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September 22, 2009

Mr. Kenneth S. Bardo
U.S. Environmental Protection Agency Region V
77 West Jackson Boulevard (LU-9J)
Chicago, IL 60604-3507

RE: Occidental Chemical Corporation, Montague, Michigan - MID 006 014 906
Revised Technical Impracticability Evaluation

Dear Mr. Bardo:

Please find enclosed three copies of revision 01 of the report titled "Post-Implementation Technical Impracticability Evaluation for Groundwater Restoration at the Occidental Chemical Corporation Site in Montague, Michigan" dated September 22, 2009. The first version of this report was submitted to the U.S. EPA on May 6, 2009, and the U.S. EPA provided comments, requested changes, and denied the original request in a letter dated July 2, 2009. In addition to the copies of the revised report, also please find enclosed three copies of a response to each comment provided by the U.S. EPA – the response to comments show each U.S. EPA comment and then provide a response from Glenn Springs Holdings, Inc.

If you have any questions concerning this submittal, please contact me at (972) 687-7506.

Sincerely,
Glenn Springs Holdings, Inc.

Clint Babcock
Project Manager

Enclosures
cc: Dan Dailey, MDEQ (P.O. Box 30241, Lansing, MI 48909) (w. 2 copies)
Joseph Branch, GSHI @ Montague Site
James Tolbert, AECOM

Post-Implementation Technical Impracticability Evaluation for Groundwater Restoration at the Occidental Chemical Corporation Site in Montague, Michigan

Revision 01
September 2009

U.S. EPA I.D. No. MID 006 014 906

CERTIFICATION STATEMENT

I certify that the information contained in or accompanying this document is true, accurate, and complete. As to those identified portions of this document for which I cannot personally verify their truth and accuracy, I certify as the company official having supervisory responsibility for the persons who, acting under my direct instructions, made the verification, that this information is true, accurate, and complete.

Clinton J Babcock — 09/21/09

Clint Babcock
Project Manager
Glenn Springs Holdings, Inc.

Date

General Comments, TI Evaluation

1) The TI Evaluation approaches DNAPL and dissolved phase contamination as inseparable issues for groundwater remediation. Section 4 proposes that the TI zone include the four DNAPL source areas, as well as the entire area of contaminated groundwater exceeding cleanup standards. However, there is adequate justification for independent evaluation of the source areas and the dissolved phase contaminant plume.

The challenges associated with remediating dissolved phase contamination differ considerably from those associated with treatment of DNAPL sources. As discussed in the TI Evaluation, dissolved phase groundwater contamination is being adequately captured by the purge well system and treated using granular activated carbon. EPA guidance on TI evaluations states that "where it is technically practicable to contain the long-term sources of contamination, such as the DNAPL zone, EPA expects to restore the aqueous contaminant plume outside the DNAPL zone to required cleanup levels. Effective containment of the DNAPL zone generally will be required to achieve this long-term objective..." Expand the TI Evaluation to consider the isolation and containment of DNAPL source areas, limiting the TI zone to the source areas, and addressing the aqueous contaminant plume. Models should be used to estimate the rate of dissolved phase contaminant transport and attenuation in the absence of contributing DNAPL sources. This information would be used to determine whether dissolved phase groundwater contamination can be successfully remediated within a reasonable timeframe using the existing purge well system and carbon treatment system, an expanded extraction system, a physical containment system such as a slurry wall, and/or another treatment technology altogether.

Response:

The Revised TI includes the evaluation of additional treatment of the dissolved groundwater plume to expedite groundwater cleanup in Section 8. The slurry wall concept is further discussed in this document as a response to Comment 22. A predictive model estimating rate of dissolved contaminant degradation in the absence of contributing DNAPL sources is presented in Section 8.3, with supporting calculations and documentation in **Appendix C** of the Revised TI Evaluation.

GSH has also expanded discussion on groundwater remedy analysis in Sections 8.5, 8.6 and 10.4 of the Revised TI.

In addition, the revised document has moved the discussion of the TI zone from Section 4 in the previous version to Section 9 of this revised version so that the TI zone can be evaluated with a discussion of the alternate remedial approach dictated by Section 5 of the U.S. EPA 1993 guidance on technical impracticability.

2) During extensive bench-scale and pilot-scale testing of innovative in-situ remedial technologies, a significant source of uncertainty discovered was the lack of knowledge regarding transformational pathways and end fate of degradation products of C-56 and C-58 DNAPL. For example, during the ISCO bench-scale tests, significant decreases in the mass of parent compounds (over 90%) were observed, but perhaps due to limitations in the coverage of current analytical test methods, a reliable mass balance for chlorine could not be calculated. Therefore, one key risk in employing any of these technologies is the possible formation of intermediate products in groundwater where the fate, transport, and risks are unknown or undefineable. Revise the TI Evaluation to include this uncertainty as another factor supporting the request for a TI waiver.

Response:

The conclusions to the discussion on ISCO have been modified. This section is now in Section 5.1 and 5.1.5.

Specific Comments, TI Evaluation

1) Section 1.2, page 3: In the fourth paragraph, a statement is made that "No residential water wells are in use

near the Site." Re-evaluate and modify this statement to address private wells that are present along Old Channel Trail.

Response:

Sections 1.2 and 1.5.3 in the Revised TI have been revised to describe municipal drinking water usage and existence of historical drinking water wells downgradient of the Site. A total of 1 well currently exists within the plume boundary south of Old Channel trail. Based upon survey performed by GSH in September 2009, this well is not being used by residents. The piping and pump has been removed from the well.

LISTED OWNER NAME	LOCATION ADDRESS	WELL DEPTH (FT BGS)
GEORGE CARROLL	7250 BLUEBERRY RIDGE DR	78

2) Section 1.3, page 4: The text identifies one of the residual source areas within the Northern Exposure Area as the Former Primary Disposal Area. In Figure 3, and elsewhere, this area is also called the Former Drum Disposal Area and the Former Primary Disposal Pile (see Figure 6). The Former Primary Ash Disposal Area is also called the Former Fly Ash Area in the report. Ensure that the text, figures, tables, and appendices in the TI Evaluation consistently identify the names of the four residual source areas.

Response:

The text and figures have been revised to consistently label and reference the four residual source areas as follows:

- Former Primary Disposal Area
- Former Primary Ash Disposal Area
- Former Fine Chemical Production Area
- Former Equalization Pond Area

In addition, further clarification text has been added to better describe the historical exposure areas, Former Drum Disposal Area and Chlor-Alkali Production Area. (Note: In Appendix A, showing historical DNAPL distribution in cross-sections, the Former Primary Ash Disposal Area is referred to as the Former Primary “Fly” Ash Disposal Area).

