or worsening of nearby groundwater quality are concerns with the source term intact. Over the long term and after the source has been removed, MNA could be effective at protecting downstream and downgradient locations from adverse impacts. Additional scientific documentation of performance (the "monitoring" or "M" in MNA) would be critical to implementation and the costs of this have been an impediment to success to date. There is a moderate long-term liability associated with MNA since the contaminants remain in place; this risk is too great as long as the source term remains. The permitting of MNA must overcome the appearance of a "do nothing" alternative, which would be difficult at the present time. If the source were removed, stability of the plume demonstrated with safeguards and action terms identified, then permitting and public acceptability may be obtainable. MNA is a mature technology currently in favor at many sites that no longer contain non-aqueous phase contaminants. At the Old Town plume, MNA is not viable in and of itself since the source area has not been removed.

3.4 Recommendations

The team supports the efforts and progress to date related to the Old Town plume. The following thrusts are recommended to maximize future success.

1. Evaluate additional technologies to complete source removal (see Remedial Alternative discussion above and technology matrix in Table 2 of Appendix D as a resource).
2. Evaluate additional technologies for plume control (see Remedial Alternative discussion above and technology matrix in Table 2 of Appendix D as a resource).
3. Continue modeling to assist in remedial design and communication.
4. Develop a long-term strategy for the plume. Efforts to date have been appropriate (e.g., aggressive source removal by excavation and collection/treatment of the primary plume using trenches). These efforts, completion of source removal and modeling may help in developing a specific and comprehensive long-term strategy that is acceptable to the regulators and stakeholders and that can be implemented and monitored. This would be a significant and relatively unusual achievement for a site of this complexity and initial contaminant levels.

4.0 BUILDING 51/64 PLUME

A plume of VOC-contaminated groundwater, known as the Building 51/64 VOC plume, extends from the southeast corner of Building 64, under Buildings 64 and 51B. This plume is defined by the presence of chlorinated ethanes such as 1,1,1-TCA and its degradative daughter (1,1-DCA). This plume also contains lower concentrations of other solvents such as the chlorinated ethenes – PCE, TCE and 1,1-DCE. In calendar year 2000, prior to a source removal (excavation) effort, chlorinated solvents were detected at high concentrations (greater than 100,000 µg/L) in the most concentrated portion of the Building 51/64 VOC plume. In this area of the plume, near the original source, contaminant solvents were comprised primarily of 1,1,1-TCA (82%) and 1,1-DCA (7%). The contaminant profile shifted toward the less chlorinated (i.e., more weathered) solvents and overall concentrations decreased as distance from the source increased. This pattern, combined with preliminary stable isotope data discussed below, suggests that some natural degradation of the solvents is occurring in the plume as it migrates. In 2000, highly contaminated soil was excavated from the source area as an interim corrective measure. According to the LBNL staff, recent data indicate that concentrations are significantly decreasing in response to the removal action. Figure 4 shows the original (circa 2000) extent of VOCs in groundwater in the Building 51/64 area.

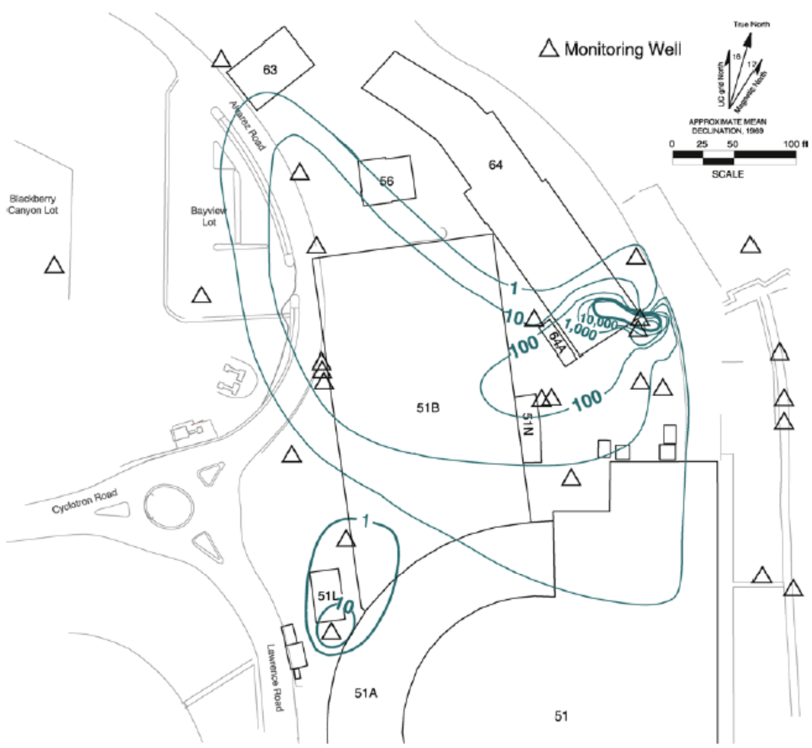


Figure 4. Groundwater Contamination (Total Halogenated Hydrocarbons in µg/L) at Building 51/64 VOC Plume (September 2000) (Source: LBNL Site Environmental Report for 2000, Chapter 6, found on LBNL website: http://www.lbl.gov/ehs/epg/html/env_protection.htm)

The source area has been successfully removed, dispersion of the plume is limited, transport of the plume is slow, and migration is confined by complex geology and formational constraints.

