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Screening of Potential Remediation Methods for the 200-ZP-1 Operable Unit at the Hanford Site

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August 2006

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Summary

A screening-level evaluation of potential remediation methods for application to the contaminants of concern (COC) in the 200-ZP-1 Operable Unit at the Hanford Site was conducted based on the methods outlined in the *Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA Interim Final* (EPA 1988). The scope of this screening was to identify the most promising remediation methods for use in the more detailed analysis of remediation alternatives that will be conducted as part of the full feasibility study. The screening evaluation was conducted for the primary COC (potential major risk drivers) identified in the remedial investigation report (DOE-RL 2006). COC with similar properties were grouped for the screening evaluation.

The screening evaluation was conducted in two primary steps. The initial screening step evaluated potential remediation methods based on whether they can be effectively applied within the environmental setting of the 200-ZP-1 Operable Unit for the specified contaminants. In the second step, potential remediation methods were screened using scoping calculations to estimate the scale of infrastructure, overall quantities of reagents, and conceptual approach for applying the method for each defined grouping of COC. Based on these estimates, each method was screened with respect to effectiveness, implementability, and relative cost categories of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) feasibility study screening process defined in the U.S. Environmental Protection Agency (EPA) guidance (EPA 1988).

Based on the screening evaluation criteria, potential remediation methods were comparatively evaluated to identify those most promising for continued evaluation as part of the feasibility study. Only a few methods are applicable to all COC. Thus, identification of the most promising potential remediation methods was categorized by COC group. Multiple scales of application may be useful for the overall remediation efforts in the 200-ZP-1 Operable Unit. For this reason, identification of the most promising potential remediation methods was also categorized by the scales of application identified in the effectiveness evaluation criteria. This resulting matrix of most promising potential remediation methods is intended to provide information to support either use of a single remedy or a “treatment train” approach as part of the feasibility study for the 200-ZP-1 Operable Unit.

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1.0 Introduction

A screening-level evaluation of potential remediation methods for application to the contaminants of concern (COC) in the 200-ZP-1 Operable Unit at the Hanford Site was conducted based on the methods outlined in the *Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA Interim Final* (EPA 1988). The scope of this screening was to identify the most promising remediation methods for use in the more detailed analysis of remediation alternatives that will be conducted as part of the full feasibility study. The screening evaluation was conducted for the primary COC (potential major risk drivers) identified in the remedial investigation report (DOE-RL 2006). The primary COC were grouped, as shown in Table 1.1, based on similarity in chemical/physical properties such as mobility and/or, for the most part, the same remediation methods would apply to each contaminant in the group. Additional human health or ecological COC that are not also primary COC were identified in the remedial investigation report as Group B and include chloroform, tetrachloroethene, 1,2-dichloroethane, antimony, iron, hexavalent chromium, and cyanide. These compounds are termed secondary COC for the purpose of the screening evaluation. The screening evaluation includes assessment of whether the potential remediation methods identified for the primary COC have a positive or negative impact on these secondary COC.

Table 1.1. Primary COC Groupings Used in the Screening Evaluation

COC Group	Contaminants
Group 1 (selected VOC)	Carbon tetrachloride and trichloroethene
Group 2 (mobile metals and radionuclides)	Chromium, technetium-99 (Tc-99), iodine-129 (I-129), and uranium (uranium-234, uranium-235, uranium-238)
Group 3 (nitrate)	Nitrate
Group 4 (tritium)	Tritium

2.0 Conceptual Model

A generalized conceptual model of the volume, nature, and extent of contamination and the environmental setting for the 200-ZP-1 Operable Unit was developed for use in the screening evaluation. For the purposes of this analysis, the conceptual model addresses the eight primary COC. The plume boundaries were selected based on the following concentrations, which are consistent with the anticipated target action levels.

- Carbon tetrachloride (5 μg/L)
- Trichloroethene (5 μg/L)
- Chromium (100 μg/L)
- Technetium-99 (900 pCi/L)
- Iodine-129 (1 pCi/L)
- Uranium (30 μg/L)
- Nitrate (45 mg/L as NO_3)
- Tritium (20,000 pCi/L)

The overall extent of these contaminants at the top of the unconfined aquifer in the 200-ZP-1 Operable Unit for fiscal year (FY) 2005 is shown in Figure 2.1. The carbon tetrachloride plume extending into the 200-UP-1 Operable Unit is considered with the 200-ZP-1 contamination.

Both the area of aquifer with contaminant levels above target action levels and the volume of contaminated aquifer are important for screening of potential remediation methods. In addition, the area and volume containing higher levels of contamination (e.g., source areas) was considered in the screening evaluation.

The conceptual model and associated figures and tables were developed using data from the *Hanford Site Groundwater Monitoring for Fiscal Year 2005* (Hartman et al. 2006) except as noted. Specifically, the areal extent of contamination at levels above the target action level and higher levels of concern are calculated from the contamination contours included in Hartman et al. (2006). Average concentrations refer to the average of the data values in Hartman et al. (2006) over the indicated timeframe. There is greater uncertainty in depth of contamination than for the lateral extent at the water table. Some plumes are known to extend farther in some directions at depth than is shown on the concentration maps at the top of the aquifer (near the water table). In general, for most constituents data are insufficient to fully define the three-dimensional extent. However, the resulting uncertainty in contaminated area is not likely to have a significant impact on the screening calculations. Where thickness of contamination is poorly defined, the contaminant volume is generally calculated as being throughout the aquifer to the top of the Ringold lower mud unit, which is ~55 m below the water table in the 200 West Area. For the 200-ZP-1 Operable Unit, the water table is on the order of 100 m below ground surface. This thickness of vadose zone is an important factor in the cost and implementability of remediation. Specific impacts of the thick vadose zone are discussed in the review of individual technologies. The aquifer is heterogeneous with vertical and lateral variations in particle size distribution and cementation that impact the hydrogeologic characteristics of the aquifer. Implementation of any technology is impacted by this heterogeneity. In some cases, this heterogeneity renders a technology unsuitable as discussed in the review of individual technologies.

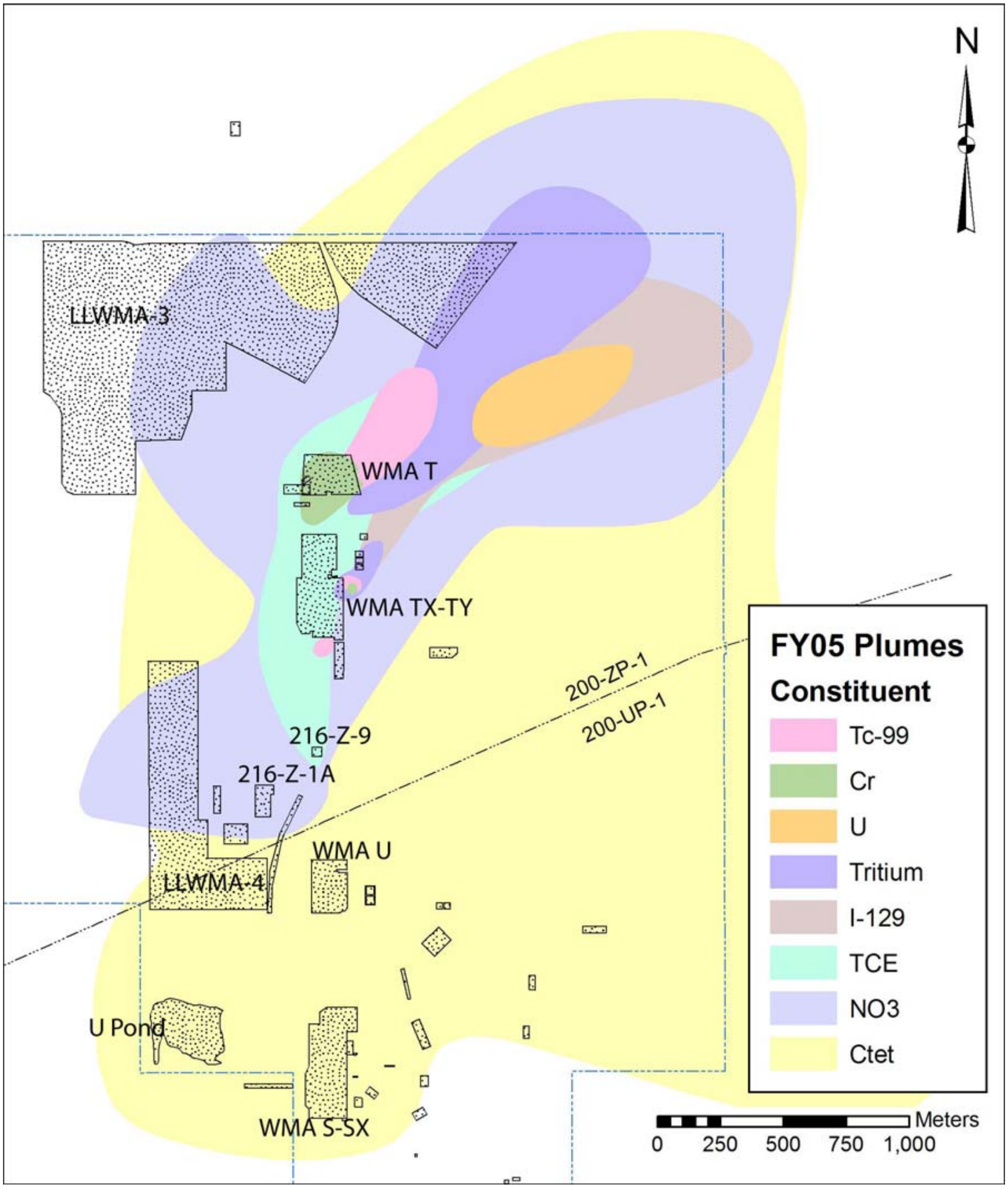


Figure 2.1. Extent of Major Constituents of Concern at Levels above Drinking Water Standards for the 200-ZP-1 Operable Unit (from Hartman et al. 2006)

The following sections define the conceptual model for each COC. Based on this information the areal extent of treatment for each COC is shown in Table 2.1. Note that these are not the exact areal extent shown for each COC, but are a selected set of areas for use in estimating the scale of treatment relevant to plume elements. The impact of treating a selected volume in terms of meeting the overall remediation goals was not assessed as part of the screening evaluation. The fate and transport evaluation necessary to assess the impact to the overall remediation goal will be conducted as part of the subsequent feasibility study.

Table 2.1. Areal Extent Considered in Screening for each Contaminant of Concern

COC	Areal Extent Considered in Screening (acre)
Carbon tetrachloride	1, 5, 25, 250, >250
Trichloroethene	1, 5, 25, 250
Chromium	1, 5, 25
Technetium-99	1, 5, 25
Iodine-129	1, 5, 25, 250
Uranium	1, 5, 25
Nitrate	1, 5, 25, 250, >250
Tritium	1, 5, 25, 250

2.1 Carbon Tetrachloride

Carbon tetrachloride forms the most extensive area of contamination in the 200-ZP-1 Operable Unit (Figure 2.2). The contamination extends into the 200-UP-1 Operable Unit. The entire area of contamination will be evaluated for the 200-ZP-1 Operable Unit because the major contaminant sources are believed to be located near the Plutonium Finishing Plant in 200-ZP-1. Other sources may also be present near the Waste Management Area (WMA) T Tank Farm; however, these have not been specifically identified. The areal extent for the plume was determined based on the near water-table concentration distribution. The thickness of the plume was determined based on the interpolated three-dimensional distribution of carbon tetrachloride in Murray et al. (2006). The thickness from the interpolated distribution was then multiplied by the corresponding areal extent from the near water-table distribution. This projection presumes that treatment would extend from the water table downward to the deepest contamination at a selected concentration level. Note that there are differences in the three-dimensional interpolation of the plume and the near water-table distribution. However, these differences were not considered for the screening evaluation.

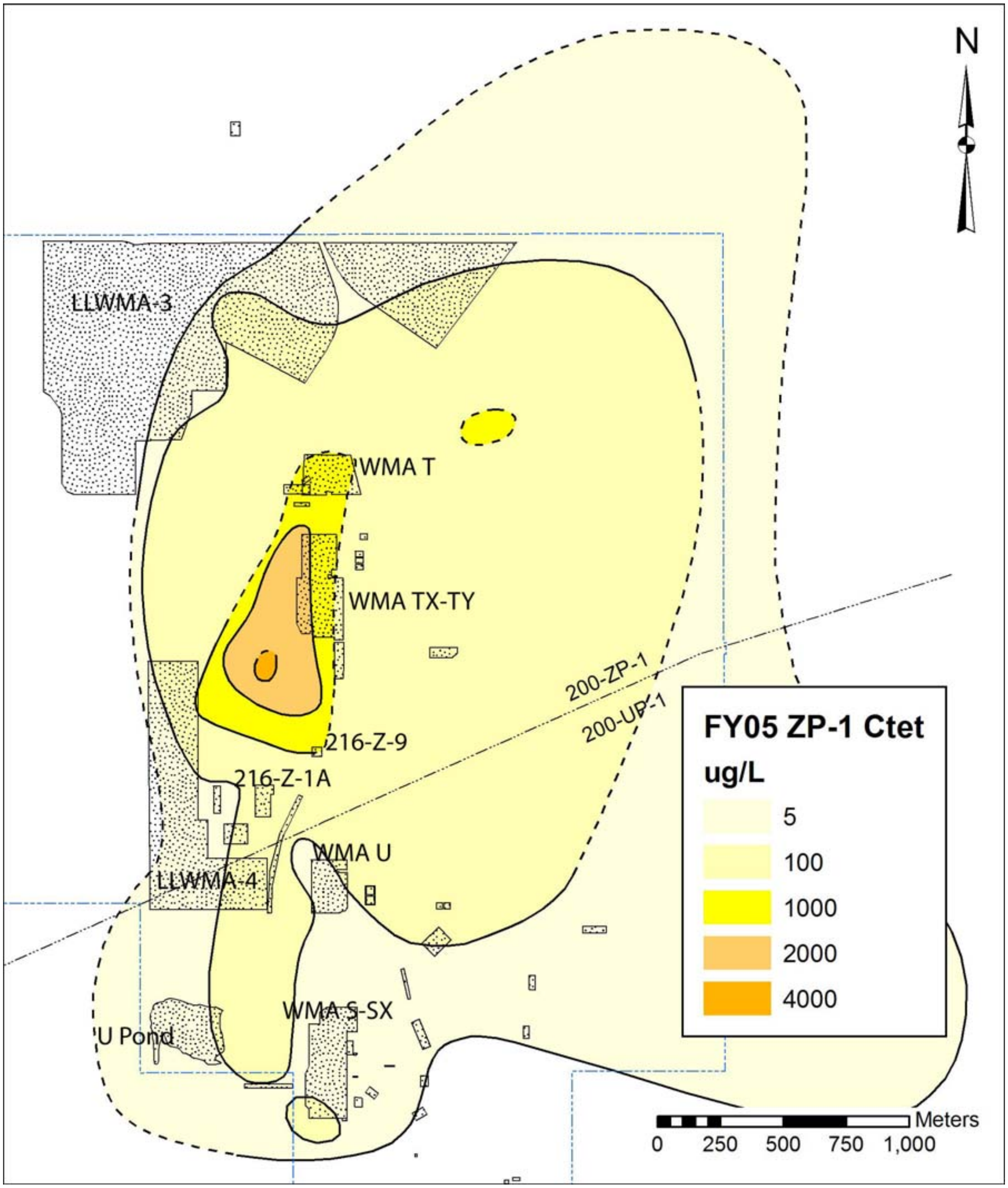


Figure 2.2. Average Carbon Tetrachloride Concentrations in 200 West Area, Top of Unconfined Aquifer

The area and volume calculations for the carbon tetrachloride contamination are summarized in Table 2.2.

Table 2.2. Area and Volume of Carbon Tetrachloride Contamination for Remediation Technology Screening

Concentration (µg/L)	Area m^2 (acre)	Thickness (m)	Aquifer Volume (m^3)
5	10,861,822 (2,700)	60	651,709,320
100	4,912,591 (1,220)	60	294,755,460
1,000	450,117 (112)	30	13,503,510
2,000	182,996 (45)	20	3,659,920
4,000	11,827 (2.9)	20	236,540

For the screening evaluation, potential continuing source areas (e.g., dense, non-aqueous phase liquid [DNAPL]) for the carbon tetrachloride plume were defined as having an areal extent of less than 1 acre and a thickness of 20 m.

2.2 Trichloroethene

The source of the trichloroethene plume (Figure 2.3) is believed to be from cribs that received waste from the Plutonium Finishing Plant. These sources are generally south of the WMA T and WMA TX-TY Tank Farms. The highest FY 2005 average concentration, 13 µg/L, was observed in extraction wells for the 200-ZP-1 interim action pump-and-treat system. The concentration and extent of trichloroethene deeper in the aquifer is poorly established. The trichloroethene plume is entirely contained within the carbon tetrachloride plume. The deepest trichloroethene detected at levels above the 5-µg/L drinking water standard was 8 µg/L at 66 m below the water table. Several other wells throughout the plume showed trichloroethene at levels above 5 µg/L at 50–60 m below the water table. A maximum contaminated thickness of 70 m was used for the screening calculations.

The area and volume calculations for the trichloroethene contamination are summarized in Table 2.3.

Table 2.3. Area and Volume of Trichloroethene Contamination for Remediation Technology Screening

Concentration (µg/L)	Area m^2 (acre)	Thickness (m)	Aquifer Volume (m^3)
5	733,218 (182)	70	51,325,260

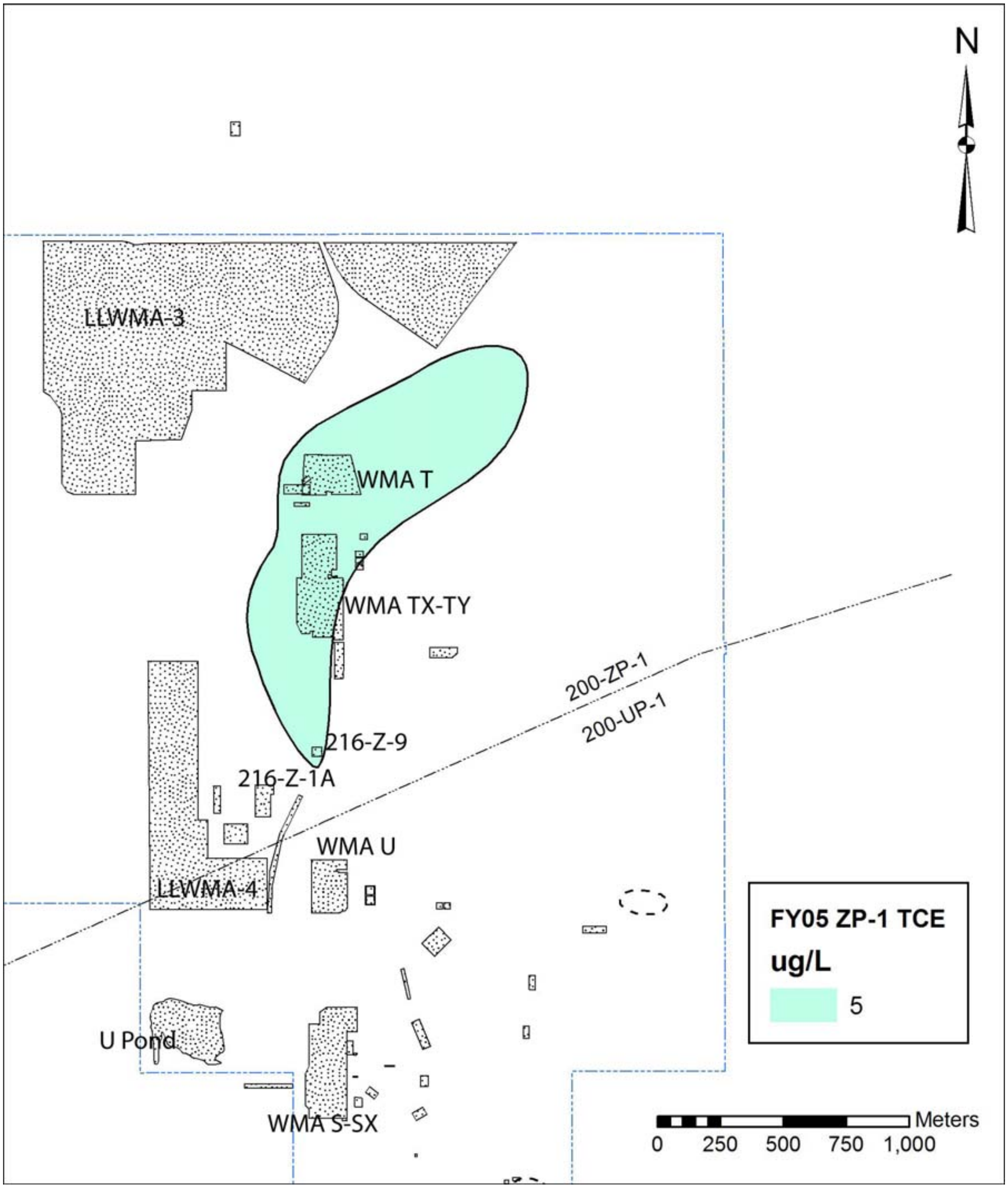


Figure 2.3. Average Trichloroethene Concentrations in 200 West Area, Top of Unconfined Aquifer

2.3 Chromium

Chromium forms two small plumes in the 200-ZP-1 Operable Unit at levels above the drinking water standard (Figure 2.4). The chromium interpretation is based on samples filtered through a 0.45-µm filter during collection. The northernmost plume is centered at the WMA T Tank Farm. The tank farm is believed to be a source of the contamination but liquid waste disposal facilities in the vicinity may also contribute. This plume has been traced downgradient (to the northeast/east) at levels less than the drinking water standard but the area mapped at levels greater than the 100 µg/L standard appears not to have grown very much in the past decade. However, south of WMA T concentrations have been increasing in well 299-W10-4 near the 216-T-36 crib. This well currently has the highest chromium concentration (670 µg/L average in FY 2005) in the operable unit.