3) Section 1.3, page 5: The dissolved groundwater plume is described as "fully contained by a purge well system installed in the 1980s." Modify this statement to better reflect site conditions. For example, a more accurate description of the dissolved groundwater plume is that OCC's monitoring well system has shown the plume to be stable (i.e., not expanding) and that the purge well system captures and contains the southern edge of the dissolved groundwater plume and prevents its discharge to White Lake.

Response:

EPA comment noted and inserted into referenced section.

4) Section 1.4.2.1, page 5: Groundwater was and may still be used as a source of drinking water in the area. Modify the text to accurately describe the past and current usage of groundwater in the area.

Response:

Text has been modified to accurately describe historical and current use of groundwater as a drinking water resource in the area proximal to the site. In addition, sections of the report (e.g. Section 1.5.3) have been modified to reference the Residential Water Well User Survey (Earth Tech, 1994) and a September 2009 survey performed by GSH.

5) Section 1.5.4, page 8: The text only discusses capping of the seven small areas in the former industrial portion of the Site. In addition to capping, excavation and off-site disposal was performed. Include a discussion of the volume of excavation performed at each of the seven areas, including the acreage or square footage of each area, and the extent of the area requiring capping. Figure 5 depicts the seven small areas and Former Burn Pit. The figure is not clear in differentiating between the localized areas and the prior excavated larger areas. For example, excavated and capped symbols, and localized soil capped areas symbols are used at nine locations. Consider identifying the unit names or dates of remediation for each of the areas in Figure 5.

Response:

Figure 5 has been revised to more clearly illustrate excavation and capping activities performed at the site. In addition, the text in the Revised TI has been modified to better reflect historical removal and capping activities summarized in Section 1.5.4.

6) Section 1.5.5, page 8: Add a figure that delineates the extent of sediment removal in White Lake and its position relative to historical source areas or historical remediation in Figures 3 and 5.

Response:

A new **Figure 6** has been added showing the extent of sediment removal performed off Dowie's Point within White Lake. This figure is now referenced in Section 1.5.5 as well as other related section such as the discussion on White Lake in Section 3.3.

7) Section 1.5.6, page 9: Cite the regulations/criteria that institutional controls are being developed under (e.g., Michigan Part 201), the legal form of the restrictions (e.g., environmental covenant), and where the restrictions would be filed (e.g., County Recorder of Deeds).

Response:

Section 1.5.6 has been modified.

8) Section 2.0, page 10: Include additional cleanup criteria for chloroform, cis-1,2- dichloroethene, trans-1,2-dichloroethene, trichloroethene, and chloride (see 2008 Annual Groundwater Monitoring Report in Appendix A). These COCs are also required to meet groundwater cleanup standards pursuant to the EPA Final Decision. The cleanup criteria for these COCs are based on groundwater standards, with the exception of chloride which is based on surface water discharge criteria. This comment also applies to Section 4.0.

Response:

Chloroform; cis-1,2-DCE; trans-1,2-DCE, TCE and chlorides have been added to the list of chemicals under the Groundwater Cleanup Standards, Section 2.0.

9) Section 3.1, page 11: The Site Conceptual Model (SCM) is graphically presented in Figure 6. A dissolved C-56 plume is shown to be present only beneath the Former Fine Chemical Production Area. Confirm that no dissolved C-56 plume exists at the other historical DNAPL entry locations (e.g., bullet 8 on page 12 states that a C-56 plume is located immediately downgradient from the source areas). The key in Figure 6 includes a yellow symbol for the dissolved VOC plume but this extensive plume is not shown in the SCM. Show the extent of the dissolved VOC plume in the foreground of the sand aquifer, and background of the DNAPL and dissolved C-56 plume. Include a symbol in the key representing the excavations at each of the historical DNAPL entry locations.

In the third paragraph, delete ",several feet bgs." after discussion of DNAPL at the Former Equalization Pond.

Response:

The Site Conceptual Model (SCM) is a generalized strike and cross-sectional view along the long-axis of the site. In the Revised TI Evaluation, the SCM **Figure 7** has been updated to include the Total VOC plume. The figure also provides more detailed visualization of C-56. The figure has been modified to also address EPA Comment 16 (below). Although the SCM serves as a generalized representation of Site conditions, and is based on lithostratigraphic and hydrogeological observations, it does not serve as a precise cross-sectional view of the Site.

Text has also been modified regarding vertical position of DNAPL relative to ground surface near the Former Equalization Pond Area.

10) Section 3.3, page 13: Site elevations in the northern and central portions are stated to vary in elevation between 630 and 640 feet AMSL. Figure 6 shows these portions of the site to vary in elevation between 680 and 690 feet AMSL. Ensure that the site elevations are consistent between the text and the figures.

Response:

Site topography ranges from 582 feet above mean sea level (amsl) at the shoreline of White Lake to 730 feet amsl at the apex of the site vault. The high area on the site not related to the vault is approximately 642 feet amsl north of the Former Equalization Pond. Topography ranges from 640-618 feet amsl at the Northern Exposure Area; 640-618 feet amsl at the Former Fine Chemical Production Area; and 642-634 feet amsl at the Former Equalization Pond Area.

Figure 7 has been adjusted to present current but approximated ground elevations in feet above mean sea level.

11) Section 3.4, page 16: In the text, groundwater is stated to be present at approximately 610 feet AMSL at the northern area. Figure 6 shows the water table in the northern area at 650 feet AMSL. Ensure that the groundwater elevations described in the text and figures are consistent. In Figure 10, show the groundwater contour lines in feet, not meters, for consistency of units throughout the report.

Response:

The text in Section 3.4 has been modified. The SCM has been modified to reflect groundwater elevations. **Figure 11** has been adjusted to present groundwater elevations in feet above mean sea level. Additionally, curvature of the groundwater contours (which resulted in an apparent westerly component of flow) was eliminated based on a verification of well elevations conducted at our request on August 31 2009. The new survey data (for wells "C", RFI MW-05-02A,B,C,D,E, RFI MW-05-04A,B,C,D,E, and MW-97-05) raised the top of casing of Well C by 2 feet relative to surrounding wells and eliminated the local westerly deviation from the southeasterly ground water flow.

12) Section 3.5.1, pages 18 and 19: Describe in this section whether DNAPL at the Former Primary Disposal Area is a source of dissolved CVOCs, C-56, and C-58 to groundwater, and the full extent of its migration. This comment also applies to Sections 3.5.2, 3.5.3, and 3.5.4.