The extremely low hydraulic conductivity has restricted the plume expansion to tens of meters over several decades. Groundwater flows primarily within the surficial units (artificial fill and colluvium) and in the sedimentary rocks of the low permeability Orinda formation. All of the contaminants are inherently biodegradable. Indeed, many of these compounds are daughter products of biodegradation that has already occurred. Contaminant concentration and studies presented to the team by Dr. Mark Conrad of LBNL on stable carbon isotope ratios at this site suggest that biodegradation, via natural attenuation, is already occurring. The site has already experienced reductions in VOCs in the monitoring wells downgradient from the location where the source was removed.

4.1 Critical Issues

The technical assistance team urges the site to consider using the 51/64 plume disposition as a template for establishing cleanup efficacy goals for closure permitting, i.e., establishing an agreed upon natural attenuation scenario with more risk-based cleanup goals based on the geology, hydrology, and biogeochemistry. Negotiations for the 51/64 treatment and closeout permits would hopefully resolve issues related to slowly approaching MCLs over the long-term. While the current strategy appears promising, it is unlikely that MCLs will be reached in the coming decades. Accordingly, this plume could serve as a template for negotiating appropriate cleanup standards for other plumes once they reach lower concentrations of contaminants similar to the 51/64 plume (e.g., Old Town and yet to be characterized plumes).

No other critical issue was identified for this site since the current remediation strategy appears to have considerable merit and MNA appears promising as a final treatment technology.

4.2 Unresolved Issues

The two unresolved issues for the Building 51/64 plume identified by the technical assistance team were that better definition of the plume is needed and that more feasibility studies are needed to use MNA as a treatment option.

Despite heroic efforts at finding, discerning, delineating and then successfully removing the source area of the VOCs, the plume definition, intermediates, daughter products and their transitions are not resolved to an extent sufficient to quantify reaction times and pathways. The daughter product 1,1-DCA concentration approaching 10% of the parent contaminant 1,1,1-TCA concentration is a convincing argument for natural attenuation. Similarly, the significant concentrations of 1,1-DCE as a likely daughter product in the TCE/PCE plumes suggest that natural microbial biodegradation processes are contributing to contaminant reduction. These daughter products were not typically major constituents of the parent solvents and their increasing appearance over time coupled with the shifts to less chlorinated cis-isomers is highly indicative of biologically mediated natural attenuation. Importantly, the stable isotope ratios, wherein the daughter products exhibit a lighter isotopic profile than the parent contaminant, are in agreement with the known biological distinction of several parts per trillion. When combined with the evidence that the overall contaminant concentrations decreased as the distance from the source increased and that those concentrations are decreasing over time at given distances, multiple lines of evidence substantiate biologically mediated natural attenuation. Further, the monitoring evidence reveals that biologically mediated natural attenuation is occurring and if the daughter and primary contaminants of concern isocontours were better defined and if those isocontours further substantiated natural attenuation, then MNA may represent a preferred treatment option. However, the location of the primary contaminant isocontours are not delineated, nor are the contours for the accumulation of daughter products defined. Further plume characterization and modeling are necessary to gain a better understanding of the primary contaminant plume size and shape as well as the isocontours of major degradation products (e.g., DCA and DCE). The delineation of the plume will also enable determination of cross-plume contributions or potential other source terms from nearby areas.

The relatively low distal (tens of meters) contaminant concentrations coupled with isotopically heavier primary contaminants and isotopically lighter daughter products follow the expected 1.5% discrimination typical of biologic reactions. Importantly, the travel distance from the likely source term, which was effectively removed in recent years, appears related to the lower contaminant concentrations, appearance of daughter products, and is in agreement with the expected isotopic distinctions of biological reactions. For these reasons, MNA appears to be a promising remediation technology for the 51/64 plume. Further documentation of MNA by isotopic signature profiles over time, better defined isocontours of daughter products versus parent contaminants, continued shifts in contaminant profiles to lighter contaminants of concern, and decreasing contaminant concentrations over time and space, coupled with improved plume modeling will likely demonstrate and substantiate the ability of MNA to provide appropriate and most suitable remediation technology.

4.3 Remedial Alternatives

Following is a discussion of the remedial alternatives summarized in Table 3 (see Appendix D).

Monitored Natural Attenuation
(Please refer to the description of MNA within the Old Town Plume discussion, on page 27.)

MNA appears to be an appropriate remediation technology for the Building 51/64 chlorinated VOC plume in these highly heterogeneous, extremely low permeability media. Should alternatives be considered, it would be appropriate to consider complements to MNA such as passive or relatively low-aggressiveness bioremediation and/or chemical treatments similar to those used as reactive barrier materials. Such lower-cost, relatively non-aggressive complements to the site remediation strategy may well add value to the long-term site remediation and decrease life cycle costs.