Information on chromium distribution with depth near WMA T is available from samples collected during drilling of well 299-W11-25B. Only samples collected with a pump are considered representative of aquifer conditions. The deepest sample with concentrations greater than 500 µg/L was approximately 11 m, and the next sample at approximately 18 m contained 64 µg/L of chromium. For the purposes of this screening, the thickness greater than 500 µg/L was approximated as 15 m and the thickness greater than 100 µg/L was approximated as 20 m. This is the only location where chromium was detected at levels above 100 µg/L in samples collected at depths greater than 10 m below the water table.

Technetium-99 and nitrate are co-contaminants found with the chromium near WMA T. Carbon tetrachloride and trichloroethene are also found at levels above their drinking water standards in the area of the chromium plume.

The second plume at levels greater than the drinking water standard at the water table is restricted to a single well, 299-W14-13, east of WMA TX-TY tank farms. The FY 2005 average filtered chromium concentration in this well was 690 µg/L. Chromium concentrations are increasing in a well ~60 m to the south but still have not reached the drinking water standard. Because this plume is defined by only one well, the area mapped at the 500 µg/L level was assumed to be approximately the same as the area greater than 100 µg/L.

Little information on the depth-distribution of chromium near WMA TX-TY is available. A depth distribution similar to technetium-99 (see below) will be assumed. The depth to the 100 µg/L drinking water standard level is estimated from the depth used for technetium-99 above the drinking water standard, 30 m. The depth for 500 µg/L chromium is estimated from the technetium-99 at levels greater than five times the technetium-99 drinking water standard, conservatively at 10 m below the water table.

Tritium, iodine-129, and Technetium-99 are co-contaminants found at high concentrations centering in the same area as the chromium at WMA TX-TY. Carbon tetrachloride, trichloroethene, and nitrate are also found at levels above the drinking water standard in the area of the WMA TX-TY chromium.

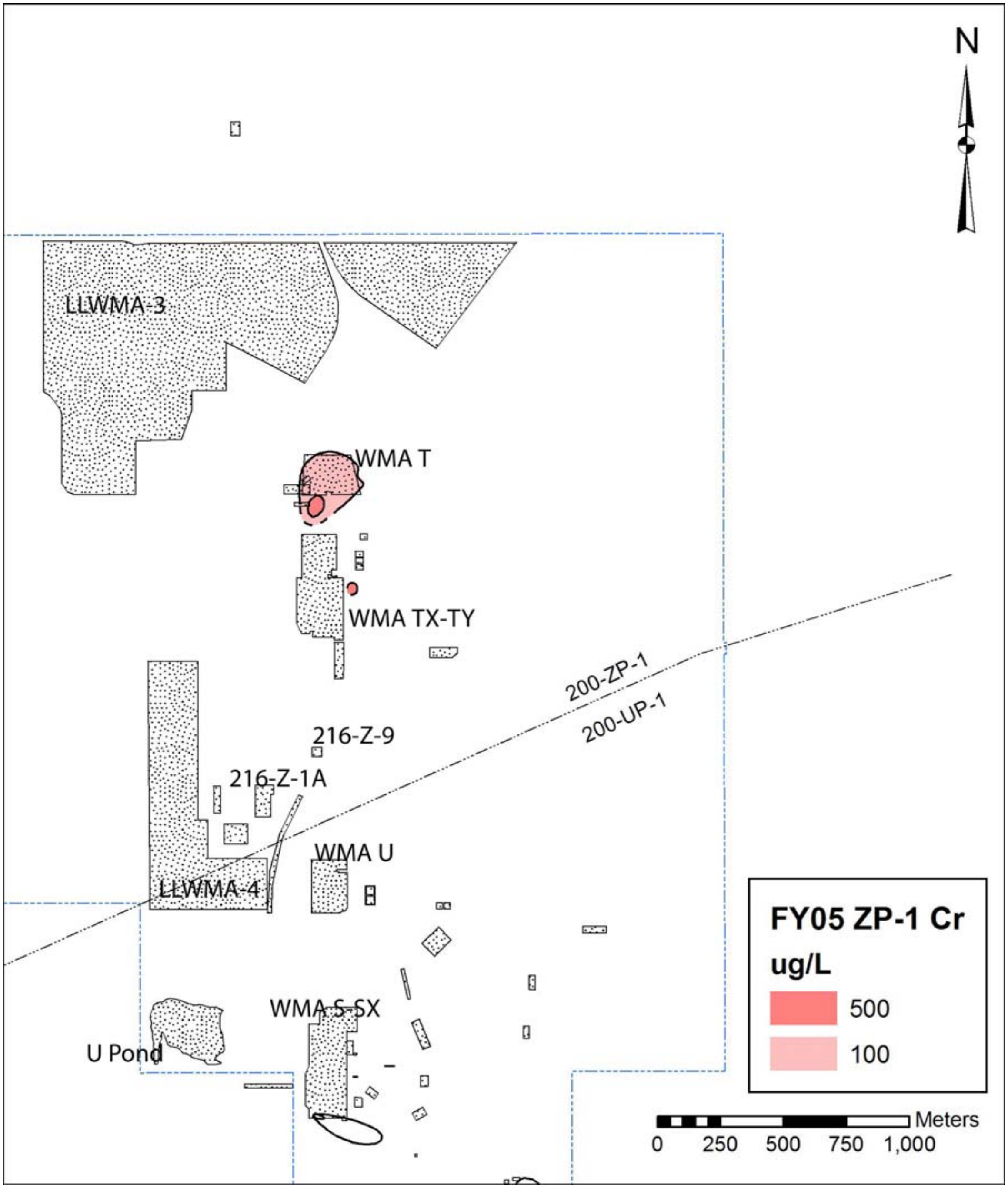


Figure 2.4. Average Chromium Concentrations in 200 West Area, Top of Unconfined Aquifer

The area and volume calculations for the chromium contamination are summarized in Table 2.4.

Table 2.4. Area and Volume of Chromium Contamination for Remediation Technology Screening

Area	Concentration (µg/L)	Area m^2 (acre)	Thickness (m)	Aquifer Volume (m^3)
WMA-T	100	52,179 (13)	20	1,043,580
	500	4,042 (1)	15	60,360
WMA-TX-TY	100	1,566 (0.4)	30	46,980
	500	1,566 (0.4)	10	15,660
Total	**100**	**53,745 (13)**	**--**	**1,090,560**
	500	**5,608 (1.4)**	**--**	**76,020**

2.4 Technetium-99

Technetium-99 is found at levels above the drinking water standard in three small plumes in the 200-ZP-1 Operable Unit (Figure 2.5).

The first plume is located in the vicinity of the WMA T Tank Farm. The tank farm is a probable source of much of the contamination but liquid waste disposal facilities appear to contribute some technetium-99, and characterization efforts are ongoing. This plume extends northeast from the source area. The highest concentration observed in wells completed at the water table was 17,000 pCi/L in well 299-W11-39. This plume, as mapped at the water table, overlaps the chromium and tritium plumes and is contained within the area of the carbon tetrachloride, trichloroethene, and nitrate plumes.

Data from drilling well 299-W11-25B indicate that the highest technetium-99 concentration, 182,000 pCi/L, was found at 10 m below the water table (Figure 2.6). However, the concentration remained above ten times the drinking water standard to the bottom of the boring at 51 m below the water table (depth of the Ringold lower mud unit, which is considered to be the bottom of the uppermost aquifer), where the result from the pumped sample was 21,200 pCi/L. For the purpose of the screening evaluation, a thickness of 55 m was used.

The second technetium-99 plume to be considered is located east of the WMA TX-TY Tank Farm in the area of the chromium, tritium, and iodine-129 plumes. Only one well, 299-W14-13, showed technetium-99 at levels above the drinking water standard. The FY 2005 average concentration was 2,200 pCi/L. The technetium-99 is also within the area of the carbon tetrachloride and nitrate plumes. The trichloroethene plume partially overlaps this technetium-99 contamination.

Some information on the depth-distribution of technetium-99 near WMA TX-TY is available from well 299-W14-11 that was drilled approximately 5 m from well 299-W14-13 (Figure 2.7). Technetium-99 concentrations were highest (75,000 pCi/L) at approximately 5 m below the water table and generally declined with depth. The deepest sample with concentrations greater than the drinking water standard

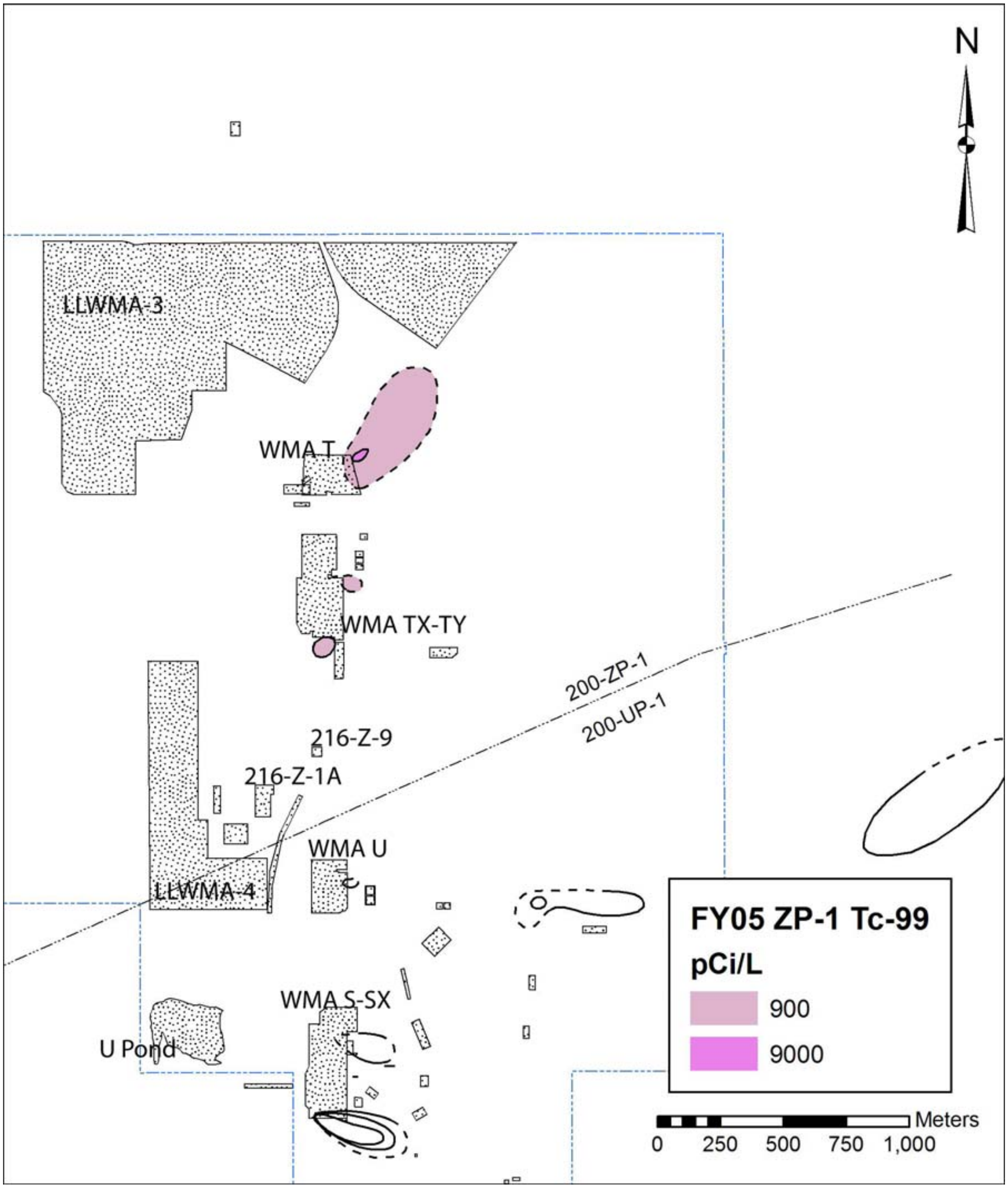


Figure 2.5. Average Technetium-99 Concentrations in 200 West Area, Top of Unconfined Aquifer

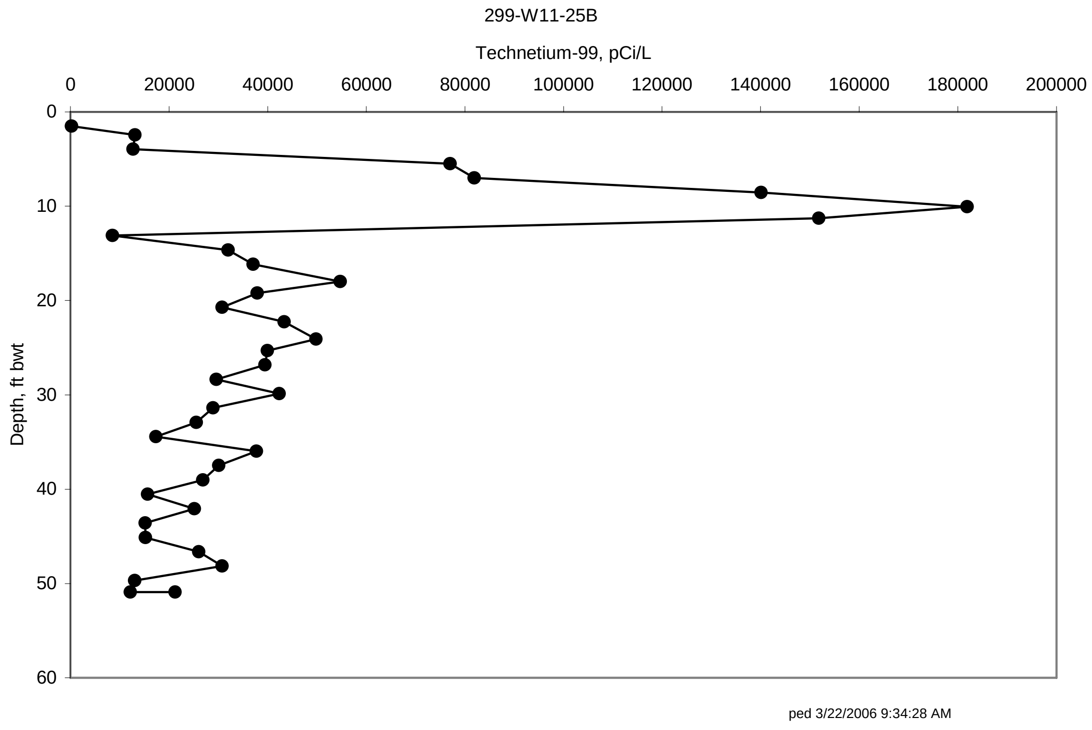


Figure 2.6. Depth-Distribution of Technetium-99 in Well 299-W11-25B

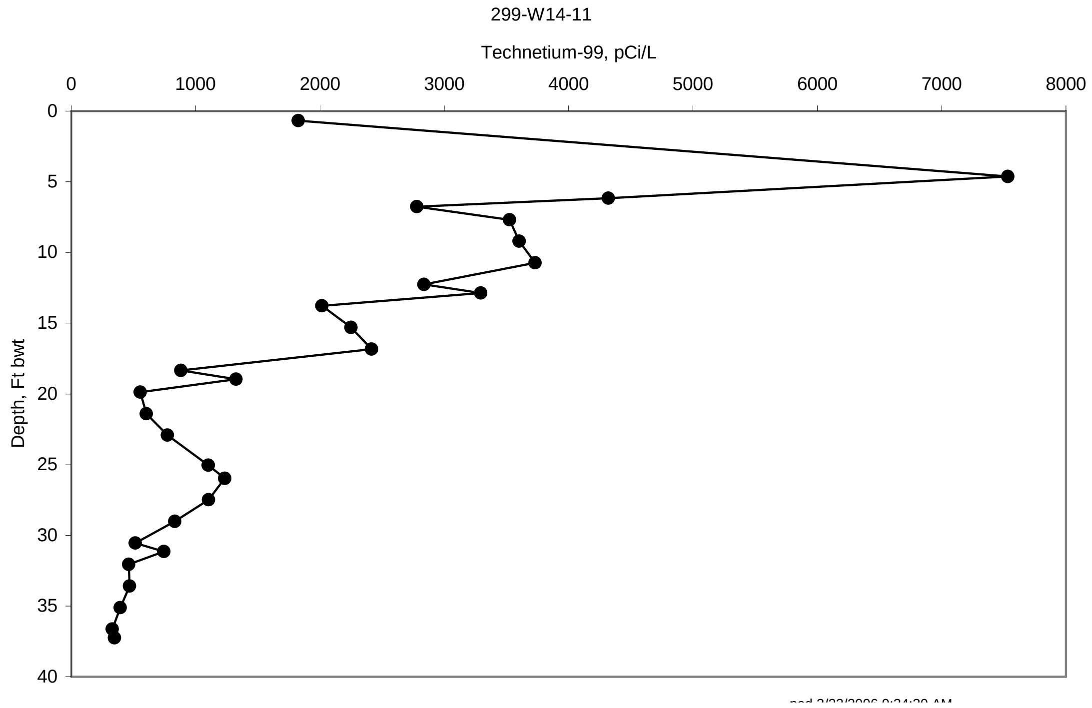


Figure 2.7. Depth-Distribution of Technetium-99 in Well 299-W14-11

was at approximately 27 m below the water table, and the subsequent sample, below the drinking water standard, was at approximately 29 m. The contamination thickness was approximated as 30 m for the screening calculations.

The third technetium-99 plume is located south of WMA TX-TY and appears to be drawn toward the south by the 200-ZP-1 interim action pump-and-treat system. The well with the highest FY 2005 average concentration contained 1,000 pCi/L of technetium-99. This plume is within the area of the carbon tetrachloride, trichloroethene, and nitrate plumes. There is no available information on the depth distribution of the technetium-99 in this plume. A thickness of 30 m was used to be consistent with the contamination on the east side of WMA TX-TY.

The area and volume calculations for the technetium-99 contamination are summarized in Table 2.5.

Table 2.5. Area and Volume of Technetium-99 Contamination for Remediation Technology Screening

Area	Concentration (pCi/L)	Area m^2 (acre)	Thickness (m)	Aquifer Volume (m^3)
WMA-T	900	106,285 (26)	55	5,845,675
	9,000	1,871 (0.5)	55	102,905
WMA-TX-TY				
East Side	900	4,284 (1)	30	128,520
South Side	900	5,274 (1.3)	30	158,220
Total	**900**	**115,843 (27)**	**--**	**6,132,415**
	9,000	**1,871 (0.5)**	**--**	**102,905**

2.5 Iodine-129

The extent of iodine-129 at levels above the drinking water standard at the water table in the 200-ZP-1 Operable Unit appears to form a single plume with the highest concentrations detected east of WMA TX-TY and extending to the northeast (Figure 2.8). It is possible that iodine-129 is present at levels very close to the drinking water standard in a single well south of WMA T, near the 216-T-36 crib, but analytical difficulties (possible technetium-99 interference, lack of confirmation at a second energy level for the detection) mean that this is uncertain. In depth, discrete samples from drilling well 299-W11-25B near the northeast corner of WMA T, iodine-129 was not detected but the detection limits were elevated above the drinking water standard.

The high-concentration part of the iodine-129 plume is coincident with high concentrations of tritium, chromium, and technetium-99. The plume is entirely contained within the carbon tetrachloride and nitrate plumes and contains the mapped extent of the uranium plume. The iodine-129 plume overlaps parts of the trichloroethene plume.

The specific sources of iodine-129 in the groundwater have not been completely defined. The high-concentration part of the plume is in the vicinity of the WMA TX-TY Tank Farms, the 216-T-26, 216-T-28, and other cribs. Although there are potentially other source areas, this vicinity is considered a continuing source of contamination.