Response:

The Revised TI Evaluation includes additional text describing the lateral and vertical extent of dissolved CSVOCs (i.e. C-Series compounds). The SCM also shows a conceptualized extent of CSVOC distribution. **Figure 13** illustrates the horizontal extent of dissolved CSVOCs at the site.

13) Section 3.6, page 21: In the second paragraph, replace "lessons" with "lessens".

Response:

Comment has been incorporated into Revised TI Evaluation.

14) Section 3.7.2, page 23: The predicted cleanup time is 1,420 years in the text but 1,480 years in Table M5 of Appendix B. Ensure that the cleanup times presented in the text and the appendix are consistent. In the text, present the plume lengths in feet, rather than meters.

Response:

Comment noted and table-to-appendix continuity corrected.

In reviewing chemical input variables used in the REMChlor Model for time-frame analysis, AECOM discovered that incorrect Retardation Factors were used in **Table M3** – Chemical Properties. Previously, chemical-specific Distribution Coefficients (K_d) were entered ($Kd = K_{oc} * f_{oc}$), rather than Retardation Factors, which also considers bulk density and porosity of soil. This error has been corrected for all values in **Appendix B**, **Table M5**. As a comparative example of the changes made, the Retardation Factor of PCE changed from 0.02 to 1.16. This yielded negligible change to projected time-frame analysis for PCE, since most of the time was related to the dissolution of the DNAPL, not the migration of the PCE. For example, at the Former Fine Chemical Production Area, using a default gamma value of 1, projected years to reach groundwater cleanup standard is still 174 years.

Retardation factor for C-56 changed from 1.954 (**Table M-3**) to 16.632 (revised **Table M-3**). This also yielded projected years to reach cleanup standard in 6900 years for the Former Fine Chemical Production Area.

15) Section 3.7.3, page 24: The predicted cleanup time for the plume from the Former Fine Chemical Production Area is 6,700 years in the text and 6,900 years in Table M5 of Appendix B. For C-58, the cleanup time is 1,980 in the text and 2,090 in Table M5. Ensure that the cleanup times presented in the text and the appendix are consistent.

Response:

Comment noted and table-to-appendix continuity corrected.

16) Section 4.0, page 25: The TI zone presented in Figure 12 is similar to the extent of the dissolved volatile organic plume depicted in Figure 10 except that the boundary of the TI zone generally extends slightly beyond the plume boundary on its west, and especially east side. Discuss and justify the enlargement of the TI zone beyond the plume boundary. Alternatively, the TI zone boundary should be identical to the plume boundary. In addition, describe whether the plume boundary in Figure 10 represents detectable quantities of COCs or the boundary where COC cleanup criteria are exceeded. At a maximum, the TI zone should only encompass the area where cleanup criteria are exceeded. Provide a composite figure or multiple figures that depict the horizontal extent of each COC that exceeds its cleanup criteria. Accurately identify the southern extent of C-66, C-56, and C-58 (these three CSVOCs are not detected at the purge well system) from each of the four DNAPL source areas and describe whether the dissolved phase portion of the C-66, C-56, and C-58 plume exceeding cleanup standards is wholly within or extends beyond the extent of DNAPL contamination depicted at each source area in Figure 12.

Response:

The Revised TI Evaluation includes a TI zone that is not larger than the contaminant plume boundary. The TI zone has been revised as **Figure 14**, based on the plume boundary which represents boundary of contaminants exceeding target cleanup values for groundwater. As presented, the TI zone boundary

is identical to the plume boundary. The revised TI represents an area approximately 18% smaller than the originally proposed TI zone. Section 4 has been moved to Section 9 to allow the TI zone to be presented after the evaluation of remedial alternatives. The movement of this section allows for a more complete presentation of the alternate remedial strategy that accompanies the TI waiver request, including the TI zone consistent with Section 5 of the U.S. EPA 1993 guidance on technical impracticability.

In addition, **Figure 13** illustrates the southern extent of C-56, C-58 and C-66 relative to the four source areas and residual DNAPL areas. Additional text has been added in Section 3 discussing the CSVOC aquifer distribution. **Appendix A** in the Revised TI presents multiple cross-sections showing vertical distribution of DNAPL at the Site. These cross-sections were previously presented in "Phase II of the DNAPL Investigation at the Occidental Chemical Site in Montague, Michigan" (Earth Tech, 2003).

17) Section 4.0, page 26: In the second paragraph, replace "western" in the last two sentences with "eastern". Delete the third paragraph.

Response:

Comment noted and error corrected. The third paragraph under Section 4.0 was deleted.

18) Section 5.1, page 27: Figure 4 is described as identifying the vertical and lateral extent of the four residual DNAPL source areas. Figure 4 only presents the lateral extent. Consider adding a cross-section figure depicting the vertical extent of DNAPL as described and discussed in detail in Section 3.5 of the report. Modify the text to state that Figure 4 only presents the lateral extent of DNAPL.

Response:

Cross-Sections showing DNAPL distribution has been added to the Revised TI Evaluation and are included in **Appendix A**. These cross-sections were previously presented in "Phase II of the DNAPL Investigation at the Occidental Chemical Site in Montague, Michigan" (Earth Tech, 2003).

19) Section 5.3.1, page 28: For hexachloroethane (C-26) under existing conditions, the correct timeframe is 325 years (see Table M5 in Appendix B). Modify the table in Section 5.3.1.

Response:

As noted in Response #14, **Table 5** was revised using corrected Retardation Factors. The Table, now in Section 4.3.1 (Former Primary Disposal Area, specifically existing conditions timeframe for C-26), is 355 years.

20) Section 5.3.5, page 30: Based on Table M5 in Appendix B, it appears that under the best scenario from the two modeled remedial approaches, cleanup times would be reduced to 4,900, not 1,980 years. Verify the statement made in this section and correct it if necessary.

Response:

Comment noted and text modified to reflect more liberal cleanup timeframe. Please note that this section number has been changed to Section 4.3.5 in the revised document.

21) Section 6.1, pages 32 to 34: The TI Outline provided on January 16, 2009, and approved by EPA on February 5, 2009, included a discussion of the use of permanganate as an ISCO technology. Include a discussion of permanganate in the TI Evaluation or provide justification for excluding this potential oxidizing agent.

Response:

A discussion of permanganate oxidation is included as Section 5.1.3 of the Revised TI Evaluation.