Since the source term has been effectively removed, MNA is the easiest technology to implement and has the lowest cost. Over the long-term, MNA can be effective at protecting downstream and down gradient sites, though there is a moderate long-term liability since the contaminants are degraded slowly in situ, rather than being aggressively treated. If safeguards and action terms could be identified, then permitting risks and public acceptability may be moderate.

For the Building 51/64 plume, MNA is a viable technology since the source term has effectively been removed and the plume does not appear to be migrating or pose significant current risks. Sentinel monitoring of contaminants at the site boundary and validation of plume reduction models over the long-term would ensure that should risks become apparent, appropriate actions could then be implemented.

Excavation
Excavation is a well-demonstrated, mature technology most appropriate for the complete removal of source materials or those grossly contaminated with non-aqueous phase liquids. Permitting risks are low since the most contaminated materials are removed from the site and disposed elsewhere. Disposal raises transportation issues, making implementation good for sources only. Other than transportation and disposal issues, excavation exhibits high public acceptability and the long-term liability is low. However, since excavation has been successfully completed for the 51/64 plume, additional excavation is not appropriate for this plume site.

Water Control
Hydraulic controls represent low cost and high dividend treatment scenarios, though hydraulic control at this site is probably not appropriate unless combined with a treatment option or MNA. The effectiveness of upgradient hydraulic control is low because decreasing flow into the plume would not likely advance cleanup goals. Even down gradient hydraulic control would likely accomplish little because of the low flow rates through the formation. Low potential dividends and high permitting risks with little outyear value would also make it difficult to implement hydraulic controls under buildings, pavement and around the engineered subsurface interferences (drain lines, pipes and conduits). Although there would be very little risk to health or safety, there may be poor public acceptability of hydraulic controls that leave contaminants in the subsurface for longer time frames. As the contaminant residence times would increase with hydraulic controls, there would be a moderate long-term liability associated with moderate to unknown costs, with little likely dividend and longer treatment times. Hydraulic control is not recommended for the 51/64 plume.

Pump and Treat
Pump and treat scenarios for ex situ treatments represent a low level of effectiveness, given the extremely low permeability and high degree of subsurface heterogeneity. Accordingly, many withdrawal wells spaced every few feet may be required, making the cost extremely high. Any such ex situ withdrawal technology would pose considerable difficulty during well installation, operations and implementation, with a considerable likelihood of less than satisfactory contaminant abatement. The high likelihood of residual contaminants remaining in the subsurface makes the permitting risk moderate to high, despite the high installation and implementation costs. If the pump and treat scenario was successful, there would be little health risk and the public would find it acceptable for the contaminants to be removed from the site. Unfortunately, any pump and treat technology in these low permeability media would necessarily last several decades or longer and likely not produce the desired results. Though pump and treat scenarios are a mature technology used elsewhere, they are not recommended here and they have not been successful in other low permeability formations.

Containment

Potential containment approaches include grouts, walls, decreased hydraulic conductivity, or non-reactive barriers. The in situ containment strategy would entomb contaminants in their current position, leaving a moderate permitting risk since the materials would remain in a rather heterogeneous subsurface media that is fractured and at some locations exhibits mechanisms of dispersal, albeit slowly. Containment would be difficult to implement beneath and around buildings and roads. The numerous underground conduits would add to the difficulty of implementation and decrease the effectiveness of entombment. The cost of three-dimensional containment on these LBNL hill slopes and in these fill materials would be high, with a very low public acceptability, as the contaminants would remain in place. Accordingly, there would necessarily be a long-term liability for the wastes and any seepage thereof. Containment of these wastes in the heterogeneous subsurface media is not recommended at this site, though the technology is mature and often recommended at other locations.

Chemical Reactive Barrier

Chemical reactive barriers represent an in situ treatment strategy that may have merit at LBNL, though this plume may not be the ideal location. Given time and flow, reactive barriers can be moderately effective, and because they treat the wastes by forming non-toxic products, they have a low permitting risk and a moderate public acceptability as the wastes are destroyed, but over long periods of time.

Major drawbacks to barriers at the 51/64 plume include the health and safety risks associated with a very large hill slope construction project in close proximity to buildings and heavily used roads. Barrier technology could be implemented with some moderate risk and at high cost. The safety procedures and massive construction infrastructure could impede road access, utilities, nearby building integrity/operations, and potentially other site actions. The length of barrier operations often exceeds a decade and, in these tight formations, treatment may endure several decades because of the time for transport of contaminants to the barrier. Long treatment times, the potential need to exchange treatment barrier contents, and the high degree of site manipulation will require the acceptance of long-term liability and likely will negatively impact public acceptance of barrier treatments. Reactive barriers are a mature technology, though success is not assured.

Bioremediation

(Please refer to the description of bioremediation within the Old Town Plume discussion, on page 26.)