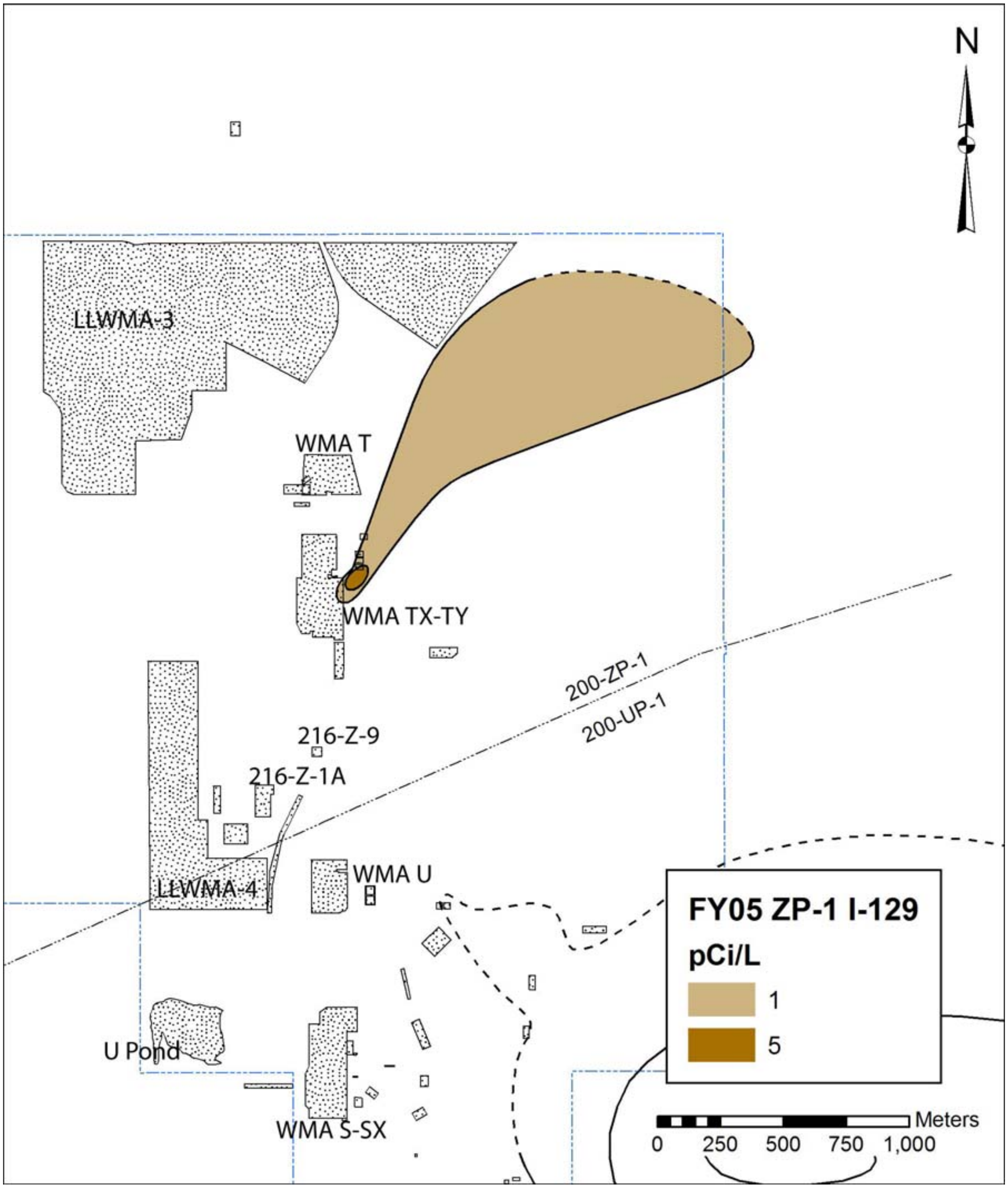
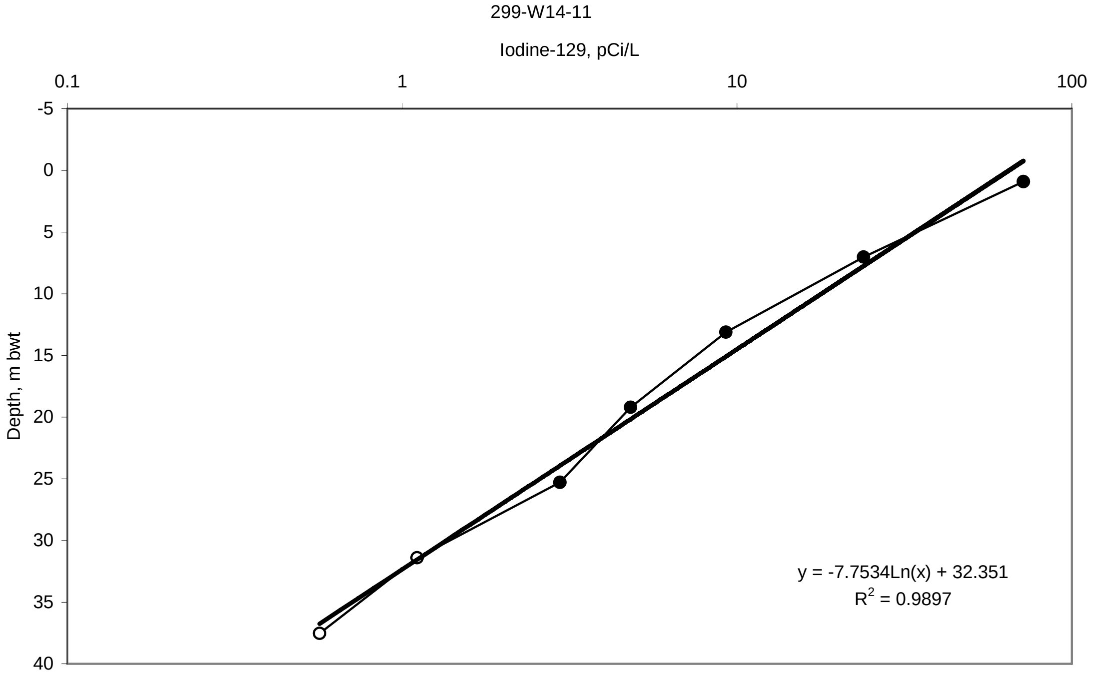


Figure 2.8. Average Iodine-129 Concentrations in 200 West Area, Top of Unconfined Aquifer

Contaminant depth for iodine-129 is not well defined throughout the plume. Characterization data from drilling well 299-W14-11 can be used to define the depth distribution near the source area. The data indicate that the iodine-129 concentration remains above the drinking water standard down to a depth between approximately 30–35 m below the water table and above 5 pCi/L to less than 20 m below the water table (Figure 2.9). For the technology screening, a thickness of 35 m was used for the contaminant thickness throughout the plume at the 1-pCi/L level and 20 m at the 5-pCi/L level.

The area and volume calculations for the iodine-129 contamination are summarized in Table 2.6.



Open symbols used for non-detect values

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Figure 2.9. Depth-Distribution of Iodine-129 in Well 299-W14-11

Table 2.6. Area and Volume of Iodine-129 Contamination for Remediation Technology Screening

Concentration (pCi/L)	Area m^2 (acre)	Thickness (m)	Aquifer Volume (m^3)
1	783,629 (195)	35	27,427,015
5	5,624 (1.4)	20	112,480

2.6 Uranium

A uranium plume has been identified north of the T Plant Canyon building (Figure 2.10). Relatively little is known regarding the source of this plume, and the extent is not well defined; 183 µg/L of uranium was detected in well 299-W11-37 in FY 2005. No data on the depth distribution of uranium are available within this plume. For the purposes of the screening of alternatives, a thickness of 35 m was assumed.

The uranium plume is overlapped by the carbon tetrachloride, trichloroethene, iodine-129, tritium, and nitrate plumes.

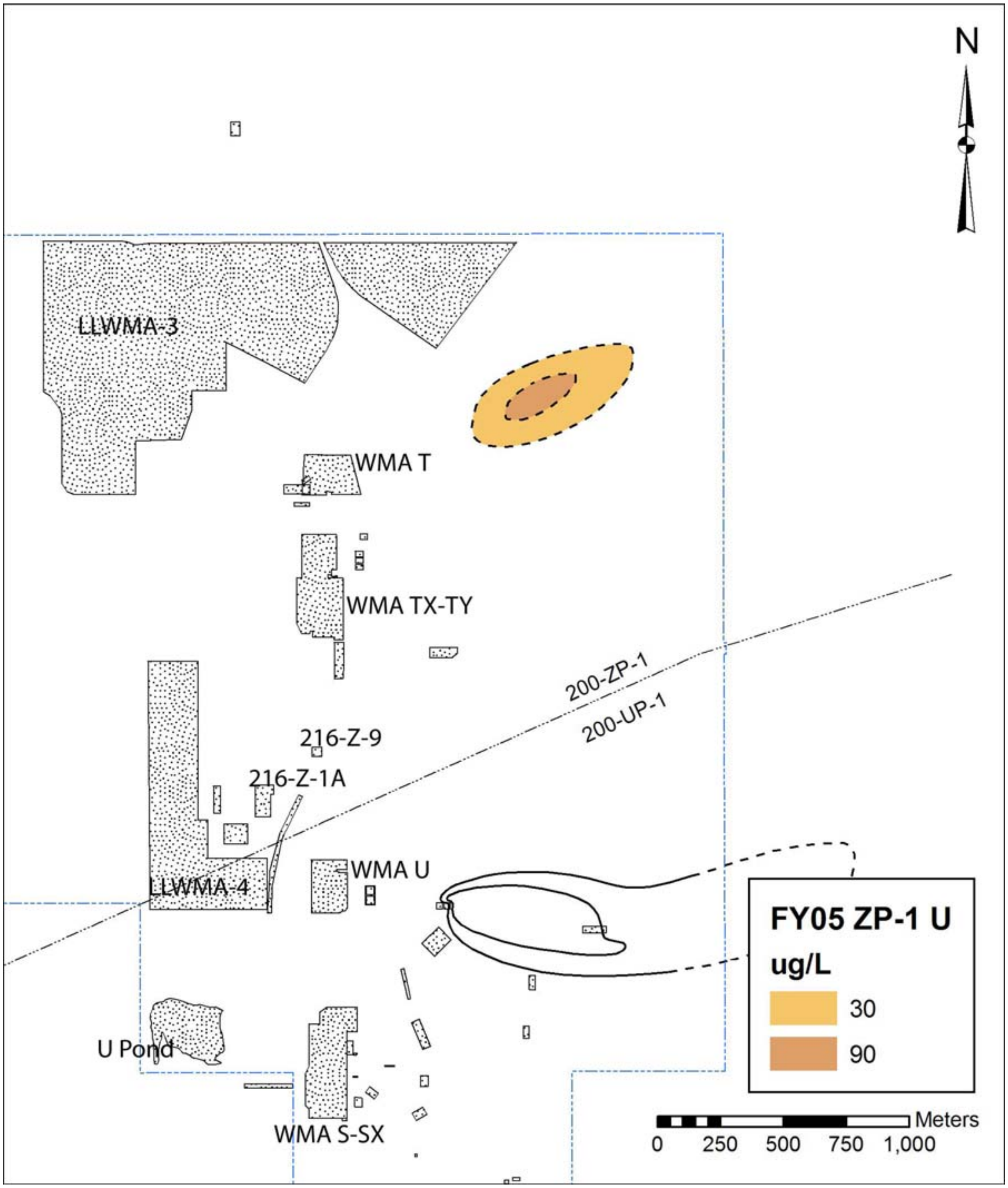

Figure 2.10. Average Uranium Concentrations in 200 West Area, Top of Unconfined Aquifer

The area and volume calculations for the uranium contamination are summarized in Table 2.7.

Table 2.7. Area and Volume of Uranium Contamination for Remediation Technology Screening

Concentration (µg/L)	Area m^2 (acre)	Thickness (m)	Aquifer Volume (m^3)
30	164,325 (41)	35	5,751,375
90	28,797 (7.2)	35	1,007,895

2.7 Nitrate

Nitrate contamination covers a large area of the 200-ZP-1 Operable Unit at levels above the drinking water standard (Figure 2.11). There are multiple sources of contamination. Some contamination originates in the vicinity of the Plutonium Finishing Plant. The highest contamination levels are associated with cribs near WMA T, although it appears the tank farm also contributed. The highest average nitrate concentration for FY 2005 near WMA T was 3,540 mg/L in well 299-W10-4 located south of the tank farm.

Nitrate was found at levels between 45 and 500 mg/L in several wells at depths between 30 and 60 m below the water table. However, no data show nitrate levels above 45 mg/L at depths greater than 60 m below the water table although fewer borings reached those depths. Thus, the assumption of contamination above 45 mg/L to the lower mud at ~55 m below the water table throughout the plume area was used for the screening calculations.

In the vicinity of WMA T, the highest nitrate concentrations are found in the upper part of the aquifer and drop below 500 mg/L at depths less than 20 m below the water table. The data for well 299-W11-25B, located east of WMA T are shown in Figure 2.12. None of the vertical-profile samples in the area show nitrate greater than 1,000 mg/L. For the screening calculations, a depth of 20 m below the water table was used to bound the 500 mg/L volume, and a depth of 10 m below the water table was used for the 1,000 mg/L volume in the vicinity of WMA-T.

A newly installed well, 299-W18-16, located near the 216-Z-1A crib and tile field has nitrate concentrations significantly higher than surrounding wells (766 mg/L). The tile field is a likely source for the higher level of contamination but the precise extent is somewhat uncertain. Concentrations of nitrate in this well were above 500 mg/L down to the maximum sampled depth (~28 m below the water table, Figure 2.13). Since the depth distribution of contamination is not well bounded, both the 500 and 45 mg/L concentrations are assumed to extend down to 55 m below the water table, approximately the top of the lower mud unit in the 200-ZP-1 Operable Unit.

One well northwest of the 200 West Area has reported nitrate at levels above the drinking water standard. The area associated with this contamination is uncertain because well coverage is sparse away from the operational areas. The thickness was assumed to be 55 m below the water table for screening purposes.

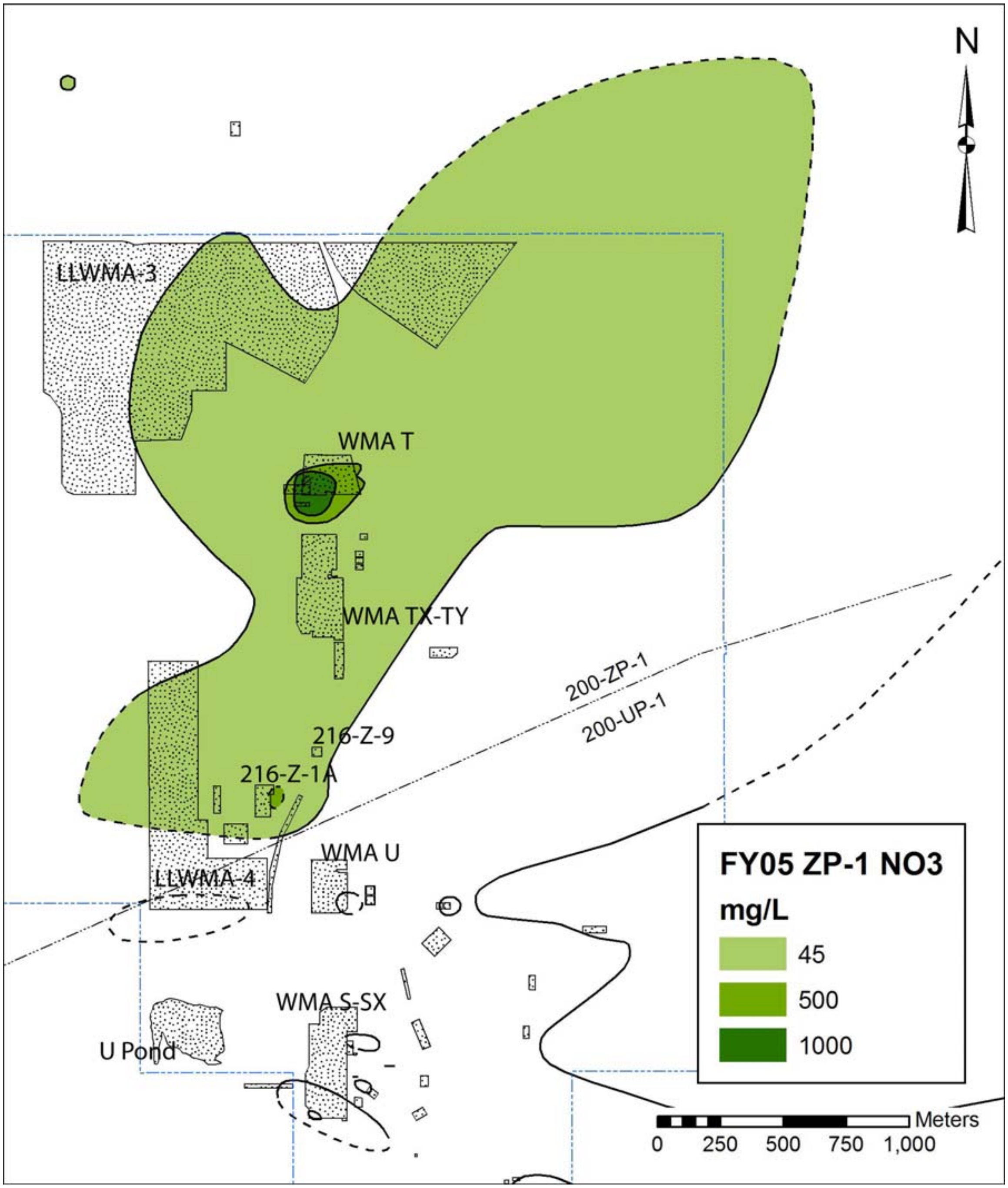

Figure 2.11. Average Nitrate Concentrations in 200 West Area, Top of Unconfined Aquifer

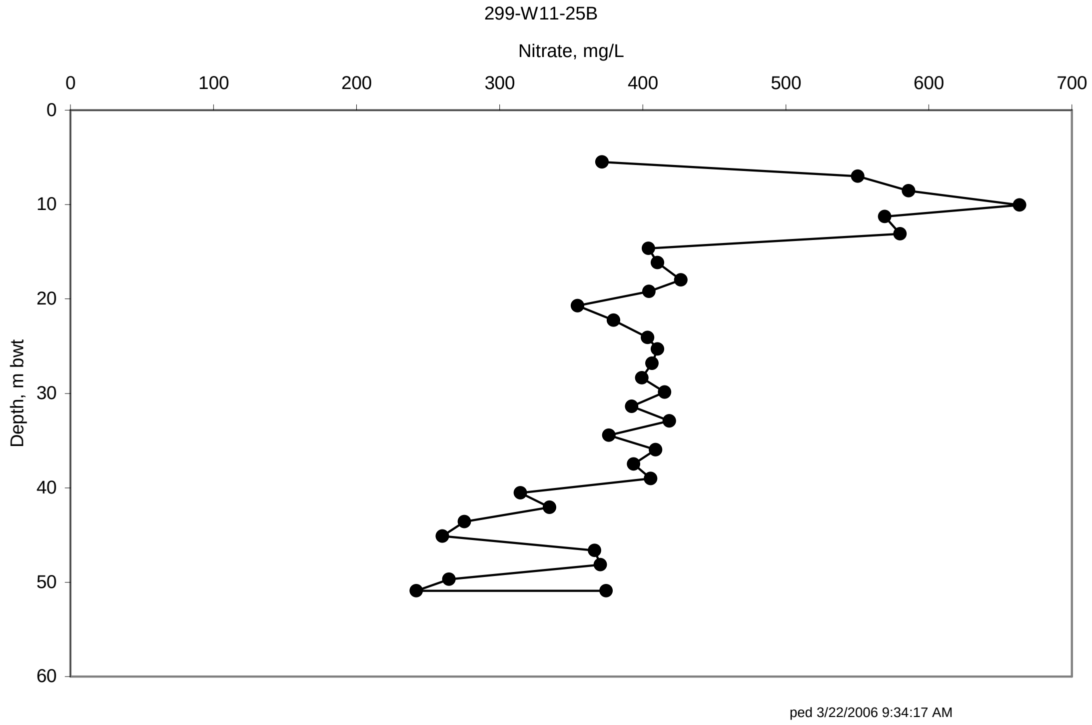

Figure 2.12. Depth-Distribution of Nitrate in Well 299-W11-25B

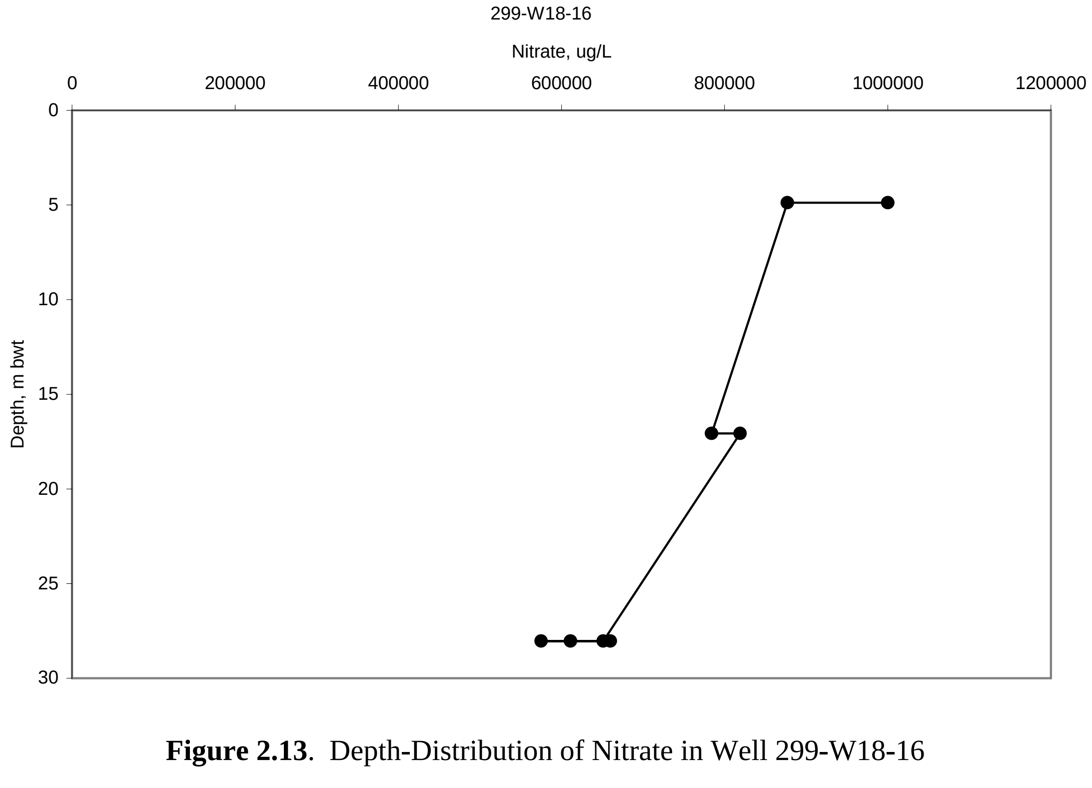

Figure 2.13. Depth-Distribution of Nitrate in Well 299-W18-16

The area and volume calculations for the nitrate contamination are summarized in Table 2.8.