22) Section 6.5.1, page 37: In the overview of physical containments, only a jet-grout containment wall is briefly discussed. Evaluate the effectiveness of a slurry wall for containing the migration of contaminants from the source areas. At a major industrial facility in Illinois, a 3,300-foot long, minimum 3-foot wide, U-shaped slurry barrier wall (initial estimated capital cost of $7 million) was constructed to a depth of 132 to 143 feet through alluvial sand and gravel, and keyed into limestone bedrock. The slurry trench was a continuous vertical excavation using a backhoe, excavator, and/or cable-operated clamshell bucket through soil supported by the properties of a soil-bentonite slurry. The slurry wall was designed to achieve a permeability criteria of 1 x 10 cm/sec and in combination with three extraction wells screened at a depth from 40 to 105 feet deep, effectively cut-off the migration of CVOCs and CSVOCs as dissolved-phase and NAPL from a landfill to the Mississippi River.

At the OCC site, the depth to the clay layer which the slurry wall would be keyed into is shallower, ranging from 100 to 130 feet, and the permeable sand deposits encountered at depth are similar in nature. The width of the plume boundary is 2,100 feet just south of the Former Fine Chemical Production Area, which would require a slurry wall less than 3,300 feet long. A slurry wall containment barrier located just south of the Former Fine Chemical Production Area could contain 99.6% of the DNAPL mass estimated to be present at the three upgradient source areas and the resulting dissolved phase plume within the industrial portion of the property. The TI zone area could be reduced by half and be wholly within OCC property. The southern-half of the OCC groundwater contaminant plume containing CVOCs might be able to be restored within a reasonable timeframe using the existing purge well system and therefore meet the goal to expedite groundwater cleanup at a portion of the site.

Revise the TI Evaluation to include an in-depth analysis of installing a slurry wall immediately downgradient of the Former Fine Chemical Production Area. The analysis should focus on the technical feasibility of a slurry wall to expedite groundwater cleanup downgradient. The slurry wall would likely be located just downgradient of the furthest extent of DNAPL from the Former Fine Chemical Production Area to ensure that the estimated 1,134,246 pounds of DNAPL mass present upgradient at three source areas (see table MD is fully contained. The southernmost extent of DNAPL consisting of tetrachloroethene, hexachlorocyclopentadiene, octachlorocyclopentene, and hexachloroethane from the Former Fine Chemical Production Area source area would need to be confirmed (in Figure 6 it is shown to extend approximately 900 feet). This data is likely available from previous DNAPL investigations. The presence of an estimated mass of 4,592 pounds of DNAPL at the Former Equalization Pond consisting mostly of hexachlorocyclopentadiene, and some octachlorocyclopentene, and tetrachloroethene (see Table M1) would need to be better understood to determine if it significantly contributes to the dissolved phase contaminant plume and would impact the ability of the current purge well system to achieve groundwater cleanup within a reasonable timeframe. If the slurry wall can effectively cut off the source areas, and contaminants present at the Former Equalization Pond do not act as a contributing and ongoing source to the dissolved phase contaminant plume present at the purge well system or can be removed, the timeframe for achieving groundwater cleanup standards in the southern-half of the contaminant plume may not be that long as groundwater flow toward the White Lake is estimated to be 1.8 feet/day or 657 feet/year. Calculate the time to clean groundwater and meet cleanup standards at the purge well system located at White Lake to determine if the time to clean is reasonable.

Response:

Section 8.0 has been added to the Revised TI Evaluation to evaluate the capture and treatment of the dissolved phase plume as an option to expedite groundwater cleanup. This option focuses on the use of purge wells to capture the impacted groundwater followed by treatment of the water. The slurry wall is not necessary for this option to be successful, and is not included in the text of the document. A slurry wall is effective in reducing pumping if the site is adjacent to a surface water body, or if a slurry wall can be placed up gradient to cut off base flow into a prospective area. In this application, the slurry wall would have been placed down gradient of the pumping wells. The pumping wells would have had to capture all of the base flow into the area even with the slurry wall. The new

Section 8.0 has been added to address the intent of this comment and also to address Comment 23, Comment 24 and General Comment 1.

This response comment uses the estimates of DNAPL mass at each DNAPL source area that were provided in the revised Phase II DNAPL Investigation Report (Earth Tech, 2003) to estimate what percent of the DNAPL is located in the northern three DNAPL source areas in contrast to the Former Equalization Pond Area. The mass estimates in the Phase II DNAPL report that have significant potential error both up and down based upon the control on the delineation of the DNAPL area and the averaging of sample results to represent each DNAPL area. The controls on the delineation of the DNAPL areas were presented in the Phase II DNAPL report. Each DNAPL area was delineated with borings that do not contain DNAPL, however, the potential variability on these mass estimates is rather large and the estimates were provided in response to a US EPA comment that required the mass estimate be included in the report. The statement that 99.6% of the DNAPL would be isolated by placing the capture zone at the Former Fine Chemical Production Area oversimplifies the information available on the actual DNAPL distribution and the potential variation in the mass estimates.

23) Section 6.5.2, pages 37 and 38: This section discusses that a physical barrier (such as a slurry wall) would not treat or remove DNAPL or dissolved constituents and that one continuous containment barrier around all four DNAPL source areas would be needed. As discussed above (Section 6.5.1), a single slurry wall combined with extraction wells, located immediately downgradient of the Former Fine Chemical Production Area is a feasible alternative to contain, collect, and treat DNAPL and dissolved constituents, provided that it results in the expedited cleanup of groundwater of the dissolved phase portion of the plume to the south extending to White Lake. Modify this section to incorporate the results of the analysis of installing a slurry wall.

Response:

This comment is addressed under Comment 22 above.

24) Section 6.5.3, pages 38 and 39: The section discusses the risk of DNAPL displacement associated with driving sheet pile. For construction of a deep slurry wall using excavation equipment and the bentonite slurry method, sheet pile would likely be unnecessary (it was not used at the Illinois site) and there would be no potential for displacing or enhancing the mobility of DNAPL. The discussion of the risk of DNAPL mobilization is limited to the driving of sheet pile and should not be a consideration in the construction of a slurry wall using the bentonite slurry method.

Response:

If the subsurface work is being performed in the DNAPL zones to solidify the DNAPL, then the existing sections still are valid. Methods to treat the dissolved phase plume are addressed under Comment 22 above.

25) Section 7.2.2, page 42: According to the discussion in Section 7.1 and the process flow diagram provided in Figure 13, the excavation option would be conducted in phases using cells of 100 by 100 feet. According to the flow diagram, excavated soil would be disposed offsite, each cell would be backfilled with clean overburden material, and attendant risks would be fully mitigated for that cell before the temporary sprung structure and excavation operations were moved to the next cell. This proposed operating procedure appears to contradict the statement in the third full paragraph that "each excavation mobilization will result in additive exposures, such that the risk to receptors of concern will tend to increase as the overall size of the excavation area increases." Because risks associated with the first cell have been mitigated prior to beginning the next phase of excavation in an adjacent cell, risk should not be considered additive. Revise this section to clarify risk associated with excavation.