Although bioremediation is an in situ treatment technology routinely applicable to organic contaminants, the heterogeneous and low permeability nature of the 51/64 subsurface media suggests that the delivery of nutrients would be extremely difficult. Though not as widely implemented, passive bioremediation is worthy of consideration at this particular plume. Passive bioremediation resembles an enhanced natural attenuation scheme where nutrients are added at discrete points and times with dispersion subsequently accomplished via passive transport. Over time, native microorganisms are stimulated to degrade the toxicants at a higher rate than they would naturally.

4.4 Recommendations

1. MNA appears to be a promising remediation technology for the 51/64 plume and demonstration of successful MNA at the site should be pursued. Isotopic signature profiles over time, better defined isocontours of daughter products versus parent contaminants, continued shift of contaminant profiles to lighter contaminants of concern, decreasing contaminant concentrations over time and space, continued observance of the several parts per trillion isotopically lighter daughter products expected from biological distinction, coupled with improved plume modeling will demonstrate and substantiate the ability of MNA to provide an appropriate and suitable remediation technology.
2. Plume 51/64 should be used as a template for negotiating cleanup efficacy standards that could then provide guidance for other plumes unlikely to reach MCLs within several decades in these extremely low permeability subsurface media. Successfully demonstrating that MNA is suitable, appropriate and effective at this plume should serve as a template for stakeholder and regulatory endorsement, enabling the site to negotiate cleanup strategies and protocols for MNA at other VOC plumes, potentially including portions of the Old Town area post source removal.
3. Passive in situ remediation should be employed as a supplement to MNA. Passive bioremediation may provide a reasonable, low-cost supplement to MNA, particularly if further coring/boring/encroachments into the subsurface occur. For example, supplementing boreholes with organics such as hydrogen-releasing compounds or nutrient supplements may prove beneficial at very low costs. Chemical reactive barrier materials may also be considered for use as fill agents for any new boreholes. Rather than using gravel, the site could consider using combinations of supplemental technologies such as zero-valent iron and/or passive bioremediation treatments at low additional costs. Although these technologies would likely be more appropriate for the Old Town site, they may add value to the remediation of the 51/64 plume.

5.0 SUMMARY AND CONCLUSIONS

During the closeout session, members of the technical assistance team conveyed to the site how impressed they were at the thoroughness of the site's investigation and attempts at remediation. Team members were uniformly pleased at the skilled detection work to identify sources, make quick remediation decisions, and change course when a strategy did not work well. The technical assistance team also noted that, to their knowledge, this is the only DOE site at which a world-class scientist has had primary responsibility for the environmental restoration activities. This has undoubtedly contributed to the successes observed and DOE should take careful note. The following overall recommendations were agreed upon:

1) The site has done a phenomenal job of characterization and identifying and removing source terms.
2) Technologies selected to date are appropriate and high impact, e.g. collection trenches are an effective remedial strategy for this complicated geology. The site should continue using technology that is adapted to the site's unique geology, such as the collection trenches.
3) The site should develop a better way to determine the basis of cleanup for all sites.
4) The sentinel well system should be evaluated and modified, if needed, to assure that the sentinel wells provide coverage to the current site boundary. Potential modifications could include installation, abandonment or relocation of wells based on the large amount of data collected since the original sentinel well system was designed.
5) Modeling to assist in remedial design and communication should continue.
6) The site should develop a plan to ensure institutional memory.
7) The most likely possibility for improving closure to 2006 is by removing the residual source of the Old Town plume and establishing the efficacy of remediation for the 51/64 plume.

6.0 REFERENCES

California Department of Health Services, 2002. *Drinking Water Standards, Proposed Regulations*. (Available on the Internet at http://www.dhs.ca.gov/ps/ddwem/publications/Regulations/regulations_index.htm#PROPOSED%20REGULATIONS.)

Charbeneau, R.X., T.C. Hazen, and B.B. Looney, 2002. *Assessment of Potential Benzene Contamination of the Ogallala Aquifer at the Pantex Plant, Texas*.

Department of Defense, 2002. *Two Phase (Dual Phase) Extraction Technology Web Page*. http://erb.nfesc.navy.mil/restoration/technologies/remed/phys_chem/phc-38.asp, 8/05/02.

EPA, 1999. *Multi-Phase Extraction: State of the Practice*. EPA 542-R-99-004, U. S. Environmental Protection Agency, Washington D.C.

EPA, 1997. Memorandum on Establishment of Cleanup Levels for CERCLA Sites with Radioactive Contamination. OSWER No. 9200.4-18.

EPA, 1995. *How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: A Guide for Corrective Action Plan Reviewers*. EPA 510-B-95-007, U. S. Environmental Protection Agency, Washington D.C.

EPA, 1990. *Development of Electro-Acoustical Soil Decontamination (ESD) Process) for In Situ Applications*, EPA/540/5-90/004, U. S. Environmental Protection Agency, Washington D.C.