Table 2.8. Area and Volume of Nitrate Contamination for Remediation Technology Screening

Area	Concentration (mg/L)	Area m^2 (acre)	Thickness (m)	Aquifer Volume (m^3)
WMA-T	500	56,453 (14)	20	1,129,060
	1,000	23,484 (5.8)	10	234,840
216-Z-1A	500	4,038 (1)	55	222,090
NW of Area	45	2,580 (0.6)	55	141,900
Major Plume	45	4,631,642 (1,150)	55	254,740,310
Total	**45**	**4,634,222 (1,151)**	**--**	**254,882,210**
	500	**60,491 (15)**	**--**	**1,351,150**
	1,000	**23,484 (5.8)**	**--**	**234,840**

2.8 Tritium

Tritium in the 200-ZP-1 Operable Unit is currently mapped as two plumes, although it is possible there is only one continuous plume at the 20,000 pCi/L level (Figure 2.14). The highest concentrations, >200,000 pCi/L, are found east of WMA TX-TY and are associated with iodine-129, chromium, technetium-99, and nitrate.

Tritium concentrations were measured during drilling of well 299-W11-43, located northeast of WMA T down to a depth of 55 m below the water table (Figure 2.15). The tritium concentration at the maximum depth was 48,000 pCi/L. This is at or near the top of the Ringold lower mud unit and was used for the assumed thickness of contamination above drinking water standards (20,000 pCi/L). However, contamination below the lower mud has not been characterized.

Tritium was detected at levels above 200,000 pCi/L in well 299-W14-11 down to 13 m below the water table (Figure 2.16). A logarithmic regression to the data provides an estimate of 200,000 pCi/L at 18 m below the water table. For screening calculations, a depth of 20 m below the water table was used to define the volume above 200,000 pCi/L. The deepest sample at this location, 37 m below the water table, was still above the 20,000-pCi/L drinking water standard.

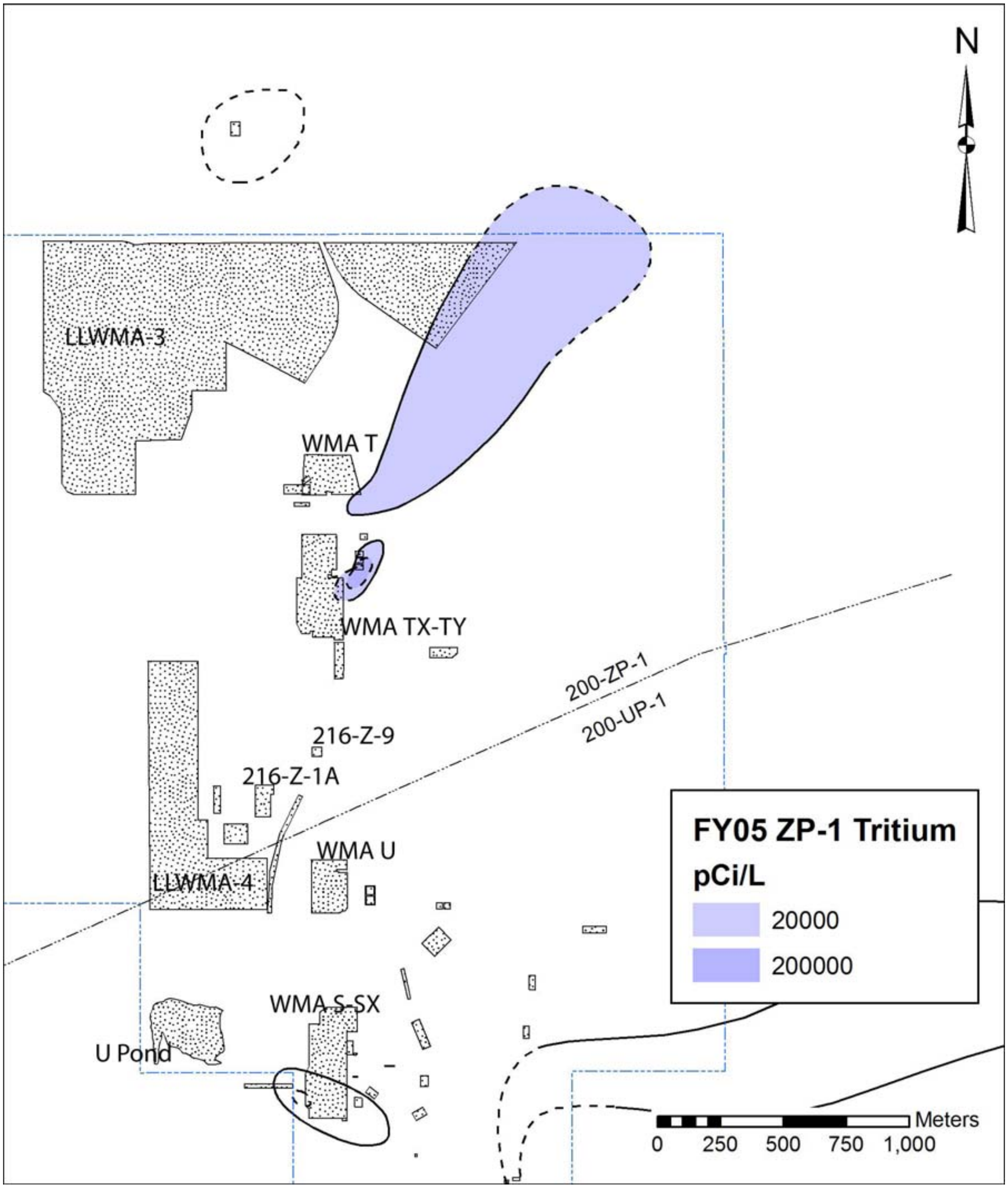

Figure 2.14. Average Tritium Concentrations in 200 West Area, Top of Unconfined Aquifer

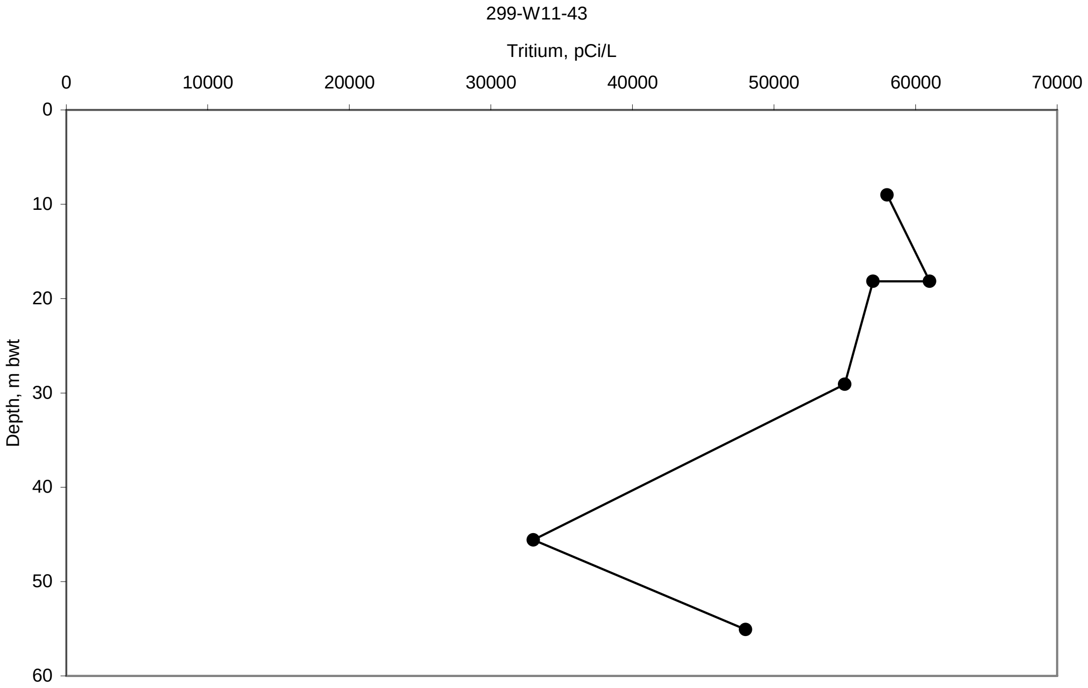

Figure 2.15. Depth-Distribution of Tritium in Well 299-W11-43

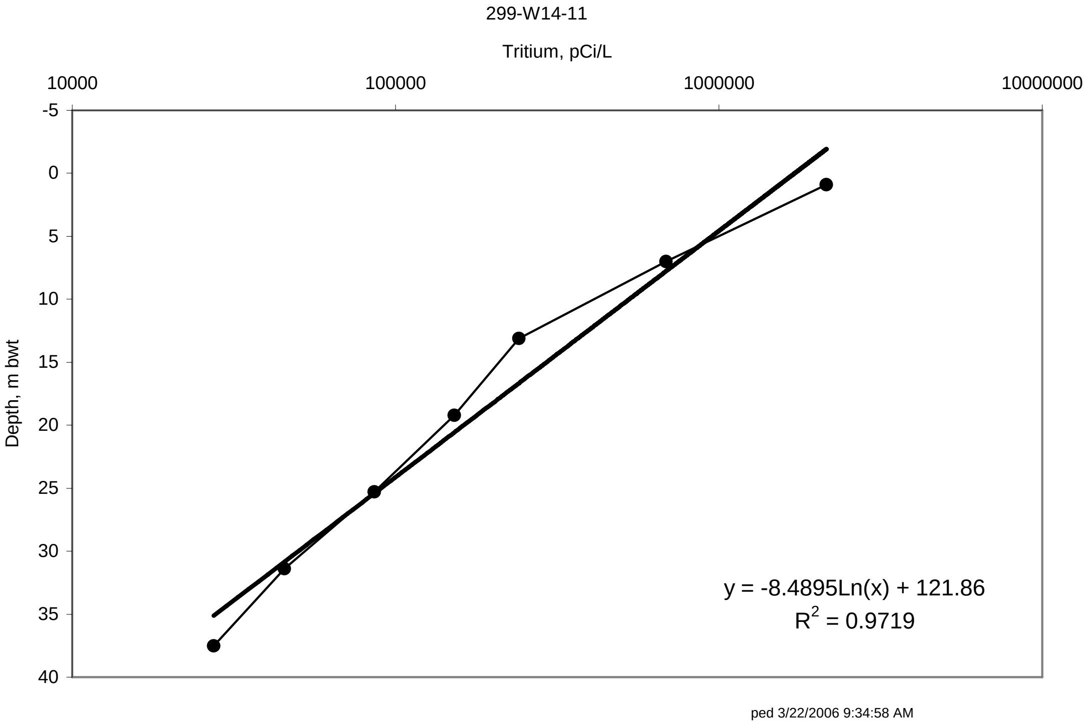

Figure 2.16. Depth-distribution of Tritium in Well 299-W14-11

The area and volume calculations for the tritium contamination are summarized in Table 2.9.

Table 2.9. Area and Volume of Tritium Contamination for Remediation Technology Screening

Area	Concentration (pCi/L)	Area m^2 (acre)	Thickness (m)	Aquifer Volume (m^3)
WMA-T	20,000	656,145 (163)	55	36,087,975
WMA-TX-TY	20,000	24,236 (6)	55	1,332,980
	200,000	7,480 (1.9)	20	149,600
Total	**20,000**	**680,381 (169)**	**--**	**374,20,995**
	200,000	**7,480 (1.9)**	**--**	**149,600**

3.0 Remediation Objectives

Target action levels identified in the *Remedial Investigation/Feasibility Study Work Plan for the 200-ZP-1 Groundwater Operable Unit* (DOE-RL 2004) were used as the remediation goal for the screening evaluation.

- Carbon tetrachloride (5 µg/L)
- Trichloroethene (5 µg/L)
- Chromium (100 µg/L)
- Technetium-99 (900 pCi/L)
- Iodine-129 (1 pCi/L)
- Uranium (30 µg/L)
- Nitrate (45 mg/L as NO_3)
- Tritium (20,000 pCi/L)

4.0 Assumptions

The following assumptions were used as part of conducting the screening evaluation:

- Contaminant distribution was based on current data for groundwater contamination. The potential for continuing contamination flux from the vadose zone was not explicitly considered. However, the screening included assessment of remediation methods potentially suitable for application to a small continuing source area in the groundwater.

- The screening evaluation considered application of remediation methods to specific treatment volumes, but did not estimate the time frame for treatment. Thus, the relative cost and effectiveness assessment were based on factors other than the treatment time frame.

- The screening evaluation was conducted using the data available and the general conceptual model presented in this report. Uncertainty in the data and conceptual model was not addressed. Instead, the evaluation assessed potential remediation methods based on application to a specified treatment volume.

- The general conceptual model used for the screening evaluation was intended to describe the volume and extent of the plume suitably for use in screening potential remediation methods. The conceptual model did not include all aspects important for defining the fate and transport of a contaminant. The evaluation assessed potential remediation methods based on application to a specified treatment volume.

5.0 Evaluation Criteria

The screening evaluation was conducted in two primary steps. The initial screening step evaluated potential remediation methods based on whether they can be effectively applied within the environmental setting of the 200-ZP-1 Operable Unit for the specified contaminants. In the second step, potential remediation methods were screened using scoping calculations to estimate the scale of infrastructure, overall quantities of reagents, and conceptual approach for applying the method for each defined grouping of COC. Based on these estimates, each method was screened with respect to effectiveness, implementability, and relative cost categories of the CERCLA feasibility study screening process defined in the U.S. Environmental Protection Agency (EPA) guidance (EPA 1988). In general, the effectiveness evaluation is related to (1) the estimated reliability of the process and whether it has been proven successful, (2) the expected ability of the method to treat the necessary volume of contaminated media, and (3) the ability to be constructed and operated without negative human or environmental impacts. Implementability is generally related to (1) the scale of effort and technical certainty that the method can be implemented at the site, (2) the availability of consumables, equipment, and services, and (3) ability to obtain permits and administratively manage the method. The relative cost is generally evaluated using a general conceptual design and relative cost estimates based on the relative capital and operation and maintenance required for each option.

The specific evaluation criteria for each of these screening categories are listed in Table 5.1. Remediation methods were eliminated from further consideration based on a comparative assessment of implementability, effectiveness, and relative cost, whereby those methods with significant uncertainty in effectiveness, significant difficulties for implementation, and relatively high costs compared to other more viable and less costly methods were identified and screened out. Innovative methods were assessed based on the available information in the literature. It may be necessary to conduct treatability studies as part of final assessment and implementation for some innovative methods. Presumptive remedies applicable within the environmental setting were retained for use in the more detailed analysis of remediation alternatives that will be conducted as part of the full feasibility study.

Table 5.1. Screening Evaluation Criteria for the Second Step of Screening

Effectiveness	Implementability	Relative Cost
• Is the method able to reliably decrease contaminant concentration, mass, or mobility to meet 1) the target concentration or 2) ten times the target concentration? • Does the method produce no hazardous products unless these are readily remediated or attenuated? • Does the method negatively impact the remediation of other COC to the extent that the remediation objectives could not be met for the other COC? • For the plume thicknesses identified in the conceptual model, is the method suitable for decreasing contaminant concentration, mass, or mobility of 1) continuing source in groundwater with an areal extent of less than 1 acre, 2) high concentrations within an areal extent of less than 5 acres, 3) high or low concentrations within an areal extent of up to 25 acres, and 4) low concentrations for an areal extent of 250 acres or greater than 250 acres? The volume of treatment for these targets will be defined based on the depth of the individual COC. • Does the method cause significant human or environmental risk during construction or operation?	• Can the method be reliably constructed and operated for the target volume (see effectiveness categories) within the Hanford aquifer (technical uncertainty at scale of application)? • Can the consumable or reagent usage be reasonably provided at the scale of application?	• Based on scoping calculations defining the scale of infrastructure and consumables, are the relative costs for capital and operation/maintenance expected to be grossly higher than for other options with similar effectiveness and implementability?

6.0 Potential Remediation Methods

The potential remediation methods for each COC grouping are shown in Tables 6.1 through 6.4. The potential remediation methods were identified from a review of EPA resources and technical literature including primarily the Hanford 200 West Area Carbon Tetrachloride Project Innovative Remediation Technology Review 1999-2000 (DOE-EM 2002: "Innovative Treatment and Remediation Demonstration [ITRD] report") and the http://www.epareachit.org and http://www.frtr.gov technology information websites. The screening focuses on categories of remediation method, not specific commercial products, unless there is only one commercial vendor for a remediation method category. Potential methods only demonstrated at the laboratory scale were not considered unless there are current efforts to obtain information from field treatability tests.

Table 6.1. Potential Remediation Methods for COC Group 1 (carbon tetrachloride and trichloroethene)

General Category	Remediation Method Category
No Action	No Action
Institutional Controls	Institutional Controls
Containment	Physical Containment • Slurry Walls • Grout Curtain • Sheet Piling Hydraulic Control
Removal, treatment, and disposal	Excavation
Monitored Natural Attenuation	Monitored Natural Attenuation (MNA)
Ex Situ Treatment	Pump-and-Treat • Physical treatment • Chemical treatment • Biological treatment • Constructed Wetlands/Phyto-Irrigation
In Situ Treatment	Chemical Oxidation
	Air Sparging
	Zero-Valent Iron
	Surfactant Flushing
	In-Well Air Stripping
	Thermally Enhanced In-Well Stripping
	Phytoremediation
	Aerobic Bioremediation • Aerobic Co-metabolism
	Anaerobic Bioremediation • Soluble substrate • Injection of long-duration substrate (e.g., a non-aqueous substrate such as vegetable oil)
	In Situ Thermal Treatment • Electrical Resistance Heating • Steam Heating • Conductive Heating
	Permeable Reactive Barriers • Zero-Valent Iron • Aerobic Biobarrier (e.g., injection of long-duration oxygen source as a barrier) • Anaerobic Biobarrier (e.g., injection of long-duration substrate as a barrier) • In Situ Redox Manipulation

Table 6.2. Potential Remediation Methods for COC Group 2 (chromium, technetium-99, iodine-129, and uranium)

General Category	Remediation Method Category
No Action	No Action
Institutional Controls	Institutional Controls
Containment	Physical Containment • Slurry Walls • Grout Curtain • Sheet Piling Hydraulic Control
Removal, treatment, and disposal	Excavation
Monitored Natural Attenuation	Monitored Natural Attenuation (MNA)
Ex Situ Treatment	Pump and Treat • Chemical treatment • Biological treatment (except I-129)
In Situ Treatment	Chemical Stabilization by Apatite (uranium)
	Chemical Stabilization by Polyphosphate (uranium)
	Nanoparticles (other than zero-valent iron)
	Down-Well Bio-Reactor/Adsorption Systems
	Reduction by Zero-Valent Iron (chromate, uranium isotopes, and Tc-99)
	Surfactant Flushing
	Phytoremediation
	Anaerobic Bioremediation • Soluble substrate – direct reduction (chromate, uranium isotopes and Tc-99) – Sulfate Reducing Bacteria (chromate, uranium isotopes and Tc-99) • Injection of long-duration substrate (e.g., a non-aqueous substrate such as vegetable oil)
	Permeable Reactive Barriers • Zero-Valent Iron (chromate, uranium isotopes and Tc-99) • Apatite barrier (uranium) • Polyphosphate barrier (uranium) • Adsorbent barriers • Multi-Zone Biobarrier • Anaerobic Biobarrier (e.g., injection of long-duration substrate as a barrier) • In Situ Redox Manipulation (chromate, uranium isotopes and Tc-99)

Table 6.3. Potential Remediation Methods for COC Group 3 (nitrate)

General Category	Remediation Method Category
No Action	No Action
Institutional Controls	Institutional Controls
Containment	Physical Containment • Slurry Walls • Grout Curtain • Sheet Piling Hydraulic Control
Removal, treatment, and disposal	Excavation
Monitored Natural Attenuation	Monitored Natural Attenuation (MNA)
Ex Situ Treatment	Pump and Treat • Chemical treatment • Biological treatment • Constructed Wetlands/Phyto-Irrigation
In Situ Treatment	Phytoremediation
	Anaerobic Bioremediation • Soluble substrate • Injection of long-duration substrate (e.g., a non-aqueous substrate such as vegetable oil)
	Permeable Reactive Barriers • Anaerobic Biobarrier (e.g., injection of long-duration substrate as a barrier) • Zero-Valent Iron • In Situ Redox Manipulation

Table 6.4. Potential Remediation Methods for COC Group 4 (tritium)

General Category	Remediation Method Category
No Action	No Action
Institutional Controls	Institutional Controls
Containment	Physical Containment • Slurry Walls • Grout Curtain • Sheet Piling Hydraulic Control
Removal, treatment, and disposal	Excavation
Monitored Natural Attenuation	Monitored Natural Attenuation (MNA)
Ex Situ Treatment	Pump and Treat • Isotopic separation

7.0 Screening

Potential remediation methods were screened in a two-step process. Section 7.1 presents the initial screening results. Screening based on scoping calculations is presented in Section 7.2.