Response:

The text, now in Section 6.2.2, was modified for clarification. The excavation area will not

"increase", as each individual excavation area will be backfilled prior to the relocation of the sprung structure. However, the risks are additive with each separate 10,000 square foot excavation area.

26) Section 8.3, page 49: The second paragraph in this section states that in situ solidification "would significantly, though not completely, reduce the rate at which DNAPL compounds leach from the treated area." The text goes on to state that "even with this reduced leaching rate, it is anticipated that the compounds would leach from the solidified source areas at concentrations exceeding the groundwater cleanup criteria." Provide additional justification explaining how this determination was made, including any site-specific data or treatability study results that were used to estimate leachable contaminant concentrations.

Response:

The statement regarding leaching of compounds from "solidified DNAPL" was primarily based on published case studies (Day, 1993; Bone, et al., 2004) and modeled sensitivity analysis results using RemCHLOR suggesting that higher gamma values (finer soils) generally took longer cleanup periods.

27) Section 9.3, page 53: The annual cost to operate and maintain the current purge well system is $1,200,000. The cumulative cost of operating the purge well system for hundreds, if not thousands of years, needs to be considered and compared to the costs associated with a potential containment remedy using a slurry wall combined with a new extraction system and the current carbon treatment system. The purge well system would still operate for a short period of time to attain groundwater cleanup standards in the southern-half of the site along with constant operation of a new extraction system upgradient of the slurry wall.

Response:

The alternate purge well system now presented in the new Section 8.0 would need to run concurrently with the existing pump and treatment system for a period of years, estimated at approximately 18 years. During this time, the costs for both systems would be incurred.

The current system has a documented compliance record. The new system may be able to pump less ground water, though to document hydraulic control, the reduction in pumping may not be that significant. In addition, no mass loading reduction would be anticipated. The base flow of groundwater will carry the same mass of chlorinated organic compounds into either system, so there will be no reduction in the mass of chlorinated VOCs loading the granular activated carbon, and, therefore, no reduction in the amount of carbon usage.

28) Section 9.4, pages 53 and 54: Add bullets to include the unsuccessful results for bench studies of reductive and oxidative technologies, ISCO technology pilot studies, and ERD pilot study to effectively treat residual DNAPL to expedite groundwater cleanup.

Response:

This change has been made to what is now Sections 5.1.3, 5.1.5, and 5.2 in the Revised TI Evaluation.

29) Appendix B, Table M5: This table illustrates, among other items, the relationship between the variable gamma (Γ) and the years required to attain the facility-specific groundwater standards for the contaminants of concern in source area DNAPLs. Γ is a power function exponent in an equation that, for a particular contaminant, relates the quantity of DNAPL mass removed to the expected concentration decline in the dissolved phase.[2] Γ is loosely related to the permeability of the geologic formation, which implies that in more permeable soils, a greater amount of the source must be removed in order to observe an equivalent decline in groundwater concentrations (the converse holds for less permeable soils)

For most source areas and contaminants (including all CVOCs), this behavior was confirmed. However, for the following combinations of source areas and contaminants, the opposite behavior was observed:

Former Fly Ash Pile:	C-56 and C-58
Former Primary Disposal Pile:	C-56 and C-58
Former Fine Chemical Production Area:	C-58

Note that although carbon tetrachloride and tetrachloroethene DNAPLs always followed the anticipated direct relationship between Γ and cleanup times, C-series compounds sometimes did and sometimes did not. For example, cleanup timeframes for C-56 increased with increasing F at the Former Fine Chemical Production Area and Former Equalization Pond.

It is recognized that many complex variables, including differences in conditions at each on- site source area, may be involved in determining the relationship between DNAPL masses and groundwater concentrations. However, given the importance of the association between Γ values and cleanup timeframes, the TI Evaluation should explain these variations for C- series compounds. Add a discussion of this issue to Appendix B.

Response:

There are many complex variables affecting the relationship between DNAPL mass and groundwater concentration. The common factors that appear to be present where the inverse gamma/time to reach cleanup criteria correlation occurs for the C-series compounds are a relatively low mass-to-area ratio and a rapid decay rate. These factors affect the rate of dissolution and the time that the model calculates to achieve cleanup criteria.

POST-IMPLEMENTATION TECHNICAL IMPRACTICABILITY EVALUATION FOR GROUNDWATER RESTORATION AT THE OCCIDENTAL CHEMICAL CORPORATION SITE IN MONTAGUE, MICHIGAN

U.S. EPA I.D. No. MID 006 014 906

Prepared for:

Glenn Springs Holdings, Inc.
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Prepared by:

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LIST OF ACRONYMNS

Acronym	Description
AOC	Area of Concern
amsl	above mean sea level
bgs	below ground surface
^{O}C	degrees Celsius
cm	centimeter
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CSVOC	Chlorinated semi-volatile organic compounds
CVOC	chlorinated volatile organic compound
COC	contaminant of concern
C-26	hexachloroethane
C-46	hexachlorobutadiene
C-56	hexachlorocyclopentadiene
C-58	octachlorocyclopentene
CT	carbon tetrachloride
DNAPL	dense non-aqueous phase liquid
ERD	enhanced reductive dechlorination
EZVI	emulsified zero valent iron
FRTR	Federal Remediation Technologies Roundtable
GSH	Glenn Springs Holdings, Inc.
HCl	hydrochloric acid
ISCO	in situ chemical oxidation
ISTD	in situ thermal desorption
ISS	in situ solidification
ITSL	initial threshold screening level
kg	kilogram
L	liter
MDEQ	Michigan Department of Environmental Quality
MICJ	Michigan Consent Judgment issued in 1979
mg	milligrams
mgd	million gallons per day
NAVFAC	Navel Facilities Engineering Command
NPDES	National Pollutant Discharge Elimination System
OCC	Occidental Chemical Corporation
PCE	tetrachloroethene
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
sec	second
SVE	soil vapor extraction
SVOC	semi-volatile organic compound
SWMU	Solid Waste Management Unit
TI	Technical Impracticability
VOC	volatile organic compound
UAO	Unilateral Administrative Order issued in 1993
U.S. DOE	United States Department of Energy
U.S. EPA	United States Environmental Protection Agency
ZVI	zero valent iron