Fulbright, H.H., A.L. Shwirian-Spann, K.M. Jerome, B.B. Looney, and V. Van Brunt, 1996. *Status and Practicality of Detritiation and Tritium Reduction Strategies for Environmental Remediation*. WSRC-RP-96-0075, Westinghouse Savannah River Company, Aiken, SC.

Gollon, P.J., N. Rohrig, M.G. Hauptmann, K. McIntyre, R. Miltenberger, and J. Naidu, October 1989. *Production of Radioacitive Material in Local Soil at AGS Fast Neturino Beam*, BNL-43558, Brookhaven National Laboratory.

Jarosch, T. R., R. J. Beleski, and D. Faust, 1994. Final Report: In Situ Radio Frequency Heating Demonstration. WSRC-TR-93-673, Westinghouse Savannah River Company, Aiken, SC.

LBNL, September 1999. *Guidelines for Generators to Meet HWHF Acceptance Requirements for Mixed Wastes at Berkeley Lab*. Waste Management Group, Environment, Health and Safety Division, Lawrence Berkeley National Laboratory, Revision 4, University of California Berkeley, CA 94720 PUB-3092. (Also available on the Internet at http://www.lbl.gov/ehs/waste/pub3092/mix/mixed_waste.htm.)

LBNL, 2000. *LBNL Site Environmental Report*. (http://www.lbl.gov/ehs/epg/html/env_protection.htm)

Lessard, E.T., 1998. *Environmental and Safety Issues Associated with a 30-GeV Proton Synchrotron*.

Nyer, E. K., S. Fam, D. F. Kidd, F. J. Johns II, G. Boettcher, P. L. Palmer, S. S. Suthersan, and T. L. Crossman, 1996. *In Situ Treatment Technology*. CRC Press, Boca Raton FL.

LBNL, February 2002. *Quarterly Progress Report for LBNL Environmental Restoration Program, Fourth Quarter of FY01*.

SCFA Lead Lab, October 2001. *SCFA Lead Lab Technical Assistance Review of Benzene Detection in Groundwater at the Pantex Plant*.

Susskind, H., 1972. *An Analysis of the Safety of the Brookhaven Linac Isotope Producer (BLIP)*, Department of Applied Science, Brookhaven National Laboratory.

APPENDIX A: TECHNICAL ASSISTANCE REQUEST

(E-mail to susan.meyer@srs.gov, fax to Susan Meyer at 803-725-4129, for the Lead Laboratory)

Tracking Number:	114
Request Title:	Technical Assistance Baseline Review at Lawrence Berkeley National Laboratory
Contact Individual:	Hemant Patel
Requesting Organization:	U.S. DOE – Oakland Operations Office
E-Mail Address:	hemant.patel@oak.doe.gov
Phone Number:	(510) 637-1568
Fax Number:	(510) 637-2031

Scope of Work:

The assistance request is for three groundwater plumes at Lawrence Berkeley National Laboratory.

Building 75 Tritium Plume – The source of groundwater contamination, primarily tritium, around Building 75 is the National Tritium Labeling Facility. Tritium concentrations are generally below the MCL of 20,000 pCi/L, except at one well where concentrations vary in the range of 20,000 to 35,000 pCi/L. Groundwater flows primarily within the relatively impermeable Orinda Formation ($K \approx 1x10^{-8}$) with the exception of locations where fill materials have been utilized.

Building 51/64 VOC Plume – The Building 51/64 plume consists primarily of 1,1,1-TCA, TCE, 1,1-DCE, 1,1-DCA, PCE, and other halogenated VOCs, with mean concentrations of total halogenated VOCs greater than 100,000 μg/L prior to source removal. Groundwater flows primarily within the surficial units (artificial fill and colluvium) and in the volcanic rocks of the relatively permeable Moraga Formation.

Old Town Area Plume – The main Old Town Area plume is multi-lobed and contains standard industrial solvents including PCE, TCA, TCE, carbon tetrachloride and their degradation byproducts.

Relatively permeable Moraga Formation volcanic rocks overlie the low permeability Orinda formation over much of the Old Town Area. Groundwater flows primarily through these units, below the surficial units. The entire LBNL site is dominated by a steep slope that has been modified by erosion of several steep stream canyons, by landslides, and by cut-and-fill activities.

Past/present corrective actions and pilot tests include:

- Sewer line leak repair, well upgrade, and emissions reduction at Building 75 (NTLF)
- Source removal (Building 51/64) and pump and treat system installation
- Source removal (sump), collection trenches, dual phase soil vapor extraction, soil heating pilot test, enhanced bioremediation pilot test utilizing methane injection, and extraction wells for plume containment (Old Town)

LBNL would like recommendations for remediating the tritium plume in a cost-effective manner, as well as suggestions for improving the current remediation plans for the 51/64 and Old Town plumes and ascertaining whether current plans are adequate.

Support:

What resource(s) have been selected?

What resources were offered, but not selected?