7.1 Initial Screening

The first step of screening eliminated remediation methods that are infeasible because they are not appropriate for application in the environmental setting of the 200-ZP-1 Operable Unit. Tables 7.1 through 7.4 list the remediation method categories screened out in this first stage and the reason they were removed from further consideration.

Table 7.1. COC Group 1 – Remediation Methods Screened Out in Initial Screening

Remediation Method Category	Reason
Containment	Grout curtains and slurry walls emplaced by trenching and sheet piling are eliminated due to the depth of the aquifer. Hydraulic control is eliminated as not applicable for large plumes in transmissive aquifers. Containment by injectable materials is retained.
Removal, treatment, and disposal	Removal, treatment, and disposal technologies are targeted at shallow contamination only.
Phytoremediation	Not appropriate for deep aquifers.
Zero-Valent Iron	Emplacement by trenching is eliminated due to the depth of the aquifer. Injectable iron is retained as a potential remediation method.
Permeable Reactive Barriers • Zero-Valent Iron	Use of zero-valent iron with emplacement by trenching is eliminated due to the depth of the aquifer. Use of injectable iron is retained as a potential permeable reactive barrier remediation method.

Table 7.2. COC Group 2 – Remediation Methods Screened Out in Initial Screening

Remediation Method Category	Reason
Containment	Grout curtains and slurry walls emplaced by trenching and sheet piling are eliminated due to the depth of the aquifer. Hydraulic control is eliminated as not applicable for large plumes in transmissive aquifers. Containment by injectable materials is retained.
Removal, treatment, and disposal	Removal, treatment, and disposal technologies are targeted at shallow contamination only
Nanoparticles	Presently, there are no deployable nanotechnologies other than zero-valent iron for remediation of the COC. Ongoing studies may result in viable remediation technologies in the future.
Phytoremediation	Not appropriate for deep aquifers
Zero-Valent Iron	Emplacement by trenching is eliminated due to the depth of the aquifer. Injectable iron is retained as a potential remediation method.
Stabilization by Apatite (by trenching)	Use of solid apatite with emplacement by trenching is eliminated due to the depth of the aquifer. Use of injectable apatite is retained as a potential permeable reactive barrier remediation method.
Permeable Reactive Barriers • Zero-Valent Iron (by trenching) • Apatite (by trenching) • Adsorbent barriers • Multi-Zone Biobarrier	Use of zero-valent iron, adsorbants, solid apatite or the multi-zone barrier with emplacement by trenching is eliminated due to the depth of the aquifer. Use of injectable iron, apatite, or polyphosphate is retained as a potential permeable reactive barrier remediation method.

Table 7.3. COC Group 3 – Remediation Methods Screened Out in Initial Screening

Remediation Method Category	Reason
Containment	Grout curtains and slurry walls emplaced by trenching and sheet piling are eliminated due to the depth of the aquifer. Hydraulic control is eliminated as not applicable for large plumes in transmissive aquifers. Containment by injectable materials is retained.
Removal, treatment, and disposal	Removal, treatment, and disposal technologies are targeted at shallow contamination only
Phytoremediation	Not appropriate for deep aquifers

Table 7.4. COC Group 4 – Remediation Methods Screened Out in Initial Screening

Remediation Method Category	Reason
Containment	Grout curtains and slurry walls emplaced by trenching and sheet piling are eliminated due to the depth of the aquifer. Hydraulic control is eliminated as not applicable for large plumes in transmissive aquifers. Containment by injectable materials is retained.
Removal, treatment, and disposal	Removal, treatment, and disposal technologies are targeted at shallow contamination only

7.2 Screening Based on Scoping Calculations

Based on the initial screening results, the potential remediation methods retained for further screening evaluation were compiled (Table 7.5). Scoping-level calculations to define the general scale of infrastructure and equipment, amendments needs, and other method-specific parameters were conducted to support assessment of each method remaining after the initial screening in terms of the effectiveness, implementability, and relative cost categories of the evaluation criteria.

Table 7.5. Remediation Methods Considered in Second Stage of Screening

General Category	Remediation Method Category (applicable COC shown in parentheses)
No Action	No Action (all)
Institutional Controls	Institutional Controls (all)
Containment	Injectable materials for stabilizing source areas (all)
Monitored Natural Attenuation	Monitored Natural Attenuation (MNA) (all)
Ex Situ Treatment	Pump and Treat • Physical treatment (air stripping/activated carbon) (carbon tetrachloride and trichloroethene only) • Chemical treatment (all) • Biological treatment (all except I-129 and tritium)
In Situ Treatment	Chemical Oxidation (carbon tetrachloride and trichloroethene only)
	Chemical Stabilization by Injectable Apatite (uranium isotopes)
	Chemical Stabilization by Polyphosphate (uranium isotopes)
	Injectable Zero-Valent Iron (carbon tetrachloride, trichloroethene, chromate, Tc-99, and uranium isotopes)
	Surfactant Flushing (all except tritium)
	In-Well Air Stripping (carbon tetrachloride and trichloroethene)
	Thermally Enhanced In-Well Stripping (carbon tetrachloride and trichloroethene)
	Down-well bioreactor/adsorption system (chromate, uranium isotopes, I-129 and Tc-99)
	Air Sparging (carbon tetrachloride and trichloroethene)
	Anaerobic Bioremediation • Soluble substrate (all except tritium) – Direct reduction (chromate, uranium isotopes and Tc-99) – Sulfate Reducing Bacteria • Injection of long-duration substrate (e.g., a non-aqueous substrate such as vegetable oil) (all except tritium)
	Aerobic Bioremediation (trichloroethene) • Aerobic Co-metabolism
	In Situ Thermal Treatment (carbon tetrachloride and trichloroethene) • Electrical Resistance Heating • Steam Heating • Conductive Heating
	Permeable Reactive Barriers • Injectable Zero-Valent Iron (carbon tetrachloride, trichloroethene, chromate, Tc-99, and uranium isotopes) • Anaerobic Biobarrier (e.g., injection of long-duration substrate as a barrier) (all except tritium) • In Situ Redox Manipulation (carbon tetrachloride, trichloroethene, chromate, Tc-99, and uranium isotopes) • Injectable Apatite Barriers (uranium isotopes) • Polyphosphate Barrier (uranium isotopes)

The following sections describe each potential remediation method and present scoping calculations to estimate the scale of infrastructure and equipment, amendments needs, and other method-specific parameters needed for evaluating the method against the criteria listed in Table 5.1 and for each COC group.

7.2.1 Physical Containment

Injection-based technologies for physical containment were examined. Injectable grout walls and freeze walls were identified as the two categories of injection technology potentially applicable to the 200-ZP-1 Operable Unit. Injectable grout barriers are installed by jet-grouting from an injection well. Grout walls or “curtains” have been used extensively in the past for civil engineering projects, but less frequently to contain hazardous waste. Jet-grouted walls are constructed by injecting grout at very high pressure (up to 6,000 psi) into the subsurface. In general, a small-diameter pilot hole is drilled to the total depth of the barrier. The hole is jet-grouted from the bottom up. Multiple, closely spaced holes are grouted to form a horizontally continuous barrier. Jet-grout barriers have been built to depths greater than 61 m, although below 30 m the vertical consistency, and thus continuity of jet-grouted barriers, are difficult to control or confirm. Typically, a Portland cement is used, although a variety of grout formulations may be used. Supersaturated solutions forming grouts in situ have been tested and applied for hydraulic control. However, this technique would have similar technical issues as for injection grouting and additional uncertainties related to its effectiveness. Thus, supersaturated grouts were not considered separately for the screening evaluation.

Frozen soil barrier technology (DOE 1999) consists of a series of subsurface heat transfer devices, known as thermoprobes, which are installed around a contaminant source and function to freeze the soil pore water. The barrier is maintained for a finite period of time, until remediation or removal of the contaminants is complete. The thermoprobes are installed with drilling techniques. The subsurface thermoprobes utilize liquid-to-gas phase change of a passive refrigerant (carbon dioxide) to remove heat from the surrounding sediment. Above-ground refrigeration units and interconnecting piping are installed and operated. Insulation and a waterproof membrane are installed at grade to prevent heat gain from the surface and minimize infiltration. Frozen soil barriers offer advantages by being “self-healing” and allowing immobilization within the frozen matrix or containment. However, unlike the grout or cement barriers, frozen barriers do require electric power for the life of the barrier. Therefore, use of these barriers is best restricted to short or medium durations of 20 years or less. Demonstration projects have been limited to shallow depths (10 m) and small areas (less than 0.15 acre).

Potentially, physical containment could be applied to all COC groups. However, the characteristics of physical containment are best suited to containing relatively small zones of contamination. For the screening evaluation, physical containment was only considered for application to small continuing source areas; in particular, application to containment of a carbon tetrachloride continuing source of less than 1 acre.

Based on the technical uncertainty and high costs, physical containment is rejected as a potential remediation technology (see Sections 7.2.1.1 through 7.2.1.3).

7.2.1.1 Effectiveness

Effectiveness Screening Criteria (see Table 2.1)	COC Group 1 (carbon tetrachloride continuing source)
Reliably meet goal?	Significant uncertainty is associated with the ability to physically contain the relatively large contaminated volume of a continuing source area at the depths of the 200-ZP-1 Operable Unit. Grout walls may be less effective for containing solvent over the long term due to diffusion of solvent through the grout wall. Freeze walls would require active operation over a very long time period.
Produce hazardous products?	No hazardous byproducts would be produced.
Negatively impact to other COC?	No negative impacts on other COC are expected.
Treat target volume?	Efficacy of physical containment placement depends on target volume depth. There is some uncertainty with placement of effective containment at the depth to groundwater plus an additional 20+ m needed to contain a continuing source area for carbon tetrachloride.
Cause risk during construction or operation?	Construction risk would be from necessary drilling.

7.2.1.2 Implementability

Implementability Screening Criteria (see Table 2.2)	COC Group 1 (carbon tetrachloride continuing source)
Reliably constructed and operated?	Grout walls effectiveness is impacted by stratigraphy and depth. Freeze walls are less sensitive to stratigraphy.
Reasonable consumable usage?	While a significant amount of grout would be needed for a 1 acre containment, consumables are not significant issue for physical containment technologies.

7.2.1.3 Relative Cost

Cost factors for physical containment are primarily associated with the large number of boreholes necessary due to the limited radius of injection for grout or for effective freezing for freeze walls. Even with an optimistic radius of influence of 3–5 m, a large number of boreholes are needed to contain a 1 acre volume. Using costs at the high end of the range for injection grouting technology ($20 per square foot of panel area), a barrier 3 m thick by 250 m long by 20 m deep would cost in the range of $1M. Costs for an application to the 200-ZP-1 Operable Unit are expected to be higher than this estimate due to higher Hanford drilling costs (due to the presence of radioactive contamination and geologic difficulties) and an overall depth of application that is deeper than existing applications. Freeze walls are expected to have a similar capital cost as for injected grout walls, but active operation to maintain cooling would be required over a very long time period.

7.2.2 Monitored Natural Attenuation

The EPA Office of Solid Waste and Emergency Response (OSWER) identifies the requirements for MNA in "Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites" (OSWER Directive 9200.4-17P, EPA 1999), hereafter referred to as the "OSWER MNA Directive." Quotations from this directive are shown in italics font. The OSWER MNA Directive defines natural attenuation processes as follows. *The "natural attenuation processes" that are at work in such a remediation approach* [MNA] *include a variety of physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater. These in-situ processes include biodegradation; dispersion; dilution; sorption; volatilization; radioactive decay; and chemical or biological stabilization, transformation, or destruction of contaminants.*

The OSWER MNA Directive provides some key considerations for determining whether MNA is an appropriate remedy for a site. These considerations and a discussion relative to each COC group are listed below.

1. *Whether the contaminants present in soil or groundwater can be effectively remediated by natural attenuation processes.*

    - COC Group 1 – Natural attenuation processes acting on carbon tetrachloride include abiotic degradation, sorption, dispersion, and dilution. Previous modeling analysis suggests that these mechanisms may significantly reduce concentrations within the plume and decrease the extent of carbon tetrachloride plume migration (Truex et al. 2001; Bergeron and Cole 2005). Natural attenuation processes acting on trichlorethene include sorption, dispersion, and dilution. These mechanisms have the potential to reduce trichlorethene concentrations and limit plume migration, but quantitative studies to define the extent of attenuation have not been conducted. Current data suggest that within the Group 1 plumes there are not significant zones with reducing conditions conducive to reductive dechlorination processes.

    - COC Group 2 – Natural attenuation processes acting on COC Group 2 include sorption, dispersion, and dilution. These mechanisms have the potential to reduce COC concentration and limit plume migration, but quantitative studies to define the extent of attenuation have not been conducted. Current data suggest that within the Group 2 plumes there are not significant zones with reducing conditions conducive to reductive dechlorination processes.

    - COC Group 3 – Natural attenuation processes acting on nitrate include dispersion and dilution. These mechanisms have the potential to reduce nitrate concentrations and limit plume migration, but quantitative studies to define the extent of attenuation have not been conducted. Current data suggest that within the Group 3 plumes there are not significant zones with reducing conditions conducive to reductive dechlorination processes.

    - COC Group 4 – Natural attenuation processes acting on tritium include radioactive decay, dispersion, and dilution. These mechanisms have the potential to significantly reduce tritium concentrations and limit plume migration.

2. *Whether or not the contaminant plume is stable and the potential for the environmental conditions that influence plume stability to change over time.*

   - COC Group 1 – Plume stability was not evaluated as part of the screening evaluation. Conditions over time will act to reduce the groundwater flow rate because surface water discharges have been significantly decreased. The degradation rate (carbon tetrachloride only), sorption, dispersion, and dilution are not expected to change over time.

   - COC Group 2 – Plume stability was not evaluated as part of the screening evaluation. Conditions over time will act to reduce the groundwater flow rate because surface water discharges have been significantly decreased. Sorption, dispersion, and dilution are not expected to change over time.

   - COC Group 3 – Plume stability was not evaluated as part of the screening evaluation. Conditions over time will act to reduce the groundwater flow rate because surface water discharges have been significantly decreased. Dispersion and dilution are not expected to change over time.

   - COC Group 4 – Plume stability was not evaluated as part of the screening evaluation. Conditions over time will act to reduce the groundwater flow rate because surface water discharges have been significantly decreased. The decay rate, dispersion, and dilution are not expected to change over time.

3. *Whether human health, drinking water supplies, other groundwaters, surface waters, ecosystems, sediments, air, or other environmental resources could be adversely impacted as a consequence of selecting MNA as the remediation options.*

   For all COC, direct use of groundwater is the only likely exposure pathway. Thus, adverse impacts depend on the controls on groundwater usage, the volume of aquifer impacted by the contaminant, and the time frame over which the groundwater remains contaminated above action levels. As such, this aspect of MNA is not directly considered in the screening evaluation.

4. *Current and projected demand for the affected resource over the time period that the remedy will remain in effect.*

   The groundwater demand is a function of administrative decisions, the volume of aquifer impacted by the contaminant, and the time frame over which the groundwater remains contaminated above action levels. As such, this aspect of MNA is not directly considered in the screening evaluation.

5. *Whether the contamination, either by itself or as an accumulation with other nearby sources (on-site or off-site), will exert a long-term detrimental impact on available water supplies or other environmental resources.*

   The groundwater availability is a function of administrative decisions, the volume of aquifer impacted by the contaminant, and the time frame over which the groundwater remains contaminated above action levels. As such, this aspect of MNA is not directly considered in the screening evaluation.

6. *Whether the estimated timeframe of remediation is reasonable compared to timeframes required for other more active methods (including anticipated effectiveness of various remedial approaches on different portions of the contaminated soil and/or groundwater).*

   The time frame for MNA is likely longer than the time frame for active remedies. The reasonableness of the time frame will be considered in the detailed analysis of the full feasibility study. As such, this aspect of MNA is not directly considered in the screening evaluation.

7. *The nature and distribution of sources of contamination and whether these sources have been, or can be, adequately controlled.*

   Due to the large vadose zone with uncertain contaminant distribution, there is some uncertainty in the long-term nature of the sources. However, efforts are underway to examine potential source control methods.

8. *Whether the resulting transformation products present a greater risk, due to increased toxicity and/or mobility, than do the parent contaminants.*

   None of the degradation or decay products for those COC that degrade or decay by natural processes under the Hanford aquifer conditions are hazardous except if there are areas with reduced geochemical conditions where carbon tetrachloride and trichlorethene can be reductively dechlorinated to other hazardous chlorinated solvents (e.g., chloroform, dichloroethene, and vinyl chloride.

9. *The impact of existing and proposed active remediation measures upon the MNA component of the remedy, or the impact of remediation measures or other operations/activities (e.g., pumping wells) in close proximity to the site.*

   Existing interim remedial actions (e.g., pump-and-treat) and most active remedies under consideration have a positive impact on natural attenuation by reducing contaminant mass/concentration and addressing source areas. Consideration of any negative impacts on MNA will be included in the assessment of potential future active remedies.

10. *Whether reliable site-specific mechanisms for implementing institutional controls (e.g., zoning ordinances) are available, and if an institution responsible for their monitoring and enforcement can be identified.*

    The Hanford Site has existing mechanisms for implementing institutional controls that are expected to remain viable for the foreseeable future.

Based on the evaluation of effectiveness, implementability, and relative cost presented below, MNA is retained as a potential remediation method for all COC groups (see Sections 7.2.2.1 through 7.2.2.3).

7.2.2.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 1	COC Group 2	COC Group 3	COC Group 4
Reliably meet goal?	MNA has the potential to significantly decrease contaminant concentration.	MNA will moderately decrease concentrations over time due to sorption, dispersion and dilution.	MNA will moderately decrease concentrations over time due to dispersion and dilution.	MNA has the potential to significantly decrease contaminant concentration.
Produce hazardous products?	MNA does not produce hazardous byproducts except if there are areas with reduced geochemical conditions.	MNA does not produce hazardous byproducts.	MNA does not produce hazardous byproducts.	MNA does not produce hazardous byproducts.
Negatively impact to other COC?	MNA of one COC does not negatively impact another.	MNA of one COC does not negatively impact another.	MNA of one COC does not negatively impact another.	MNA of one COC does not negatively impact another.
Treat target volume?	MNA is independent of volume.	MNA is independent of volume.	MNA is independent of volume.	MNA is independent of volume.
Cause risk during construction or operation?	MNA has no construction or operational risk.	MNA has no construction or operational risk.	MNA has no construction or operational risk.	MNA has no construction or operational risk.

7.2.2.2 Implementability

Implementability Screening Criteria (see Table 11)	COC Group 1	COC Group 2	COC Group 3	COC Group 4
Reliably constructed and operated?	MNA has no construction or operational problems, but the need to long-term monitoring and the potential need for a contingency remedy if natural attenuation does not limit plume migration are operational risks.	MNA has no construction or operational problems but the need to long-term monitoring and the potential need for a contingency remedy if natural attenuation does not limit plume migration are operational risks.	MNA has no construction or operational problems but the need to long-term monitoring and the potential need for a contingency remedy if natural attenuation does not limit plume migration are operational risks.	MNA has no construction or operational problems but the need to long-term monitoring and the potential need for a contingency remedy if natural attenuation does not limit plume migration are operational risks..
Reasonable consumable usage?	MNA has no significant consumable usage.	MNA has no significant consumable usage.	MNA has no significant consumable usage.	MNA has no significant consumable usage.

7.2.2.3 Relative Cost

MNA is expected to have a cost comparable to other options. The primary cost factors are costs for the initial MNA evaluation, monitoring well costs, and long-term monitoring costs.

7.2.3 Pump-and-Treat

Pump-and-treat is a baseline remedy for all COC groups and, as such, will be carried forward for the more detailed analysis in the feasibility study.

7.2.4 Chemical Oxidation

This category of remediation method includes use of strong oxidants such as hydrogen peroxide, Fenton's Reagent, permanganate, persulfate, and ozone. These oxidants can degrade organic contaminants and are therefore potentially applicable to COC Group 1. A primary factor in applying chemical oxidation is overcoming the oxygen demand within the aquifer during injection of the oxidant. As oxidant is injected, it quickly reacts with oxidizable materials in the aquifer (including the contaminant). With radial injection flow, the volume of aquifer, and therefore the mass of oxidizable materials associated with aquifer solids, increases with the square of the distance from the injection point. As a scoping calculation, therefore, the oxidant demand was estimated based on the mass of oxidizable material in the aquifer as a function of radial distance from a well and for target treatment volumes.