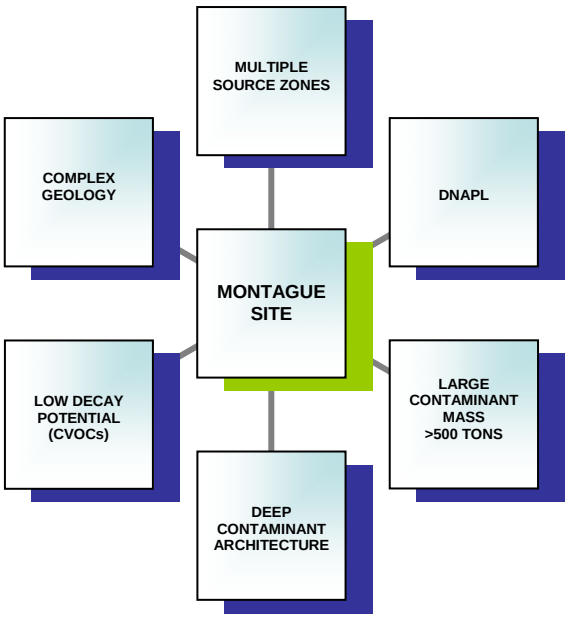
1.0 INTRODUCTION

Occidental Chemical Corporation (OCC) operated a chemical plant on Old Channel Trail in Montague Township, Michigan (the Site). At this Site, OCC produced several products such as chlorine gas from 1954 through 1982 and produced hexachlorocyclopentadiene (C-56) from 1954 through 1977. Significant remedial activities were performed from 1979 through 1982 under a consent judgment with the State of Michigan when all of the manufacturing operations for C-56 were removed from the site or placed in an on-site secure landfill and waste materials and impacted soils were excavated and placed in the on-site secure landfill. Currently, Glenn Springs Holdings, Inc. (GSH) is operating the ongoing groundwater collection and treatment system, providing post-closure care for the landfill, and maintaining the Site. GSH is also complying with the requirements of the Resource Conservation and Recovery Act (RCRA) Corrective Action under an administrative order with the United State Environmental Protection Agency (U.S. EPA). GSH and OCC are both wholly owned subsidiaries of Occidental Petroleum Corporation.

In 1993, the U.S. EPA Region 5 issued a Unilateral Administrative Order (UAO) to address RCRA Corrective Action requirements at the Site (U.S. EPA, 1993a). Under the UAO, GSH investigated the nature and extent of the remaining impacts at the site; evaluated the risks form the remaining impacted soil, groundwater, and lake sediment; and presented a Corrective Measures Study that described methods to address the remaining impacted soil, groundwater, and lake sediment.

Following their review of the investigations and corrective measures studies, the U.S. EPA issued a Statement of Basis in February of 2001 (U.S. EPA, 2001a) and held a public meeting to gather public input on their recommendations. Following the public comment period, the U.S. EPA issued the Final Decision for the Site in July of 2001 (U.S. EPA, 2001b). Most of the requirements of the Final Decision have been implemented, such as dredging sediment in White Lake and excavation and cover of specific on-site soils. Other requirements are long-term obligations that GSH continues to comply with, such as collection and treatment of groundwater by the purge well system. This evaluation focuses on one of requirement in the Final Decision: "Evaluation and implementation of feasible on-site collection/treatment options for contaminated groundwater and residual waste to expedite groundwater cleanup." (U.S. EPA, 2001b).

Complex Remedial Challenges



Residual contamination in the form of dense non-aqueous phase liquid (DNAPL) is present at the site. The DNAPL is primarily composed of both C-56 and octachlorocyclopentene (C-58), though the composition of the DNAPL varies, and locally also includes the chlorinated volatile organic compounds (CVOCs) carbon tetrachloride (CT), tetrachloroethene (PCE), and hexachloroethane (C-26). GSH has delineated the extent of the DNAPL and has implemented numerous treatability bench-scale and pilot scale studies to evaluate feasible options for treatment or removal of DNAPL with the intent of expediting groundwater cleanup. At this time, a Technical Impracticability (TI) Waiver is being requested because potential remedies have been demonstrated to be impractical. Remediation to successfully expedite achieving the groundwater cleanup criteria defined for the Site is compounded by several challenging factors, including:

- Multiple residual DNAPL source areas at the site.
- Presence of physically varying and co-mingled fully chlorinated organic constituents, including CVOCs and chlorinated semi-volatile organic compounds (CSVOCs) C-56 and C-58.

- Presence of DNAPL entrained within stratified glacial sands that compose the aquifer.
- Presence of thin and discontinuous stratified silt and clay beds found throughout the aquifer that retain DNAPL.
- A DNAPL architecture ranging in depth from 25 to 70 feet below ground surface (bgs).
- Estimated total DNAPL mass of 568 tons and estimated DNAPL volume of 82,500 gallons.
- Risk uncertainties associated with C-56 and C-58 volatilization to ambient air during remediation activities.
- Potential for remedies to mobilize DNAPL into lower horizons of the sand aquifer, exacerbating and expanding the current dissolved plume.

This document presents an evaluation of the identified remedial approaches for addressing residual waste to expedite groundwater cleanup at the Site. GSH is submitting this Post-Implementation TI Evaluation as recommended by Region V, U.S. EPA, in a letter dated from December 4, 2008 "Approval with Modifications of the ERD Pilot Test Report, DNAPL Treatment Evaluation Report, and ISTD (in situ thermal desorption) Treatment Evaluation Report." This TI evaluation was based on a TI Outline presented to U.S. EPA and approved on February 5, 2009. This TI Evaluation is presented as a "post-implementation" evaluation as soil removal, exposure control, and groundwater control remedies have already been implemented at the site. Contaminated soils were removed from various locations and contained in an on-site landfill (also referred to as the "vault") as part of a State of Michigan Consent Judgment (MICJ) issued final on October 30, 1979. As part of the response actions to the 1979 Consent Judgment, a series of purge wells were also installed and continue to operate near the shoreline of White Lake, down gradient of residual source areas. The purge wells induce negative flow from White Lake and prevent dissolved contaminants of concern from entering the lake. The operation of these purge wells has been documented to halt the flow of contaminated groundwater to White Lake (U.S. EPA, 2001a; Earth Tech, 2000a, Conestoga-Rovers & Associates, 2009).

This TI Evaluation was developed based on a review of Guidance for Evaluating the Technical Impracticability of Ground-Water Restoration (U.S. EPA, 1993b) and the Handbook of Groundwater Protection and Cleanup Policies for RCRA Corrective Action (U.S. EPA, 2001c). This TI evaluation also incorporates the discussion presented in Technical Impracticability Decisions for Ground Water at Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Response Action and RCRA Corrective Action Sites (United States Department of Energy (U.S. DOE), 1998).