Requested Start Date:	1/1/02	**Requested Completion Date:**	4/15/02
Estimated Cost:			

Submitted By:

APPENDIX B: PARTICIPANTS AND CONTACT INFORMATION

SCFA LEAD LAB TECHNICAL ASSISTANCE: LAWRENCE BERKELEY NATIONAL LABORATORY BASELINE REVIEW
MAY 15-16, 2002 BERKELEY, CA

Name	Organization	E-Mail	Phone	Fax
Technical Assistance Team:				
John Evans	PNNL	John.evans@pnl.gov	509-376-0934	509-372-1704
Terry C. Hazen	LBNL	TCHazen@lbl.gov	510-486-6223	510-486-7152
Brian Looney	SRTC	Brian02.looney@srs.gov	803-725-3692	803-725-7673
Tommy J. Phelps	ORNL	phelpstj@ornl.gov	865-574-7290	865-576-3899
Terry Sullivan	BNL	Tsullivan@bnl.gov	631-344-2840	631-344-4486
Others:				
Christina Richmond	EnviroIssues	crichmond@enviroissues.com	206-269-5041	206-269-5046
Iraj Javandel	LBNL	ijavandel@lbl.gov	510-486-6106	510-486-8694
Hemant Patel	DOE-OAK	Hemant.patel@oak.doe.gov	510-637-1568	510-637-2031
Salma El-Safwany	DOE-OAK	Salma.elsafwany@oak.doe.gov	510-637-1548	510-637-2003
Mark Conrad	LBNL	MSConrad@lbl.gov	510-486-6141	510-486-5496
Jens Birkholzer	LBNL	JTBirkholzer@lbl.gov	510-486-7134	510-486-5686

Quanlin Zhou	LBNL	QLZHOU@lbl.gov	510-486-5344	510-486-5686
Carl Schwab	DOE/B50	Carl.schwab@oak.doe.gov	510-486-4298	510-486-4710

*David Eaton, INEEL, kindly provided additional technical expertise on mixed waste regulatory issues.

APPENDIX C BACKGROUND ON TECHNICAL ASSISTANCE TEAM

JOHN C. EVANS

Staff Scientist, Grade 5, Field Hydrology and Chemistry Group
Battelle-Pacific Northwest Laboratory
Sigma 5 Building, Rm. 1220 MSIN K6-96, 3110 Port of Benton Blvd, PO Box 999
Richland, WA 99352
(509) 376-0934
john.evans@pnl.gov

Education:
Ph.D. in Chemistry, University of California at San Diego (1971)

Areas of Expertise:
- Source term characterization
- Groundwater monitoring
- Contaminant source removal
- In-situ remediation

TERRY C. HAZEN

Head, Center for Environmental Biotechnology
Head, Microbial Ecology & Environmental Engineering Department
Lead, Environmental Remediation Technology Program
Lawrence Berkeley National Laboratory
Earth Sciences Division, MS 70A-3117
Berkeley, CA
(510) 486-6223
tchazen@lbl.gov

Education:
Ph.D. in Microbial Ecology, Wake Forest University, Winston-Salem, North Carolina (1978)

Areas of Expertise:
- Bioremediation (In Situ and Ex Situ)
- In Situ Remediation
- Water Quality

BRIAN B. LOONEY

Senior Fellow Research Engineer
Savannah River Technology Center
Building 773-42A, Aiken, SC
(803) 725 3692 or (803) 725 2418
brian02.looney@srs.gov

Education:
Ph.D. in Environmental Engineering, University of Minnesota (1984)

Areas of Expertise:

- Innovative characterization methods, sensors and samplers
- Bioremediation, heating, and chemical remediation technologies
- Cleanup of source zone contamination (using destruction and/or enhanced removal methods), and methods for dilute fringe contamination (barometric pumping and phytoremediation)

TOMMY J. PHELPS

Environmental Sciences Division, Oak Ridge National Laboratory
Oak Ridge, TN 37831-6036,
865-574-7290, email: phelpstj@ornl.gov

Education:
Ph.D. in Bacteriology, University of Wisconsin, Madison (1985)

Areas of Expertise:

- Bioremediation
- Microbiology

TERRY SULLIVAN

Staff Scientist
Environmental Research Division, Brookhaven National Laboratory
Building 830, P. O. Box 5000
Upton, NY 11973
(631) 344-2840
tsullivan@bnl.gov

Education:
Ph.D. in Nuclear Engineering, University of Illinois (1983)

Areas of Expertise:

- Subsurface characterization and modeling
- Low-level waste source term analysis and disposal performance assessment
- Source term analysis and modeling of the tritium plume at BNL
- Long term performance for caps and covers
- Risk assessments