For many aquifers, the organic carbon content of the aquifer sediments is an important source of oxidizable material. There are limited site-specific data for the organic carbon content within the remediation study area. A value of 0.0007 (g-organic carbon/g-soil) for the fraction of organic carbon was used in the screening evaluation based on the average of reported values in Truex et al. (2001) and Riley et al. (2005). A unit oxidant demand of 0.033 mole-O_2/kg-soil for an f_{oc} of 0.0007 was estimated based on a bulk density of 1.8 and a generalized organic carbon formula of $C_{187}H_{186}O_{89}$ (Sposito 1989). For comparison, Schnarr et al. (1998) measured an oxidant demand of 0.025 mole-$KMnO_4$/kg-soil for an f_{oc} of 0.00027 in oxidation tests at a field test site in a sandy aquifer. Converting the oxidant demand from Schnarr et al. (1998) into moles of molecular oxygen and assuming a proportional relationship to the f_{oc}, the measured oxidant demand is equivalent to 0.05 mole-O_2/kg-soil for an f_{oc} of 0.0007. The unit oxidant demand for Schnarr et al. (1998) may be higher than estimated for the Hanford sediment because Schnarr's data include oxidant demand associated with minerals in addition to the demand from organic carbon. As an example, 1.5 million O_2-equivalent moles of a strong oxidant would be required to overcome the oxygen demand of sediment organic carbon for a treatment cylinder with a 20-m radius and a depth interval of 20 m using an oxygen demand of 0.033 mole-O_2/kg-soil. Additional oxidant would be required to support contaminant degradation. Because large quantities of strong oxidant are needed to overcome oxidant demand, even in low organic-content sediment, use of strong oxidants is typically limited to small volumes. For the screening evaluation, chemical oxidation was only considered for application to small continuing source areas.

Based on the evaluation of effectiveness, implementability, and relative cost presented below, chemical oxidation is retained as a potential remediation method for carbon tetrachloride (part of COC Group 1) only for application to a small potential continuing source zone (see Sections 7.2.4.1 through 7.2.4.3).

7.2.4.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 1
Reliably meet goal?	Likely reliable to reduce concentrations in a small volume. Potential issues with permanganate usage due to solids formation (Schroth et al. 2001). Fenton's reagent effectiveness demonstrated in the laboratory with an average of 42.8 mole of hydrogen peroxide consumed per mole of carbon tetrachloride degraded (Watts et al. 2005).
Produce hazardous products?	No hazardous byproducts are produced.
Negatively impact to other COC?	Likely no impact if applied in a small volume such as the core of a continuing source area for carbon tetrachloride or trichlorethene.
Treat target volume?	Only applicable for small volume such as with a continuing source area.
Cause risk during construction or operation?	Construction risk would be from necessary drilling. Operational risk is associated with handling of strong oxidants during injection time frame.

7.2.4.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 1
Reliably constructed and operated?	Uniform distribution of oxidant with a long well screen may be problematic.
Reasonable consumable usage?	Large quantities of oxidant would be needed unless only a limited volume were treated.

7.2.4.3 Relative Cost

For an example application in a treatment cylinder of 20-m radius and depth interval of 20 m (e.g., a core of the potential carbon tetrachloride continuing source area), 1.5 million O_2-equivalent moles would be on the order of 51,000 kg of hydrogen peroxide and 300,000 kg of potassium permanganate. With Fenton's reagent, the subsurface may need to also be amended with Fe(III). Cost factors for chemical oxidation are associated with the relatively high reagent usage and handling of the reagent during injection. For application to a small volume such as the core of the potential carbon tetrachloride continuing source area, costs may be comparable to other potential active remedies. Costs are expected to be higher than other potential remedies for any larger volumes due to the high reagent usage.

7.2.5 Injectable Apatite Solution

Hydroxyapatite [$Ca_5(PO_4)_3OH$] has been found to be very effective in sequestration of many dissolved metals including strontium and uranium. Such divalent metal oxyanions do react with dissolved phosphate to precipitate and immobilize the heavy metal. Apatite sequestration is expected to be minimally effective with chromium, technetium, and iodine groundwater contamination. Thus, for the screening evaluation, apatite was only considered for applicable to uranium as part of COC Group 2 (Fuller et al. 2002; Flury and Harsh 2000; Bostick et al. 2003). Because of the depth to groundwater, application of solid phase apatite is not feasible and will not be considered as a viable technology for the site. However, apatite minerals can be formed in situ from injection of soluble reagents (Moore et al. 2004). This method relies on injection of calcium citrate and phosphate solutions. The calcium is complexed with citrate during the injection and does not react with the phosphate until the citrate is degraded by microorganisms in the subsurface. Thus, the apatite formation can be distributed over a radial distance of meters to ~10 m away from the injection well depending on the subsurface hydrology and the microbial citrate degradation rate. This technique is currently being tested for application to strontium contamination at the Hanford 100 N Area. Injectable apatite would be considered an innovative treatment option.

Based on the evaluation of effectiveness, implementability, and relative cost presented below, injectable apatite is retained as a potential remediation method for uranium (part of COC Group 2) over an areal extent of less than 5 acres. This is an innovative technology that would likely need treatability testing (see Sections 7.2.5.1 through 7.2.5.3).

7.2.5.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 2 (uranium only)
Reliably meet goal?	Likely reliable to reduce concentrations in a small volume. Laboratory-scale studies show promise. Field-scale testing yet to be conducted.
Produce hazardous products?	No hazardous byproducts are produced.
Negatively impact to other COC?	Likely no impact if applied in a small volume such as the uranium plume. Residual phosphate could stimulate microbiological growth.
Treat target volume?	Distribution of the reagents meters to ~10 m from the injection point is expected. As such volumetric treatment of up to 5 acres could be achieved with a reasonable number of access wells.
Cause risk during construction or operation?	Construction risk would be from drilling necessary.

7.2.5.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 2 (uranium only)
Reliably constructed and operated?	Uniform distribution of reagents possible with proper engineering and hydraulic control. Treatability testing is needed.
Reasonable consumable usage?	Treatability testing is needed to assess design of the remediation system.

7.2.5.3 Relative Cost

The injectable apatite remediation method is an innovative technology still under development. Cost factors are primarily related to the radius of influence that can be obtained. It is expected that a radius of influence similar to injection of a long-duration substrate for anaerobic bioremediation will be possible. As such, costs for injectable apatite could be comparable to other technologies at an areal extent of less than 5 acres where well costs would be similar to an anaerobic bioremediation application.

7.2.6 Stabilization by Polyphosphate

Another phosphate-based technology for stabilization of uranium using phosphate is presently in development. This technology uses injection of liquid polyphosphate to stabilize uranium. It is not applicable to the other COC. This technology stabilizes uranium by a different mechanism than apatite stabilization.

The process uses polymers of phosphate to release phosphate at a slow, controlled rate into groundwater downgradient of the application point. The presence of phosphate in groundwater, even in minor concentrations (10^{-8} M), promotes the formation of autunite–group minerals, $X_{3-n}^{(n)*}[(UO_2)(PO_4)]_2 \cdot xH_2O$, thereby limiting the mobility of the uranyl cation (UO_2^{2+}) in the subsurface environment. The use of soluble long-chain polyphosphate reagent delays precipitation of the autunite, thereby mitigating plugging of the formation near the application point. By tailoring the polyphosphate chain, the hydrolysis reaction that releases the phosphate into the water can be engineered and the uranium stabilization rate controlled. Because autunite sequesters uranium in the oxidized form, U^{6+}, rather than forcing reduction to U^{4+}, the possibility of re-oxidation and subsequent re-mobilization is negated. Extensive laboratory testing demonstrates the very low solubility of autunite. In addition to autunite, excess phosphorous may result in apatite mineral formation, providing a secondary, long-term source of treatment capacity.

Deployment polyphosphate may be designed to treat a horizontal extent as well as vertical zone of uranium in the groundwater and at the water-table interface. The liquid form of the reagent facilitates application to and transport within the contaminated groundwater plume. Uranium transport studies in columns packed with contaminated sediment from the Hanford 300 Area indicate that a polyphosphate solution reduces the concentration of uranium in water to near the drinking water standard (30 µg/L) (Wellman et al. 2006). Polyphosphate would be considered an innovative treatment option.

Based on the evaluation of effectiveness, implementability, and relative cost presented below, polyphosphate is retained as a potential remediation method for uranium (part of COC Group 2) over an areal extent of less than 5 acres. This is an innovative technology that would likely need treatability testing (see Sections 7.2.6.1 through 7.2.6.3).

7.2.6.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 2 (uranium only)
Reliably meet goal?	Likely reliable to reduce concentrations in a small volume. Laboratory-scale studies show promise. Field-scale testing yet to be conducted.
Produce hazardous products?	No hazardous byproducts are produced.
Negatively impact to other COC?	Likely no impact if applied in a small volume such as the uranium plume. Residual phosphate could stimulate microbiological growth.
Treat target volume?	Distribution of the polyphosphate meters to ~10 m from the injection point is expected. As such volumetric treatment of up to 5 acres could be achieved with a reasonable number of access wells.
Cause risk during construction or operation?	Construction risk would be from necessary drilling.

7.2.6.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 2 (uranium only)
Reliably constructed and operated?	Uniform distribution of polyphosphate possible with proper engineering and hydraulic control. Treatability testing is needed.
Reasonable consumable usage?	Treatability testing is needed to assess design of the remediation system.

7.2.6.3 Relative Cost

The polyphosphate remediation method is an innovative technology still under development. Cost factors are primarily related to the radius of influence that can be obtained. It is expected that a radius of influence similar to injection of a long-duration substrate for anaerobic bioremediation will be possible. As such, costs for polyphosphate could be comparable to other technologies at an areal extent of less than 5 acres where well costs would be similar to an anaerobic bioremediation application.

7.2.7 Injectable Zero-Valent Iron

Emplacement of zero-valent iron particles in the subsurface provides an electron source for dechlorination of carbon tetrachloride and trichlorethene (COC Group 1) and reduction of chromium, technetium-99, uranium, and nitrate (COC Groups 2 and 3, except iodine-129). Typically, zero-valent iron is applied as a permeable reactive barrier. Potentially, it could be deployed in a manner more suitable for volumetric treatment (e.g., Quinn et al. 2005). However, for volumetric treatment, the extent to which the particles can be distributed is a key issue for consideration. Present technology permits placement of small-scale iron particles from wells to radial distances of about 3–7 m (GeoSierra 2005). Similarly, low radial influences are observed with current applications of emulsified zero-valent iron (Quinn et al. 2005 and personal communication J. Quinn). Because large quantities of zero-valent iron are needed for large volume treatment (see Table 7.6) and the small radius of influence, zero-valent iron is typically limited to small volumes application or for permeable reactive barrier applications (see Section 7.2.15).

Based on the evaluation of effectiveness, implementability, and relative cost presented below, zero-valent iron for volumetric treatment is eliminated as a potential remediation method for all COC groups (see Sections 7.2.7.1 through 7.2.7.3).

Table 7.6. Zero-Valent Iron Required as a Function of Aquifer Volume

Radius or Areal Extent	Volume of Aquifer (m^3)	Mass of Zero-Valent Iron[(a)] (kg)
Radius of 3 m at 20 m depth	565	8,300
Radius of 7 m at 20 m depth	3,079	45,000
Radius of 20 m (multiple wells needed)	25,133	370,000
4,000 m^2 (~1 acre) at 20 m depth (multiple wells needed)	80,000	1,170,000
(a) Calculated using a porosity of 0.3 and for a 10% zero-valent iron emulsion filling 20% of the pore space.		

7.2.7.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 1	COC Group 2	COC Group 3
Reliably meet goal?	Likely reliable to reduce concentrations in a small area. However, may not be adequate for carbon tetrachloride DNAPL contamination in a continuing source area.	Likely reliable for chromium. Tc-99 and uranium likely reduced to meet goal, but can re-oxidize over time.	Likely reliable for nitrate.
Produce hazardous products?	Reductive dechlorination of carbon tetrachloride and trichlorethene may lead to hazardous byproducts.	No hazardous byproducts.	No hazardous byproducts.
Negatively impact to other COC?	No negative impacts expected.	No negative impacts expected.	No negative impacts expected.
Treat target volume?	Only applicable for small volume such as with a continuing source area.	Only applicable for small volume not likely relevant to overall COC Group 2 plume treatment.	Only applicable for small volume not likely relevant to overall nitrate plume treatment.
Cause risk during construction or operation?	Primary risk would be from significant amount of necessary drilling.	Primary risk would be from significant amount of necessary drilling.	Primary risk would be from significant amount of necessary drilling.

7.2.7.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 1	COC Group 2	COC Group 3
Reliably constructed and operated?	Uniform distribution of iron with a long well screen may be problematic. Very large number of wells necessary.	Uniform distribution of iron with a long well screen may be problematic. Very large number of wells necessary.	Uniform distribution of iron with a long well screen may be problematic. Very large number of wells necessary.
Reasonable consumable usage?	Very large amounts of iron necessary for volumetric treatment.	Very large amounts of iron necessary for volumetric treatment.	Very large amounts of iron necessary for volumetric treatment.

7.2.7.3 Relative Cost

Cost factors for zero-valent iron are associated with the relatively high reagent usage and large number of wells needed due to the limited radius of injection. Nano-zero-valent iron in powder form costs over $16 per pound, and emulsified zero-valent iron costs more than $20 per gallon for a 10% iron solution (personal communication, J. Greg Booth, Applied Science & Advanced Technologies, Inc.). The cost of the emulsified zero-valent iron, even for a treatment cylinder volume represented by a 20-m radius and a depth interval of 20 m, would be on the order of $6M. Costs for zero-valent iron as a volumetric treatment are expected to be higher than other potential remedies due to the high reagent usage and large number of wells for the relatively large treatment volumes associated with 200-ZP-1 COC.

7.2.8 Surfactant Flushing

This technology employs surfactant mixtures (i.e., nonionic and anionic) in injection wells at levels generally around 1% to 3% with or without additional chemicals (cosolvents, alcohols, inorganic salts, etc.) to promote the mobilization and/or solubilization of nonaqueous phase liquid (NAPL). Solubilization of sorbed contaminants may also occur. The surfactants function by lowering the NAPL-water interfacial tension and decreasing capillary forces within the porous media, which creates a micro-emulsion system and solubilizes the contaminant. In most demonstrations, surfactants or cosolvents are pumped through the aquifer displacing at least one or more pore volumes of groundwater, followed by several pore volumes of water to remove the residual surfactant. Various well configurations are used including single vertical circulation wells and injection/extraction well networks. Recovered contaminant with recovered surfactant is processed ex-situ using a variety of treatment processes.

Applicability of surfactant flushing appears to be most relevant to carbon tetrachloride (COC Group 1) because DNAPL may be present in the aquifer. Surfactant flushing is not likely to be appropriate for treating other COC groups because of the difficulty in selecting and applying an effective yet selective surfactant to inorganic contaminants that would not also mobilize large quantities of non-target minerals in the formation. Thus, for the screening evaluation, surfactant flushing was only considered for application to small continuing source areas.

Based on the evaluation of effectiveness, implementability, and relative cost presented below, surfactant flushing is retained as a potential remediation method for carbon tetrachloride (part of COC Group 1) for small continuing source areas (see Sections 7.2.8.1 through 7.2.8.3).

7.2.8.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 1 (carbon tetrachloride only)
Reliably meet goal?	Likely able to reduce concentrations in a known area of DNAPL. Significant uncertainty related to ability to mobilize and then capture the contamination and to effectively treat DNAPL in low permeability zones.
Produce hazardous products?	Residual surfactant could promote reductive dechlorination of carbon tetrachloride and trichlorethene, which may lead to hazardous byproducts. Otherwise, hazardous products are not expected.
Negatively impact to other COC?	Surfactant flushing could disperse other contaminants.
Treat target volume?	Only applicable for a NAPL area.
Cause risk during construction or operation?	Primary risk would be from significant amount of necessary drilling.

7.2.8.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 1
Reliably constructed and operated?	Ex-situ separation and recovery of halogenated solvent could be problematic. Re-cycling or accumulation of surfactant may be difficult.
Reasonable consumable usage?	Surfactant consumption could be uneconomic based upon recycle rates and efficiency of COC recovery.

7.2.8.3 Relative Cost

Cost factors for surfactant flushing are associated with the wells and groundwater recirculation infrastructure needed to inject the surfactant and then ensure capture of the mobilized contaminants. Another cost factor is the above-ground equipment needed to treat, or separate and treat, the extracted contaminants. As such, costs for surfactant flushing are expected to be somewhat higher than for other technologies such as bioremediation because of the importance of hydraulic control. Costs may be comparable to other source area treatment technologies such as chemical oxidation and thermal treatment.

7.2.9 In-Well Air Stripping (and Thermally Enhanced In-well Air Stripping)

In-well air stripping (vapor stripping) is the process of injecting air into a well below the water table to cause air-lift pumping of water from a bottom well screen to an upper well screen, where the groundwater and air are separated. This process induces a recirculation pattern in the aquifer where contaminated water is drawn into the lower well screen and flows back into the formation at the upper well screen. At the same time, the air contacting the groundwater in the well causes mass transfer of volatile contaminants from the groundwater to the gas phase, which is typically captured by a vacuum extraction blower. Contaminant concentrations eventually decline as groundwater circulates through the aquifer around the treatment well. Variants of the technology use in-well reactors, submersible pumps, ozone injection, soil vapor extraction, and/or vadose zone biodegradation. There are four patented commercial variations of this technology (DOE 2002): NoVOCs (MACTEC, Inc.), UVB (IEG-Technologies Corp.), Density Driven Convection (Wasatch Environmental, Inc.), and C-Sparger (K-V Associates, Inc.). A variety of applications have been documented (EPA 1998). In-well air stripping is applicable to volatile organic compounds and is therefore relevant to COC Group 1.

Key properties that determine the effectiveness/implementability of this technology are: contaminant properties (i.e., Henry's Law constant), hydraulic conductivity of the aquifer, anisotropy of the aquifer, distance between upper and lower well screens (i.e., thickness of contaminated saturated zone), recirculation flow rate, thickness of vadose zone, and the natural groundwater flow gradient. The volatility of the chemical and the contact (distance/duration of contact, surface area/size of bubbles) between the groundwater and the air phase will determine the effectiveness of the mass transfer and removal of contaminant. Aquifer properties and physical geometry of the system impact the radius of influence for the well. In situations of low anisotropy (ratio of horizontal to vertical hydraulic conductivity), the radius of influence is lower as the recirculation gets more "short circuited." At high anisotropy, recirculation will be harder to develop, and there is potential for the plume to spread. Technology reports (DOE 2002; EPA 1995) indicate that a typical radius of influence is two to three times the distance between the upper and lower well screens. The hydraulic conductivity of the aquifer, induced pumping rate, and natural gradient for groundwater flow will all impact the radius of influence and the treatment effectiveness. In-well air stripping has been demonstrated both in the laboratory (e.g., Katz and Gvirtzman 2000) and at actual sites (e.g., DOE 2002).

Potentially, in-well air stripping could be configured to treat a specified volume or serve as a treatment barrier. Using an estimate for the radius of influence of two times the distance between upper and lower screens and a nominal screen length of 5 m, a radius of influence and associated per-well treatment volume can be calculated (Table 7.7). Treatment depth intervals greater than 30 m for calculating the radius of influence were not considered because the largest depth interval in the references reviewed was about 30 m. For treating thicker contaminated intervals, a separate shallow and deep treatment system would be needed (e.g., two 30-m intervals versus one 60-m interval).

Table 7.7. Estimated Radius of Influence and Treatment Volumes for an In-Well Air Stripping Well

Depth Interval (m)	Estimated Radius of Influence (m)	Areal Extent of Treatment Zone m^2 (acre)	Estimated Treatment Volume (m^3)
15	10	314 (0.08)	4,700
20	20	1,256 (0.31)	25,000
25	30	2,827 (0.7)	71,000
30	40	5,026 (1.2)	151,000

While it is possible to thermally enhance the effectiveness of in-well air stripping, this type of enhancement is not necessary for carbon tetrachloride or trichlorethene because they are sufficiently volatile for effective extraction at the ambient groundwater temperature. Thus, thermally enhanced in-well air stripping is eliminated as a potential remediation method for COC Group 1.

Based on the evaluation of effectiveness, implementability, and relative cost presented below, in-well air stripping is retained as a potential remediation method for COC Group 1 for application to treat an areal extent of up to 25 acres or as a barrier technology (see Sections 7.2.9.1 through 7.2.9.3). Treatability testing would likely be required for the in-well air stripping technology.

7.2.9.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 1
Reliably meet goal?	Effective extraction depends on the ability to recirculate contamination into the air stripping well. Testing would be needed to verify performance at Hanford. Performance as a barrier is less certain than performance as a volumetric treatment. Treatment is for dissolved-phase contaminants, not DNAPL.
Produce hazardous products?	No hazardous byproducts.
Negatively impact to other COC?	No negative impacts expected.
Treat target volume?	In-well air stripping may be suitable over an areal extent of up to 25 acres using the estimated radius of influence shown in Table 7.7. For treatment volumes above 25 acres, a large number of wells would be needed because COC Group 1 contaminants are present over a thick interval at larger areal extent.
Cause risk during construction or operation?	Construction risk would be from a significant amount of necessary drilling. Because contamination is extracted to the surface, the operation risk is similar to that of a pump-and-treat system.

7.2.9.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 1
Reliably constructed and operated?	Construction and operation of the system is straightforward.
Reasonable consumable usage?	Consumable usage is similar to that of a pump-and-treat system.