1.1 Report Organization

The report is organized into four basic components: 1) an introduction, where a basic site history is presented in context with the TI process, 2) presentation of the site conceptual model which considers site conditions, and presence of contaminant related to potential receptors, 3) presentation of remedial evaluation, and 4) a conclusions section. Tables, figures and appendices are also included in the TI Evaluation.

The report is organized into ten sections, consisting of:

- Introduction
- Groundwater Cleanup Standards
- Site Conceptual Model
- Groundwater Restoration Potential
- Relevant Technologies
- Excavation & Disposal
- In-Situ Solidification
- Groundwater Extraction and Treatment
- Applicable TI Zone

- Conclusions
- References

Section 3.0 (Site Conceptual Model) constitutes considerable text in discussion of the Site complexities. GSH has presented the Site Conceptual Model first, with a discussion of contaminant chemistry, site conditions, geology and hydrogeology, and fate and transport in following sections.

1.2 Technical Impracticability (TI) Statement

The U.S. EPA has defined a process for determining whether achieving target remediation goals for contaminated aquifers is technically impractical from an engineering perspective. The process is site-specific and evolves as new technologies are developed and demonstrated (U.S. EPA, 1993b; U.S. Army Environmental Center, 2004).

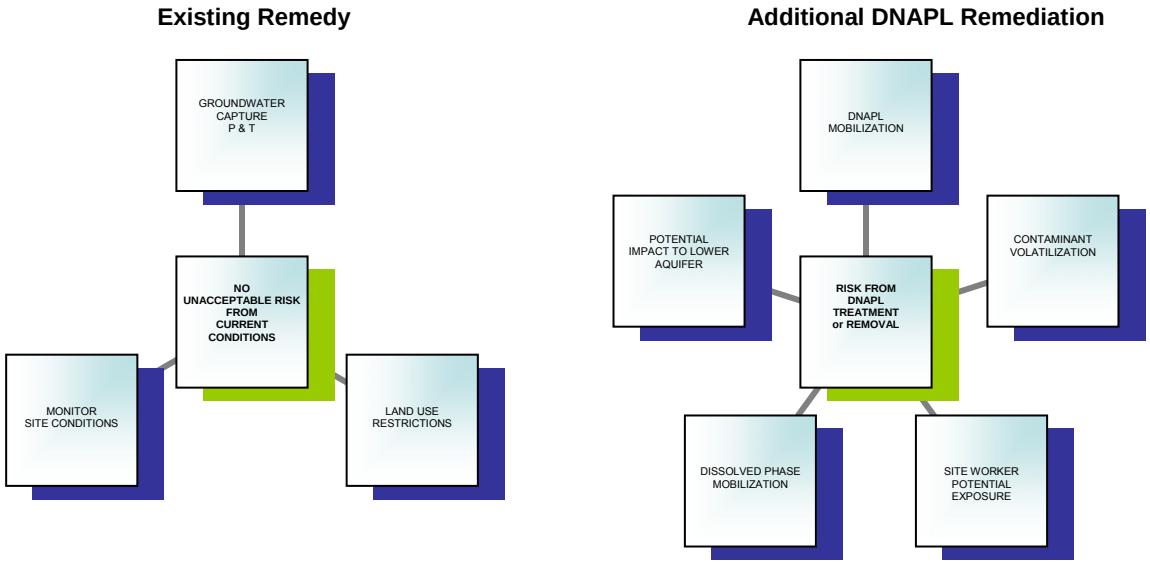
Two criteria need to be met in order to apply for a TI Waiver: (1) engineering infeasibility, and (2) unreliability. A remedial action may be considered technically infeasible from an engineering perspective if current technologies cannot be implemented within a "reasonable timeframe". A remedial action or strategy is considered unreliable if it is shown that proposed remedy alternatives are not likely going to be protective in the future. In some instances, remedial alternatives may be considered unreliable due to the potential for exacerbation of the site conditions, such as risks of contaminant mobilization increased (U.S. EPA, 1993b; U.S. Army Environmental Center, 2004).

This TI evaluation was prepared as a post-implementation TI Evaluation. A remedy is in place that has been demonstrated to be protective of human health and the environment. Furthermore, bench tests and pilot tests have already been implemented to evaluate options to further expedite groundwater cleanup. This evaluation is not a "presumptive remedy approach". Under the MICJ, UAO and Final Decision, numerous remedial actions were performed from 1979 through 2009.

This TI Evaluation is a "post-implementation" evaluation performed after 30 years of active remediation, after investigation, extensive contamination source removals, focused remedial actions, and testing and evaluation of traditional and experimental chemical, biological and physical treatment technologies. Site conditions are well known and understood. DNAPL and dissolved contaminants are defined, and exposures and risks are controlled through engineering and institutional controls. No residential water wells are used down gradient of residual source areas or within the dissolved plume boundary (residential drinking water wells are discussed further in Section 1.5.3). An active groundwater capture system captures and contains the southern edge of the dissolved groundwater plume and prevents discharge to White Lake. Currently no unacceptable risks exist at the Site (Earth Tech, 2000a).

This TI Evaluation centers upon an estimated mass of 568 tons of residual contaminants residing primarily as DNAPL in the upper sand aquifer at the Site. Several remedial options are evaluated in this TI Evaluation. Innovative chemical and biological methods to address DNAPL have been evaluated through bench and pilot studies and shown to be ineffective at treating the DNAPL. Physical methods to address the DNAPL (excavation and solidification) are evaluated further in this evaluation. From a human exposure perspective, residual contaminant removal/isolation or treatment increases risks compared to leaving the residual material in place due to 1) increased exposure scenarios (excavation) and 2) contaminant mobilization (excavation, isolation and solidification).

Comparison of Risk Scenarios:
Current Conditions Compared to DNAPL Solidification or Removal



A well-defined and stable CVOC and CSVOC plume exists at the site that is completely captured by purge wells down-gradient adjacent to White Lake. Since it is technically infeasible to treat the DNAPL at the site, this document also evaluates restoring the down gradient aqueous contaminant plume outside of the DNAPL zone to required cleanup levels. While it is technically feasible to replicate the current pump and treat system at a second location in the aquifer to achieve cleanup criteria in portions of the aquifer, this options is not practical, as the dominant consequence of the additional treatment would be to achieve cleanup criteria under an area of the aquifer where deed restrictions will prohibit the use of the groundwater as a source of drinking water. At best, a limited area would achieve cleanup criteria more rapidly in an area where there is no exposure to the groundwater and where there is an alternate source of drinking water already provided for use – using this method it is still technically infeasible to remediate the DNAPL and achieve cleanup criteria throughout the plume as required by the US EPA.