APPENDIX D: EVALUATION OF REMEDIAL STRATEGIES

Table 1. National Tritium Labeling Facility Plume

Remediation Technology	**Remediation Strategy**	**Effectiveness**	**Permitting Risk**	**Implementability**	**Health and Safety Risk**	**Cost**	**Public Acceptability (Stakeholder)**	**Long-term Liability**	**Technical Maturity**	**Overall Recommendations**
Excavation	Removal	Limited because non-point source	Acceptable	Intrusive	Relatively increases risk than no action	High	High; however, the public may have transportation concerns.	Minimal, except for slope instability	Mature	Inappropriate; does more harm than good.
Water Control	Hydraulic control	Upgradient: high Downgradient: high	Upgradient: low risk Downgradient: moderate risk	Upgradient: Good Downgradient: Good	Upgradient: Low Downgradient: Low	Upgradient: Low Downgradient: Low	Upgradient: High Downgradient: Moderate	Upgradient: Moderate Downgradient: Moderate	Mature	The best strategy
Pump and Treat	Ex-situ treatment	There are no known cost-effective technologies for separation and treatment of ^3H in GW.	NA	NA	NA	Very high	High	NA	No	Not recommended
Containment	Containment	A few strategic uses	Low	Moderate	Low	Moderate	Moderate to low (because not doing anything)	Moderate to high	Mature	Not as good as water but may have strategic application. (Example: old pipes and high flow sand lenses.)
Phytoremediation	removal	Low	Low	Easy	Low	Low	Low (transferring to air)	Moderate	Mature	Not recommended to change from existing baseline
Chemical Reactive/ Bioremediation	In Situ treatment	No	NA	NA	NA	NA	NA	NA	No	Not recommended

Remediation Technology	**Remediation Strategy**	**Effectiveness**	**Permitting Risk**	**Implementability**	**Health and Safety Risk**	**Cost**	**Public Acceptability (Stakeholder)**	**Long-term Liability**	**Technical Maturity**	**Overall Recommendations**
Monitored Natural Attenuation	In Situ treatment	Medium	Low	Easy	Low	Low	Low	Moderate	Mature	Viable; best with hydraulic control.
Metered discharge to sanitary sewers (Pump and Sewer)	Ex-situ treatment	Dilution	Not necessary	Easy	Low	Low	Low	Moderate	Mature	Not recommended (worse than leaving where it is)

Table 2. Old Town Plume

Remediation Technology	**Remediation Strategy**	**Effectiveness**	**Permitting Risk**	**Implementability**	**Health and Safety Risk**	**Cost**	**Public Acceptability (Stakeholder)**	**Long-term Liability**	**Technical Maturity**	**Overall Recommendations**
Excavation	Removal	May be applicable to remaining source (still have 17 feet further)	High	Difficult	High, due to potential building instability	High for additional (Require lots of engineering)	High	Low	Mature	Only appropriate for remaining source after engineering studies
Soil Vapor Extraction (SVE)	Removal	Limited: source zone sediments have low permeability, high heterogeneity. Technology only applicable to contaminants above the groundwater.	Low	Easy – But see Effectiveness for discussion of limitations	Low	Low but will require long period of sustained operation	High	Moderate – requires extended operation	Mature	Could be a component of source zone cleanup, with enhancements to improve mass transfer and removal rates
Surfactant Flushing and Cosolvent Flushing	Chemical extraction	Limited: heterogeneous source zone; requires complete control of fluids for injection, contact and recovery.	Moderate – Requires control of system to eliminate undesirable mobilization and loss of source solvent.	Difficult	Low	High	Moderate (see permitting risk)	Low	Available	Not recommended. There are better choices
Sparging	Chemical (phase) extraction	Limited: heterogeneous source zone.	Moderate – Requires documentation that air injection will not spread source contaminant.	Difficult	Low	High	Moderate	Low	Available	Not recommended. There are better choices
Source Zone Isolation Methods	Containment	Low	Moderate	Difficult	Moderate	High	Low	High	Mature	Not recommended. There are better choices

Remediation Technology	Remediation Strategy	Effectiveness	Permitting Risk	Implementability	Health and Safety Risk	Cost	Public Acceptability (Stakeholder)	Long-term Liability	Technical Maturity	Overall Recommendations
Chemical Oxidative Technologies	In Situ treatment	Limited: heterogeneous source zone; requires complete control of fluids for injection and contact	High	Difficult	High – requires storage, handling, and use of large volumes of strong oxidants.	High	Moderate	Low	Young	Not recommended. There are better choices
Radiant/ Conductive Heating	In Situ treatment	Moderate	Low	Easy	Low	Moderate	High	Low	Mature	Viable with steps to prove extraction efforts
Joule Heating (Six-Phase Heating)	In Situ treatment	Moderate	High: Joule has problems that are known to regulators	Difficult due to interferences	High	High (cost influenced by power needs, short circuiting)	Moderate	Low	Young	Difficult because of cultural interferences, not demonstrably superior to other heating
ElectroOsmosis	Enhanced removal	Limited but may be promising for heterogeneous low permeability system. Only removes dissolved source.	Low	Difficult due to young technology	Low	High	High	Low	Young	Pilot test recommended
Steam Flushing	In Situ treatment	Low because of poor delivery	High	Difficult	High	High	Moderate (removing source)	Low	Young for this material	Not recommended. There are better choices
Radio Frequency heating	In Situ treatment	Moderate	Moderate	Difficult due to interferences	Moderate	High	Moderate	Low	Young	Difficult because of cultural interferences, not demonstrably superior to other heating
Sonic Enhancement	In Situ improvements	Low to moderate	Moderate	Moderate	Low	Low	Moderate	Low	Very young	Worthy of investigation if past limitations can be overcome