7.2.9.3 Relative Cost

Cost factors for in-well air stripping include well drilling and above-ground vapor treatment. The number of wells is highly dependent on the effective radius of influence for contaminant extraction that is obtained. A site-specific treatability test would likely be needed to determine the radius of influence. Based on the estimated radii of influence and associated treatment volumes listed in Table 7.7, the number of wells per treatment volume can be estimated. For an areal treatment extent above about 25 acres, the number of wells required to apply in-well air stripping will likely increase cost significantly compared to the cost for other viable options.

Applied as a treatment barrier, well spacing can be determined from information in Table 7.7. Costs are directly related to the radius of influence by determining the number of wells needed for a barrier application.

7.2.10 Down-Well System

Down-well treatment systems place a bioreactor or adsorption media within the well bore. Such technology is presently developmental and has not been deployed at a large scale. The technology requires treating groundwater within the relatively limited volume of the well bore. Biological treatment systems require a definite control volume to contain the biological process for a specific detention or reaction time. Down-well sorption systems are limited by the media-holding capacity of the well bore. Consequently, frequent media replacement may be needed. For the screening evaluation, down-well systems were considered as potentially applicable to COC Group 2.

Based on the evaluation of effectiveness, implementability, and relative cost presented below, down-well treatment is eliminated as a potential remediation method (see Sections 7.2.10.1 through 7.2.10.3).

7.2.10.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 2
Reliably meet goal?	Significant uncertainty in the ability to reduce contaminant concentration.
Produce hazardous products?	No hazardous by products.
Negatively impact to other COC?	No negative impacts expected.
Treat target volume?	Potentially applicable to the same aquifer volume as for in-well air stripping based on expected recirculation patterns.
Cause risk during construction or operation?	Primary risk would be from significant amount of drilling necessary.

7.2.10.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 1
Reliably constructed and operated?	Complex construction and maintenance concerns due to small volume available for the treatment system within the well.
Reasonable consumable usage?	Reagent or consumable costs could be uneconomic based upon limited operating efficiencies.

7.2.10.3 Relative Cost

Cost factors for down-well treatment include well drilling and maintenance of the treatment process. The number of wells is highly dependent on the effective radius of influence for contaminant extraction that is obtained. A site-specific treatability test would likely be needed to determine the radius of influence. Based on the estimated radii of influence and associated treatment volumes listed in Table 7.7, the number of wells per treatment volume can be estimated. For an areal treatment extent above about 25 acres, the number of wells required for application of down-well treatment will likely increase cost significantly compared to the cost for other viable options.

Applied as a treatment barrier, well spacing can be determined from information in Table 7.7. Costs are directly related to the radius of influence by determining the number of wells needed for a barrier application.

7.2.11 Air Sparging

Air sparging involves injecting a gas (usually air/oxygen) under pressure into the saturated subsurface to volatilize organic groundwater contaminants. Volatilized vapors migrate into the vadose zone where they are extracted via vacuum, generally by a soil vapor extraction system installed into the vadose zone. Air sparging is applicable to the COC Group 1 volatile organic contaminants. Sites with relatively permeable, homogeneous soil conditions favor the use of air sparging due to greater effective contact between sparged air and the media being treated and effective extraction of volatilized vapors. Other appropriate site variables include relatively large saturated thicknesses and depths to groundwater. Saturated thicknesses and depths to groundwater control the area of influence of a sparging well and the number of wells needed. Because air transport through an aquifer is more difficult than water transport, compared to the sensitivity of technologies that recirculate water, air sparging tends to be more sensitive to heterogeneities.

Site conditions that preclude effective air sparging include:

- Fine-grained, low-permeability soils that decrease air flow
- Lithology that includes a low-permeability layer overlying the aquifer, which would inhibit effectively capturing volatilized vapor in the vapor recovery wells
- Heterogeneous soils, which foster channeling of sparge air or vapor flow.

The nominal thickness of the COC Group 1 is 70 m with a similar depth to the water table. This thickness/depth is approximately two times greater than is typical for deeper applications of air sparging.

Based on the evaluation of effectiveness, implementability, and relative cost presented below, air sparging is retained as a potential remediation method for COC Group 1 for application to treat small, focused areas of groundwater contamination up to 5 acres in area and for thicknesses of less than 30 m (see Sections 7.2.11.1 through 7.2.11.3). Treatability testing is likely needed before implementation to assess the ability to effectively sparge and collect the contamination.

7.2.11.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 1
Reliably meet goal?	Effective extraction depends on whether heterogeneous layers within the aquifer will be conducive to effective sparging and the ability to collect sparged vapors in the vadose zone. Testing would be needed to verify performance at Hanford.
Produce hazardous products?	No hazardous byproducts.
Negatively impact to other COC?	No negative impacts expected.
Treat target volume?	The suitability of air sparging is a function of the permeability and vertical stratigraphy of the aquifer and vadose zone. Air sparging may be suitable over smaller areas with higher target concentrations. For treatment over large plume size areas, a large number of wells would be needed because nominally sparging and vapor recovery is limited to the radii of influence not exceeding 30 m.
Cause risk during construction or operation?	Construction risk would be from a significant amount of necessary drilling. Because contamination is extracted to the surface, the operation risk is similar to that of a pump-and-treat system.

7.2.11.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 1
Reliably constructed and operated?	Construction and operation of the system is straightforward.
Reasonable consumable usage?	Consumable usage is similar to that of a pump-and-treat system for treatment of extracted vapors.

7.2.11.3 Relative Cost

Cost factors for air sparging include well drilling and above-ground vapor treatment. The number of wells is highly dependent on the effective radius of influence for contaminant extraction that is obtained. A site-specific treatability test would likely be needed to determine the radius of influence. For an areal treatment extent above about 25 acres, the number of wells required for application of air sparging will likely increase cost significantly compared to the cost for other viable options. Applied as a treatment barrier, costs are directly related to the radius of influence.

7.2.12 Anaerobic Bioremediation

Carbon tetrachloride can be dechlorinated under anaerobic conditions to either CF or non-hazardous compounds depending on the subsurface conditions (Truex et al. 2001). Trichlorethene can be directly reduced to ethene by some bacteria as part of anaerobic reductive dechlorination reactions (e.g., DeBruin et al. 1992; Freedman and Gossett 1989), though reductive dechlorination or trichlorethene may also result in DCE and VC as persistent dechlorination products. Anaerobic dechlorination reactions require that an appropriate substrate is present and the dechlorinating bacteria can effectively compete for the substrate against other microorganisms that can also use the substrate with other electron acceptors. Nitrate, chromium technetium-99, and uranium can also be reduced under anaerobic conditions and converted to non-hazardous products (for nitrate) or to insoluble chemical forms (for chromium, technetium-99, and uranium). The biomass that grows during anaerobic bioremediation may also increase the adsorption of other contaminants such as iodine-129, potentially enhanced through reduction of the iodine (Muramatsu et al. 2004). Thus, anaerobic bioremediation is potentially applicable to COC Groups 1, 2, and 3.

In situ anaerobic bioremediation relies on effective distribution of substrate and activity of appropriate bacteria. A groundwater recirculation system could be used to distribute a soluble substrate (e.g., molasses) over large distances to attempt enhancing reductive dechlorination of carbon tetrachloride or trichlorethene and reduction of chromium, technetium-99, and uranium. However, the success in stimulating dechlorination without producing hazardous byproducts, and contaminant reduction versus other types of anaerobic activity, is dependent on the microbial ecology and groundwater geochemistry (e.g., presence of other electron acceptors). The ability to stimulate appropriate microbial activity would need to be evaluated to confirm whether remediation goals will likely be met.

In situ anaerobic bioremediation could also be implemented by distributing a long-duration substrate such as vegetable oil into the aquifer. Because the substrate is less accessible to the bacteria, it is not consumed as it is distributed and can provide a long-term food supply once in place. The key property with this technology is the hydraulic conductivity of the aquifer. The radius of the treatment zone depends on how well the substrate can be injected into and distributed through the aquifer formation. A secondary property of interest is the length of time that the substrate lasts, which impacts the frequency of "regenerating" the treatment zone. The radius of influence for long-duration substrate injection will be less than that for a soluble substrate. Functionally, a radius of about 7 m for oil distribution is similar to what has been achieved for other applications of this technology.

Based on the evaluation of effectiveness, implementability, and relative cost (presented below), in situ anaerobic bioremediation is retained as a potential remediation method for COC Groups 1, 2, and 3 for application to treat an areal extent of up to 5 acres (see Sections 7.2.12.1 through 7.2.12.3). For thick contaminated intervals such as for COC Group 1, multiple injection well intervals would likely be needed.

7.2.12.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 1	COC Group 2	COC Group 3
Reliably meet goal?	There is moderate uncertainty in meeting the goals because complete dechlorination to non-hazardous compounds may not be obtained.	There is moderate uncertainty in meeting the goals for Tc-99 and uranium because these compounds can reoxidize readily and become mobile again after being microbially reduced and temporarily immobilized. It is likely that goals for chromium could be met because it remains stable and immobile after microbial reduction. Increased adsoption of I-129 and reduction may also occur.	It is likely that goals for nitrate could be met because it will likely be reduced to nitrogen gas.
Produce hazardous products?	Reductive dechlorination of carbon tetrachloride and trichlorethene may lead to hazardous byproducts.	No hazardous byproducts.	Likely no hazardous byproducts.
Negatively impact to other COC?	No negative impacts expected.	No negative impacts expected.	No negative impacts expected.
Treat target volume?	Bioremediation can treat large or small volumes, but will require numerous wells for larger volumes due to a limited radius of influence for substrate distribution.	Bioremediation can treat large or small volumes, but will require numerous wells for larger volumes due to a limited radius of influence for substrate distribution.	Bioremediation can treat large or small volumes, but will require numerous wells for larger volumes due to a limited radius of influence for substrate distribution.
Cause risk during construction or operation?	Primary risk would be from a significant amount of necessary drilling.	Primary risk would be from a significant amount of necessary drilling.	Primary risk would be from a significant amount of necessary drilling.

7.2.12.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 1	COC Group 2	COC Group 3
Reliably constructed and operated?	Uniform distribution of substrate with a long well screen may be problematic. Very large number of wells necessary.	Uniform distribution of substrate with a long well screen may be problematic. Very large number of wells necessary.	Uniform distribution of substrate with a long well screen may be problematic. Very large number of wells necessary.
Reasonable consumable usage?	Very large amounts of substrate necessary for large treatment volumes.	Very large amounts of substrate necessary for large treatment volumes.	Very large amounts of substrate necessary for large treatment volumes.

7.2.12.3 Relative Cost

Cost factors for anaerobic bioremediation are a function of well costs, the amount of substrate required to maintain appropriate conditions over the desired treatment volume, and the longevity of the substrate. Long-duration substrates can only be distributed a short distance from injection wells. Thus, use of vegetable oil or similar long-duration substrates would be limited to small volumes because the cost for injection wells would render bioremediation much more expensive than other potential options at larger volumes. For instance, assuming a 7-m effective radius for vegetable oil injection stimulating bioremediation within a radius of influence of 14 m, 9 wells per acre are necessary. Soluble substrates can be distributed over larger volumes but are not long lasting and would require frequent injection. Thus, use of soluble substrates would also be limited to relatively small volumes because the cost of substrate injection via groundwater recirculation wells at large volumes would render bioremediation much more expensive than other potential options.

7.2.13 Aerobic Bioremediation (co-metabolism)

Trichlorethene can be co-metabolically oxidized by some bacteria in the presence of molecular oxygen and substrates such as methane, toluene, and phenol (e.g., Chang and Alvarez-Cohen 1995). This method is only applicable to trichlorethene (part of COC Group 1). In situ aerobic bioremediation relies on effective distribution of reagents and activity of appropriate bacteria. In addition to using air, pure oxygen or dilute concentrations of hydrogen peroxide are other methods for oxygenating the injected water. This technology requires that bacteria that utilize monooxygenase enzymes (e.g., methanotrophs – bacteria that use methane as a substrate) are present in the aquifer to support co-metabolic trichlorethene degradation. The ability to stimulate appropriate microbial activity would need to be evaluated to confirm whether remediation goals will likely be met. Biological degradation processes would not produce hazardous products (trichlorethene is destroyed, not transformed).

Treatment would be stimulated through either injection of methane and oxygen as gases directly into the target zone or through groundwater recirculation, where methane and oxygen would be dissolved into the water at the surface and then injected into the aquifer. In situ aerobic bioremediation requires a significant design effort. Not only must the ability to stimulate appropriate microbial activity be assessed, but also a number of design issues for the substrate and oxygen system must be addressed.

Based on the evaluation of effectiveness, implementability, and relative cost presented below, in situ aerobic bioremediation is retained as a potential remediation method for trichlorethene (part of COC Groups 1) for application to treat an areal extent of up to 5 acres (see Sections 7.2.13.1 through 7.2.13.3). However, treatment of the full contaminated thickness may require multiple substrate distributions systems (e.g., one shallow and one deep).

7.2.13.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 1 (trichlorethene only)
Reliably meet goal?	Effective treatment depends on the ability to distribute the substrate and oxygen with the contamination and the presence of appropriate bacteria. Testing would be needed to verify performance at Hanford.
Produce hazardous products?	No hazardous byproducts.
Negatively impact to other COC?	No negative impacts expected.
Treat target volume?	Bioremediation can treat large or small volumes, but will require numerous wells for larger volumes due to a limited radius of influence for substrate and oxygen distribution.
Cause risk during construction or operation?	Primary risk would be from significant amount of necessary drilling. Small operational risks may be associated with handling methane and oxygen

7.2.13.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 1 (trichlorethene only)
Reliably constructed and operated?	Uniform distribution of substrate and oxygen with a long well screen may be problematic. Large number of wells necessary for large volumes.
Reasonable consumable usage?	Large amounts of substrate necessary for large treatment volumes.

7.2.13.3 Relative Cost

Cost factors are primarily associated with the ability to distribute oxygen and methane in the aquifer and therefore the number of wells required. Relatively large-scale application of aerobic bioremediation has been demonstrated at the DOE Savannah River Site. This type of application at Hanford may be viable over similar treatment volumes and have costs similar to other potential options.

7.2.14 In Situ Thermal Treatment

In situ thermal treatment is applicable to volatile and semi-volatile compounds and is primarily applied for treatment of NAPL contaminant rather than dissolved-phase contaminant. As such, in situ thermal treatment is considered for carbon tetrachloride only because it is the only COC potentially present as a NAPL in the groundwater (part of COC Group 1).

In situ thermal treatment increases the temperature of the subsurface to enhance the extraction of liquid-, dissolved-, or vapor-phase contamination. For instance, liquid-phase extraction can be enhanced if the viscosity of NAPL contamination decreases sufficiently with increased temperature. Dissolved-phase extraction can be enhanced if the solubility of the contaminant increases with temperature or if NAPL is volatilized and it dissolves in an aqueous phase at higher concentrations than before heating. While it is not clear that this mechanism plays a strong role in removing large amounts of contaminant mass, it is important to consider for containment of the contamination and may be relevant near the end of the treatment period. Vapor-phase extraction is typically a key component of in situ thermal treatment. Raising the temperature volatilizes NAPL so that it can be extracted in the soil gas. In addition, raising the subsurface temperature can boil groundwater, enhancing pathways for vapor transport to the surface. Multi-phase extraction can also be used to more aggressively remove contaminant mass, but this increases the treatment burden for above-ground equipment.

Through the above mechanisms, in situ thermal treatment can effectively enhance extraction of NAPL contaminant from the subsurface. Several techniques for in situ thermal treatment have been applied for site remediation. This screening evaluation primarily focuses on electrical resistance heating and steam injection. Electrical resistance heating (e.g., six-phase soil heating) has been applied to enhance extraction of chlorinated solvents from the saturated and unsaturated subsurface zones (Fain et al. 2002; Hudson et al. 2002; Pope et al. 2002; Smith et al. 2000; Beyke et al. 2000a). Hydrocarbon contamination has also been treated using electrical resistance heating (e.g., Beyke et al. 2000b). Similarly, steam injection has been applied recently to enhance removal of chlorinated solvents (Jepsen et al. 2002), chlorinated solvents mixed with hydrocarbons (Larson et al. 2002; Adams and Smith 1998), PCBs mixed with hydrocarbons (Cote et al. 2002), and hydrocarbons (Dablow and Balshaw-Biddle 1998). For carbon tetrachloride, the homogeneous hydrolysis rate (abiotic degradation) is significantly increased at higher temperatures (Jeffers et al. 1989, 1996; Truex et al. 2001) and may be an important component of the overall carbon tetrachloride mass removal during thermal treatment.

Both site and contaminant properties can limit the effectiveness of in situ thermal treatment in reaching remediation goals, especially if the goal is source removal (versus source reduction). Heterogeneous subsurface hydrologic conditions can impact the distribution of heat and the pathways for contaminant extraction. For each site remediation, the combination of remediation goals, subsurface complexities, and contaminant properties will impose operational constraints and determine the remediation cost for use of in situ thermal treatment as a means to enhance contaminant extraction. Specific remediation goals for NAPL may vary between sites. In some cases, source reduction or containment is sufficient. In other cases, source removal is needed. The remediation goal affects the treatment cost because more heating time and energy are needed to reach lower residual concentrations in the subsurface. Other cost drivers for in situ thermal treatment include 1) stratigraphic layering that impacts the heating or extraction efficiency, 2) thickness of the vadose zone column through which contaminant must be extracted, 3) groundwater flux rate (heat losses), 4) overall size/depth/thickness of contaminated zone, and 5) presence of non- or semi-volatile contaminants.

Because of the characteristics and cost drivers for thermal treatment technologies, only application to small, continuing source areas for carbon tetrachloride was considered.

Based on the evaluation of effectiveness, implementability, and relative cost presented below, thermal treatment is retained as a potential remediation method for carbon tetrachloride (part of COC Group 1) for small, continuing source areas for the portion of the aquifer (see Sections 7.2.14.1 through 7.2.14.3). There would be increasing costs and uncertainty in treatment for increasing treatment depth into the aquifer.

7.2.14.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 1 (carbon tetrachloride only)
Reliably meet goal?	Likely reliable to reduce concentrations in a small volume. Potential issues with thermal treatment are associated with effective extraction of the vapor-phase contaminants in a heterogeneous subsurface without spreading of the contamination.
Produce hazardous products?	No hazardous products are produced.
Negatively impact to other COC?	No negative impacts to other COC.
Treat target volume?	Only applicable for small volume such as with a continuing source area.
Cause risk during construction or operation?	Construction risk would be from necessary drilling. Operational risk is associated with vapor-phase treatment processes and electrical/steam equipment.

7.2.14.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 1 (carbon tetrachloride only)
Reliably constructed and operated?	Electrodes and/or other system components are deeper than previous applications. Operation is similar to previous applications.
Reasonable consumable usage?	Electricity use will be large for a finite period of time, but this consumption has been effectively addressed for other applications.

7.2.14.3 Relative Cost

Cost factors are primarily associated with installation of the wells and/or electrodes necessary for treatment. Costs are expected to be similar to other potential active remedy options for source area treatment. Thus, thermal treatment is retained as potential remediation method for small continuing source areas.

7.2.15 Permeable Reactive Barriers

Permeable reactive barrier (PRB) technology is an interception technology designed to treat contaminant as it passes through the treatment zone. This technology relies on having sufficient knowledge of the contaminant plume location and the groundwater flow paths. In general, PRB may act on the contaminants flowing through by destroying the contaminant in a reaction (biological or abiotic), by adsorption of the contaminant onto the PRB media, or by precipitation resulting from a chemical reaction. The PRB technology may be implemented as a funnel-and-gate system or an interception wall. The funnel-and-gate system uses physical barriers (e.g., sheet piling or a low-permeability material such as a clay or grout) on two sides to direct groundwater (and contaminant plume) flow through a smaller permeable treatment zone. An interception wall is a continuous treatment zone wide enough to intersect with the expected span of the contaminant plume. The groundwater flow velocity controls the duration of the remediation effort and the design of the PRB. The PRB must be designed with a suitable thickness (or multiple walls in series) to provide enough residence time for reaction (destruction), adsorption, or precipitation of the contaminant to, at, or below the desired downgradient concentration. A funnel-and-gate system is impractical to install for the depth and extent of the contamination and will not be considered further. Treatment variants that are applicable to the COC Group 1, 2 (except iodine-129), and 3 include zero-valent iron, in situ redox manipulation, and biodegradation. Phosphate-based barriers such as injectable apatite and polyphosphate are potential innovative methods applicable to the uranium plume. A PRB is not considered applicable to iodine-129 or tritium COC. The specific PRB variants are discussed in more detail below.

7.2.15.1 Zero-Valent Iron PRB

Zero-valent iron is most often installed in a trench-and-fill system, but can be installed by injection of material into the aquifer through wells. Present technology permits placement of small-scale iron particles from wells to radial distances of about 3–7 m (GeoSierra 2005). Similarly, low radial influences are observed with current applications of emulsified zero-valent iron (Quinn et al. 2005 and personal communication, J. Quinn). Emplacement of zero-valent iron particles in the subsurface provides an electron source for dechlorination of carbon tetrachloride and trichlorethene (COC Group 1) and reduction of chromium, technetium-99, uranium, and nitrate (COC Groups 2 and 3, except iodine-129).

Based on the evaluation of effectiveness, implementability, and relative cost presented below, zero-valent iron as a PRB is eliminated as a potential remediation method for all COC Groups (see Sections 7.2.15.1.1 through 7.2.15.1.3).

7.2.15.1.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 1	COC Group 2	COC Group 3
Reliably meet goal?	Likely reliable to reduce concentrations in a barrier application.	Likely reliable for chromium. Tc-99 and uranium likely reduced to meet goal, but can re-oxidize over time.	Likely reliable for nitrate.
Produce hazardous products?	Reductive dechlorination of carbon tetrachloride and trichlorethene may lead to hazardous byproducts.	No hazardous byproducts.	No hazardous byproducts.
Negatively impact to other COC?	No negative impacts expected.	No negative impacts expected.	No negative impacts expected.
Treat target volume?	A PRB could be emplaced at the downgradient edge of a selected treatment volume.	A PRB could be emplaced at the downgradient edge of a selected treatment volume.	A PRB could be emplaced at the downgradient edge of a selected treatment volume.
Cause risk during construction or operation?	Primary risk would be from significant amount of necessary drilling.	Primary risk would be from significant amount of necessary drilling.	Primary risk would be from significant amount of necessary drilling.

7.2.15.1.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 1	COC Group 2	COC Group 3
Reliably constructed and operated?	Uniform distribution of iron with a long well screen may be problematic. Very large number of wells necessary.	Uniform distribution of iron with a long well screen may be problematic. Very large number of wells necessary.	Uniform distribution of iron with a long well screen may be problematic. Very large number of wells necessary.
Reasonable consumable usage?	Very large amounts of iron necessary for even moderate barrier lengths.	Very large amounts of iron necessary for even moderate barrier lengths.	Very large amounts of iron necessary for even moderate barrier lengths.

7.2.15.1.3 Relative Cost

Cost factors for zero-valent iron are associated with the relatively high reagent usage and large number of wells needed due to the limited radius of injection. Nano-zero-valent iron in powder form costs over $16 per pound, and emulsified zero-valent iron costs more than $20 per gallon for a 10% iron solution.[1] The cost of the emulsified zero-valent iron for a PRB of 300 m over a depth interval of 20 m, assuming a radial influence of 7 m per well and only one line of injection wells (total of about 22 wells), would be on the order of $15M.

7.2.15.2 In Situ Redox Manipulation PRB

In Situ Redox Manipulation (ISRM) involves the injection of a reducing solution (e.g., sodium dithionite) and the creation of a zone of ferrous iron that can facilitate the chemical reduction of the contaminants. After the reducing solution has been injected and allowed to react with the aquifer sediments, the solution is extracted from the aquifer to remove unreacted reagent, sulfate, etc. The ferrous iron created by reaction with the reagent remains in place and reacts to reduce contaminants and oxygen or oxidized solutes carried into the barrier. In addition to the general PRB design issues of groundwater flow path and barrier thickness, key properties that determine the effectiveness/ implementability of ISRM are the hydraulic conductivity of the aquifer and the natural iron content of the aquifer sediments. The hydraulic conductivity of the aquifer affects the ability and rate of distribution of the reagent. The amount of natural iron in the aquifer sediments affects the distribution of the reagent and the resulting reactivity of the barrier. Too little iron will result in an ineffective reducing barrier, and too much iron will result in fast consumption of the reagent and a correspondingly small radius of influence. A proof-of-principle test at the Hanford Site had an apparent radius of influence of about 8 m (DOE 2000). An ISRM PRB in the subsurface provides an electron source for dechlorination of carbon tetrachloride and trichlorethene (COC Group 1) and reduction of chromium, technetium-99, uranium, and nitrate (COC Groups 2 and 3, except for iodine-129).

Based on the evaluation of effectiveness, implementability, and relative cost presented below, ISRM as a PRB is retained as a potential remediation method for COC groups 1, 2, and 3 (except for iodine-129) (see Sections 7.2.15.2.1 through 7.2.15.2.3).

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[1] Personal communication to the authors from J. Greg Booth, Applied Science & Advanced Technologies, Inc., Baton Rouge, Louisiana, July 25, 2005.

7.2.15.2.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 1	COC Group 2	COC Group 3
Reliably meet goal?	Likely reliable to reduce concentrations in a barrier application.	Likely reliable for chromium. Tc-99 and uranium likely reduced to meet goal, but can re-oxidize over time.	Likely reliable for nitrate.
Produce hazardous products?	Reductive dechlorination of carbon tetrachloride and trichlorethene may lead to hazardous byproducts.	No hazardous byproducts.	No hazardous byproducts.
Negatively impact to other COC?	No negative impacts expected.	No negative impacts expected.	No negative impacts expected.
Treat target volume?	A PRB could be emplaced at the downgradient edge of a selected treatment volume.	A PRB could be emplaced at the downgradient edge of a selected treatment volume.	A PRB could be emplaced at the downgradient edge of a selected treatment volume.
Cause risk during construction or operation?	Primary risk would be from significant amount of necessary drilling.	Primary risk would be from significant amount of necessary drilling.	Primary risk would be from significant amount of necessary drilling.

7.2.15.2.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 1	COC Group 2	COC Group 3
Reliably constructed and operated?	Uniform distribution of reagent (e.g., dithionite) with a long well screen may be problematic. Very large number of wells necessary.	Uniform distribution of reagent (e.g., dithionite) with a long well screen may be problematic. Very large number of wells necessary.	Uniform distribution of reagent (e.g., dithionite) with a long well screen may be problematic. Very large number of wells necessary.
Reasonable consumable usage?	Very large amounts of reagent (e.g., dithionite) necessary for even moderate barrier lengths.	Very large amounts of reagent (e.g., dithionite) necessary for even moderate barrier lengths.	Very large amounts of reagent (e.g., dithionite) necessary for even moderate barrier lengths.

7.2.15.2.3 Relative Cost

The cost factors for ISRM are the drilling costs, reagent costs, and the frequency of re-injection. Using a presumed radius of influence of 8 m per well, the total reducing solution volume as a function of depth is shown in Table 7.8. At a cost of $0.625/gal for this solution (Envirochem Technology Services), the cost of the dithionite for a PRB of 300 m over a depth interval of 20 m, assuming a radial influence of 8 m per well and two lines of injection wells (total of about 36 wells), would be on the order of $3.2M.

Table 7.8. Volume of Dithionite Solution as a Function of Treatment Depth

Treatment Depth	Volume of Aquifer[(a)] (m^3)	Volume of Dithionite[(b)] (gal)
15 m	3,016	239,000
20 m	4,021	319,000
30 m	6,032	478,000

(a) Calculated with an 8-m radius of influence.

(b) Calculated using a porosity of 0.3 and for dithionite filling 100% of the pore space.

7.2.15.3 In Situ Anaerobic Bioremediation PRB

Carbon tetrachloride can be dechlorinated under anaerobic conditions to either CF or non-hazardous compounds depending on the subsurface conditions (Truex et al. 2001). trichlorethene can be directly reduced to ethene by some bacteria as part of anaerobic reductive dechlorination reactions (e.g., DeBruin et al. 1992; Freedman and Gossett 1989), though reductive dechlorination or trichlorethene may also result in DCE and VC as persistent dechlorination products. The anaerobic dechlorination reactions require that an appropriate substrate is present and that the dechlorinating bacteria can effectively compete for the substrate against other microorganisms that can also use the substrate with other electron acceptors. Nitrate, chromium, technetium-99, and uranium can also be reduced under anaerobic conditions and converted to non-hazardous products (for nitrate) or to insoluble chemical forms (for chromium, technetium-99, and uranium). The biomass that grows during anaerobic bioremediation may also increase the adsorption of other contaminants such as iodine-129, potentially enhanced through reduction of the iodine. Thus, anaerobic bioremediation is potentially applicable to COC Groups 1, 2, and 3.

The success in stimulating dechlorination without producing hazardous byproducts and contaminant reduction versus other types of anaerobic activity is dependent on the microbial ecology and groundwater geochemistry (e.g., presence of other electron acceptors). The ability to stimulate appropriate microbial activity would need to be evaluated to confirm whether remediation goals will likely be met.

An in situ anaerobic bioremediation PRB would be implemented by distributing a long-duration substrate such as vegetable oil into the aquifer. Because the substrate is less accessible to the bacteria, it is not consumed as it is distributed and can provide a long-term food supply once in place. The key property with this technology is the hydraulic conductivity of the aquifer. The radius of the treatment zone depends on how well the substrate can be injected into and distributed through the aquifer formation. A secondary property of interest is the length of time that the substrate lasts, which impacts the frequency of “regenerating” the treatment zone. The radius of influence for long-duration substrate injection used for the screening evaluation is about 7 m for oil distribution, similar to what has been achieved for other applications of this technology.

Based on the evaluation of effectiveness, implementability, and relative cost (presented below), Anaerobic Bioremediation as a PRB is retained as a potential remediation method for COC groups 1, 2, and 3 (see Sections 7.2.15.3.1 through 7.2.15.3.3).

7.2.15.3.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 1	COC Group 2	COC Group 3
Reliably meet goal?	There is moderate uncertainty in meeting the goals because complete dechlorination to non-hazardous compounds may not be obtained.	There is moderate uncertainty in meeting the goals for Tc-99 and uranium because these compounds can reoxidize readily and become mobile again after being microbially reduced and temporarily immobilized. It is likely that goals for chromium could be met because it remains stable and immobile after microbial reduction. Increased adsoption of I-129 and reduction may also occur.	It is likely that goals for nitrate could be met because it will likely be reduced to nitrogen gas.
Produce hazardous products?	Reductive dechlorination of carbon tetrachloride and trichlorethene may lead to hazardous byproducts.	No hazardous byproducts.	Likely no hazardous byproducts.
Negatively impact to other COC?	No negative impacts expected.	No negative impacts expected.	No negative impacts expected.
Treat target volume?	Bioremediation can be applied as a treatment barrier, but will require numerous wells for long barriers due to a limited radius of influence for substrate distribution. The rate of biological reactions would need to be sufficient to treat the contaminants within the residence item of the barrier. Thus the design must consider the necessary barrier thickness.	Bioremediation can be applied as a treatment barrier, but will require numerous wells for long barriers due to a limited radius of influence for substrate distribution. The rate of biological reactions would need to be sufficient to treat the contaminants within the residence item of the barrier. Thus, the design must consider the necessary barrier thickness.	Bioremediation can be applied as a treatment barrier, but will require numerous wells for long barriers due to a limited radius of influence for substrate distribution. The rate of biological reactions would need to be sufficient to treat the contaminants within the residence item of the barrier. Thus, the design must consider the necessary barrier thickness.
Cause risk during construction or operation?	Primary risk would be from significant amount of necessary drilling.	Primary risk would be from significant amount of necessary drilling.	Primary risk would be from significant amount of necessary drilling.

7.2.15.3.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 1	COC Group 2	COC Group 3
Reliably constructed and operated?	Uniform distribution of substrate with a long well screen may be problematic. Very large number of wells necessary.	Uniform distribution of substrate with a long well screen may be problematic. Very large number of wells necessary.	Uniform distribution of substrate with a long well screen may be problematic. Very large number of wells necessary.
Reasonable consumable usage?	Very large amounts of substrate necessary for long barriers.	Very large amounts of substrate necessary for long barriers.	Very large amounts of substrate necessary for long barriers.

7.2.15.3.3 Relative Cost

Cost factors for anaerobic bioremediation are a function of well costs, the amount of substrate required to maintain appropriate conditions within the barrier, and the longevity of the substrate. Long-duration substrates can only be distributed a short distance from injection wells. However, substrate volume and costs are likely similar or lower than those for other PRB reagents (e.g., ISRM).

7.2.15.4 Injectable Apatite Barrier

Hydroxyapatite [$Ca_5(PO_4)_3OH$] has been found to be very effective in sequestration of many dissolved metals including strontium and uranium. Such divalent metal oxyanions do react with dissolved phosphate to precipitate and immobilize the heavy metal. Apatite sequestration is expected to be minimally effective with chromium, technetium, and iodine groundwater contamination. Thus, for the screening evaluation, apatite was only considered for applicable to uranium as part of COC Group 2 (Fuller et al. 2002; Flury and Harsh 2000; Bostick et al. 2003). Because of the depth to groundwater, application of solid phase apatite is not feasible and will not be considered as a viable technology for the site. However, apatite minerals can be formed in situ from injection of soluble reagents (Moore et al. 2004). This method relies on injection of calcium citrate and phosphate solutions. The calcium is complexed with citrate during the injection and does not reaction with the phosphate until the citrate is degraded by microorganisms in the subsurface. Thus, the apatite formation can be distributed over a radial distance of meters to ~10 m away from the injection well depending on the subsurface hydrology and the microbial citrate degradation rate. This technique is currently being tested for application to strontium contamination at the Hanford 100-N Area. Injectable apatite would be considered an innovative treatment option.

Based on the evaluation of effectiveness, implementability, and relative cost presented below, injectable apatite is retained as a potential remediation method for uranium (part of COC Group 2) as a barrier (see Sections 7.2.15.4.1 through 7.2.15.4.3). This is an innovative technology that would likely need treatability testing.

7.2.15.4.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 2 (uranium only)
Reliably meet goal?	Likely reliable to reduce concentrations as a barrier. Laboratory-scale studies show promise. Field-scale testing yet to be conducted.
Produce hazardous products?	No hazardous byproducts are produced.
Negatively impact to other COC?	Likely no impact if applied as a barrier for the uranium plume. Residual phosphate could stimulate microbiological growth.
Treat target volume?	Distribution of the reagents meters to ~10 m from the injection point is expected. As such a barrier application similar to an anaerobic biobarrier is likely possible.
Cause risk during construction or operation?	Construction risk would be from drilling necessary.

7.2.15.4.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 2 (uranium only)
Reliably constructed and operated?	Uniform distribution of reagents possible with proper engineering and hydraulic control. Treatability testing is needed.
Reasonable consumable usage?	Treatability testing is needed to assess design of the remediation system.

7.2.15.4.3 Relative Cost

The injectable apatite remediation method is an innovative technology still under development. Cost factors are primarily related to the radius of influence that can be obtained. It is expected that a radius of influence similar to injection of a long-duration substrate for anaerobic bioremediation will be possible. As such, costs for injectable apatite could be comparable to other technologies for a barrier where well costs would be similar to an anaerobic bioremediation biobarrier.

7.2.15.5 Polyphosphate Barrier

Another phosphate-based technology for stabilization of uranium using phosphate is presently in development. This technology uses injection of liquid polyphosphate to stabilize uranium. It is not applicable to the other COC. This technology stabilizes uranium by a different mechanism than apatite stabilization.

The process uses polymers of phosphate to release phosphate at a slow, controlled rate into groundwater downgradient of the application point. The presence of phosphate in groundwater, even in minor concentrations (10^{-8} M), promotes the formation of autunite–group minerals, $X_{3-n}^{(n)*}[(UO_2)(PO_4)]_2 \cdot xH_2O$, thereby limiting the mobility of the uranyl cation (UO_2^{2+}) in the subsurface environment. The use of soluble long-chain polyphosphate reagent delays precipitation of the autunite, thereby mitigating plugging of the formation near the application point. By adjusting the length of the polyphosphate chain, the hydrolysis reaction that releases the phosphate into the water can be engineered and the uranium stabilization rate controlled. Because autunite sequesters uranium in the oxidized form, U^{6+}, rather than forcing reduction to U^{4+}, the possibility of re-oxidation and subsequent re-mobilization is negated. Extensive laboratory testing demonstrates the very low solubility of autunite. In addition to autunite, excess phosphorous may result in apatite mineral formation, providing a secondary, long-term source of treatment capacity.

Deployment polyphosphate may be designed to treat a horizontal extent as well as vertical zone of uranium in the groundwater and at the water-table interface. The liquid form of the reagent facilitates application to and transport within the contaminated groundwater plume. Uranium transport studies in columns packed with contaminated sediment from the Hanford 300 Area indicate that a polyphosphate solution reduces the concentration of uranium in water to near the drinking water standard (30 µg/L) (Wellman et al. 2006). Polyphosphate would be considered an innovative treatment option.

Based on the evaluation of effectiveness, implementability, and relative cost presented below, polyphosphate is retained as a potential remediation method for uranium (part of COC Group 2) as a barrier (see Sections 7.2.15.5.1 through 7.2.15.5.3). This is an innovative technology that would likely need treatability testing.

7.2.15.5.1 Effectiveness

Effectiveness Screening Criteria (see Table 5.1)	COC Group 2 (uranium only)
Reliably meet goal?	Likely reliable to reduce concentrations as a barrier. Laboratory-scale studies show promise. Field-scale testing yet to be conducted.
Produce hazardous products?	No hazardous byproducts are produced.
Negatively impact to other COC?	Likely no impact if applied as a barrier for the uranium plume. Residual phosphate could stimulate microbiological growth.
Treat target volume?	Distribution of the polyphosphate meters to ~10 m from the injection point is expected. As such a barrier application similar to an anaerobic biobarrier is likely possible.
Cause risk during construction or operation?	Construction risk would be from drilling necessary.

7.2.15.5.2 Implementability

Implementability Screening Criteria (see Table 5.1)	COC Group 2 (uranium only)
Reliably constructed and operated?	Uniform distribution of polyphosphate possible with proper engineering and hydraulic control. Treatability testing is needed.
Reasonable consumable usage?	Treatability testing is needed to assess design of the remediation system.

7.2.15.5.3 Relative Cost

The polyphosphate remediation method is an innovative technology still under development. Cost factors are primarily related to the radius of influence that can be obtained. It is expected that a radius of influence similar to injection of a long-duration substrate for anaerobic bioremediation will be possible. As such, costs for polyphosphate could be comparable to other technologies as a barrier where well costs would be similar to an anaerobic bioremediation biobarrier.

8.0 Results of Screening Evaluation

Based on the screening evaluation criteria, potential remediation methods were comparatively evaluated to identify those most promising for continued evaluation as part of the feasibility study. Only a few methods are applicable to all COC. Thus, identification of the most promising potential remediation methods is categorized by COC group. Multiple scales of application may be useful for the overall remediation efforts in the 200-ZP-1 Operable Unit. For this reason, identification of the most promising potential remediation methods is also categorized by the scales of application identified in the effectiveness evaluation criteria (Table 5.1). Using this matrix of most promising potential remediation methods provides information to support either use of a single remedy or a “treatment train” approach as part of the feasibility study. Table 8.1 lists the potential remediation methods recommended for further assessment in the subsequent feasibility study as a function of both COC group and scale of application.

Table 8.1. Summary of Potential Remediation Methods Recommended for Further Assessment for Each COC Grouping Based on the Results of the Screening Evaluation

Target	COC Group 1	COC Group 2	COC Group 3	COC Group 4
Continuing Source (<1 acre) (areal extent over thickness of plume defined in Section 2)	• Pump-and-Treat • MNA • Chemical Oxidation (carbon tetrachloride) • Surfactant Flushing (carbon tetrachloride) • Anaerobic Bioremediation • Anaerobic Bioremediation as a PRB • Aerobic Bioremediation (trichlorethene) • Thermal Treatment (carbon tetrachloride) • In-Well Air Stripping • ISRM as a PRB • Air Sparging	• Pump-and-Treat • MNA • Anaerobic Bioremediation • Anaerobic Bioremediation as a PRB • ISRM as a PRB (except I-129) • Injectable Apatite (U) • Polyphosphate (U) • Injectable Apatite Barrier (U) • Polyphosphate Barrier (U)	• Pump-and-Treat • MNA • Anaerobic Bioremediation • Anaerobic Bioremediation as a PRB • ISRM as a PRB	• P&T • MNA
High Concentrations (<5 acres) (areal extent over thickness of plume defined in Section 2)	• Pump-and-Treat • MNA • Anaerobic Bioremediation • Anaerobic Bioremediation as a PRB • Aerobic Bioremediation (trichlorethene) • In-Well Air Stripping • ISRM as a PRB • Air Sparging	• Pump-and-Treat • MNA • Anaerobic Bioremediation • Anaerobic Bioremediation as a PRB • ISRM as a PRB (except I-129) • Injectable Apatite (U) • Polyphosphate (U) • Injectable Apatite Barrier (U) • Polyphosphate Barrier (uranium)	• Pump-and-Treat • MNA • Anaerobic Bioremediation • Anaerobic Bioremediation as a PRB • ISRM as a PRB	• P&T • MNA
Low or High Concentrations (25 acres) (areal extent over thickness of plume defined in Section 2)	• Pump-and-Treat • MNA • Anaerobic Bioremediation • Anaerobic Bioremediation as a PRB • Aerobic Bioremediation (trichlorethene) • In-Well Air Stripping • ISRM as a PRB	• Pump-and-Treat • MNA • Anaerobic Bioremediation • Anaerobic Bioremediation as a PRB • ISRM as a PRB (except I-129)	• Pump-and-Treat • MNA • Anaerobic Bioremediation as a PRB • ISRM as a PRB	• P&T • MNA
Low Concentrations (250 acres or greater) (areal extent over thickness of plume defined in Section 2)	• Pump-and-Treat • MNA • Anaerobic Bioremediation as a PRB • ISRM as a PRB	• Pump-and-Treat • MNA • Anaerobic Bioremediation as a PRB • ISRM as a PRB (except I-129)	• Pump-and-Treat • MNA • Anaerobic Bioremediation as a PRB • ISRM as a PRB	• P&T • MNA

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