Remediation Technology	Remediation Strategy	Effectiveness	Permitting Risk	Implementability	Health and Safety Risk	Cost	Public Acceptability (Stakeholder)	Long-term Liability	Technical Maturity	Overall Recommendations
Fracturing	In Situ improvements	Moderate	Moderate to high	Difficult due to interferences	Moderate	High	Moderate	Low	Young	Difficult because of cultural interferences
Soil mixing	In Situ improvements	Moderate	Moderate	Moderate	Moderate to high (no worse than fracturing)	Moderate to high	Moderate	Low	Mature	Worthy of investigation, could complement other technologies
Water Capture and reinjection	Hydraulic control	Upgradient: low (broad area) Downgradient: moderate within plume	Upgradient: moderate Downgradient: moderate	Difficult due to buildings, topography, engineered structures, etc.	Upgradient: Low Downgradient: Low	Moderate	Low	High	Mature	Probably not applicable unless in combination with treatment
Pump and Treat	Ex-situ treatment	Low without source removal	Low	Moderate	Low	Moderate (collection wall system working reasonably well in this geology)	High	High without source removal	Mature	Recognized as an interim action.
Chemical Reactive Barrier	In Situ treatment	Low without source removal	Moderate because raising pH	Moderate	Moderate	High	Moderate	High without source removal	Mature	Applicable with implementation in trenches but problematic without source removal
Bioremediation	In Situ treatment	Low, passive better	Low	Low, passive better	Low	Active: High Passive: Low	High	Long-term: low Passive: Moderate	Mature	Possible, recommended as supplemental
Monitored Natural Attenuation	In Situ treatment	Low because too much quantity	High	Easy	Low	Low	Low	High	Mature	Not appropriate for this site until source is removed and plume is demonstrably remediated by active techniques

Table 3. Building 51/64 Plume

Note: The technical assistance team did not consider certain physical and chemical techniques because this is a large, diffusive plume and the source has been removed. Thermal treatments, oxidative treatments, and using surfactants were considered but deemed not applicable. Phytoremediation was considered for diffusive plumes, but roots do not grow that deep (25 feet). Cryogenic remediation (a physical technique) was not considered because slope falls in.

Remediation Technology	**Remediation Strategy**	**Effectiveness**	**Permitting Risk**	**Implementability**	**Health and Safety Risk**	**Cost**	**Public Acceptability (Stakeholder)**	**Long-term Liability**	**Technical Maturity**	**Overall Recommendations**
Monitored Natural Attenuation	In Situ treatment	Moderate	Moderate (trying to overcome appearance that not doing anything)	Easy	Low	Low	Moderate without source	Moderate	Mature	Viable
Excavation	Removal	Complete source removal	Low	Good for source only	NA to remainder	Done for source	High; however, the public may have transportation concerns.	Low	Mature	Only appropriate for source (done)
Water Control	Hydraulic control	Upgradient: low Downgradient: low	Upgradient: high Downgradient: high	Difficult due to buildings, etc.	Upgradient: Low Downgradient: Low	Unknown	Low	Moderate	Mature	Probably not applicable unless in combination with treatment or MNA
Pump and Treat	Ex-situ treatment	Difficult because of heterogeneity and low permeability	Low to moderate	Moderate to difficult (will require many wells)	Low	High because of difficulty installing wells	High	High – must run forever	Mature	Not recommended
Containment (grout, walls, other physical containment)	Containment	Low	Moderate	Difficult	Moderate – many manipulations and containments still present	High	Low	High	Mature	Not recommended
Chemical Reactive Barrier	In Situ treatment	Medium	Low	Moderate	Moderate- large construction operation	High	Moderate because will take a long time	Moderate to high (will have to replace wall in 18 years)	Mature	Viable but more applicable to Old Town site

Remediation Technology	Remediation Strategy	Effectiveness	Permitting Risk	Implementability	Health and Safety Risk	Cost	Public Acceptability (Stakeholder)	Long-term Liability	Technical Maturity	Overall Recommendations
Bioremediation	In Situ treatment	Active: Low (delivery difficult) Passive: better	Low	Active: Low Passive: better	Low	Active: High Passive: Low	High	Low passive	Mature	Passive recommended as supplemental

APPENDIX E PICTURES

NTLF Plume

The stack through which airborne tritium is released from the NTLF is located upslope of the facility.

Dr. Iraj Javandel explains to the technical assistance team the site's previous remediation efforts and current detection of tritium.

Old Town Plume

Trench behind LBNL Building 7. This is the location of the original source of the Old Town plume – a sump filled with PCE.

Pump and treat equipment located near Building 5.

A slope within the area of the Old Town plume.

Remediation equipment

Building 51/64 Plume

The Building 51/64 plume is traveling down this slope toward Building 46.

Members of the technical assistance team met with site representatives to discuss remediation efforts.