1.3 Site Background

GSH manages the corrective measures at the Site for OCC. Both GSH and OCC are wholly owned subsidiaries of Occidental Petroleum Corporation. GSH currently retains two full-time on site specialists that manage the Site, maintain the groundwater treatment system, monitor groundwater conditions across the site, monitor site conditions, and manage habitat restoration.

The Site is located on approximately 880 acres at 7601 Old Channel Trail in Muskegon County, Montague Township, Michigan (T12N, R17W, Southeast ¼ of Section 30). The Site is bounded on the south by White Lake and Old Channel Trail, on the east by Whitbeck Road, on the west by Lamos Road, and on the north by Hancock Street. The portion of the site that is currently impacted does not extend all of the way north to Hancock Street nor west to Lamos Road, and maps of the site show the impacted area that includes the former industrialized area just north of Old Channel Trail and west of Whitbeck Road. The lake front area of the Site lies along the northern shoreline of White Lake which flows into Lake Michigan which is located approximately 1.5 miles west of the Site. **Figure 1** is the General Site Location Map. **Figure 2** is the Site Features Map.

The Site was occupied by the former Hooker Chemical and Plastics Company plant from 1952 to 1983. The facility produced chlorine gas, caustic, C-56, muriatic acid, anhydrous hydrochloric acid (HCl), and hydrogen. The chlor-alkali production of chlorine gas involved using passing natural brine recovered from deep underlying bedrock through electrolytic cells. Historical Site features, including Areas of Concern (AOCs) and Solid Waste Management Units (SWMUs) presented in this TI Evaluation are primarily based on the UAO and are shown in **Figure 3**. The Site has a long regulatory environmental history further

discussed in Section 1.4. The specific AOCs are discussed further in the Current Conditions Report (WW Engineering and Science, 1994).

DNAPL exists geographically at four residual source areas identified at the Site:

1. Former Primary Disposal Area (within the Northern Exposure Area)
2. Former Primary Ash Disposal Area (within the Northern Exposure Area)
3. Former Fine Chemical Production Area (within the Central Exposure Area)
4. Former Equalization Pond Area

These identified source areas constitute the "residual waste" areas referred to in U.S. EPA's Final Decision (U.S. EPA, 2001b). DNAPL architecture, or how the DNAPL exists spatially within the aquifer, is discussed in Section 3.5. In general, DNAPL exists vertically near and below the water table disseminated with water within the pore-spaces of sand and finer-grained glacial sediments. An Extent of DNAPL Map is shown as **Figure 4**. Vertical profiles (cross-sectional views at residual source areas) showing DNAPL distribution are presented in **Appendix A**. Further discussion of DNAPL distribution is provided in Section 3.5.

A groundwater contaminant plume is present at the site. However, monitoring of GSH's purge well system has shown the contaminant plume to be stable (i.e., not expanding) and that the purge well system captures and contains the southern edge of the dissolved groundwater plume and prevents its discharge to White Lake. Localized areas of groundwater exceeding the cleanup criterion for C-56 are present near the individual residual DNAPL source areas. The southern edge of the dissolved groundwater plume from the residual DNAPL source areas is captured by a purge well system installed in the 1980s. The groundwater capture system has a performance record from the 1990s and 2000s documenting that it fully and effectively contains the dissolved plume from the DNAPL areas. The system consists of a series of eight purge wells (Pb, Pc, Pd, Pe, Pf, Pg, Ph, and Pi) which capture approximately 1 million gallons per day (mgd) of groundwater. Chlorinated organic compounds are removed from the groundwater through treatment with granular activated carbon, and the treated groundwater is discharged through a National Pollutant Discharge Elimination System (NPDES) permitted outfall into White Lake. This system completely halts the flow of chlorinated organic compounds to White Lake.

Groundwater on the site and within the plume boundaries is not used for drinking water purposes, and deed restrictions are being placed on an area encompassing the stable plume to prohibit the use of groundwater as a source of drinking water in the future. Residences located down gradient from the source areas use treated municipal drinking water provided by the City of Montague. A limited number of residential properties lie over the plume, and the municipal drinking water for all of these houses is provided and paid for by GSH. Additional discussion of residential wells and supplied drinking water is provided in Section 1.5.3.

1.4 Regulatory History

The historic impacts at the site are regulated through enforceable agreements with the State of Michigan and the U.S. EPA (U.S. EPA, 1993a). These agreements are described below, and a chronological timeline is presented in **Table 1**.

1.4.1. State of Michigan Consent Judgment (MICJ)

A MICJ was issued October 30, 1979. Under the 1979 Consent Judgment, OCC completely removed the equipment and materials for the production of C-56 at the site. OCC further excavated the impacted soils identified by the consent judgment, often down to the water table, and were placed in a secure on-site landfill. Drinking water was provided to off-site residential properties that were near or over the plume. A groundwater collection and treatment was installed and modified to assure that it completely halted the flow of groundwater contaminated with chlorinated organic compounds into White Lake. Groundwater monitoring programs were developed and implemented for the secure on-site landfill that isolated the impacted soils and equipment as well as for the groundwater collection system. After the implementation

of the requirements in the 1979 Consent Judgment, some impacted soils remained at the site that were not addressed in the MICJ; these remaining impacts were later addressed under RCRA Corrective Action requirements.

1.4.2. Unilateral Administrative Order (UAO)

In 1993, the U.S. EPA Region 5 issued a UAO to OCC to implement RCRA Corrective Action requirements at the Site (U.S. EPA, 1993a). The UAO required the implementation of a RCRA Facility Investigation (RFI), Corrective Measures Study (CMS) and Corrective Measures Implementation. The objectives stipulated in the UOA were to 1) fully determine and document the nature and extent of known and suspected contamination, 2) to evaluate adequacy and protectiveness of activities performed under the MICJ, 3) determine if interim action measures are needed, 4) determine if supplemental or additional long-term corrective action measures should be implemented, and 5) to implement interim and/or long-term corrective measures, if deemed necessary by the U.S. EPA.

1.4.2.1. RCRA Site Characterization

In response to the UAO, in January 1994 GSH submitted the "Description of Current Conditions" (WW Engineering & Science, 1994). This report provided a comprehensive overview of the Site including facility background, known nature and extent of contamination, and implementation of interim measures. As part of the evaluation of current conditions, GSH evaluated groundwater use in the area and documented that no groundwater was being used as a source of drinking water or any other residential purpose (Earth Tech, 1994), though groundwater had historically been used as a source of drinking water. The Current Conditions report was followed by a series of investigations and reports that further characterized the site. These reports are summarized in **Table 2**.

The RFI was performed to determine the nature and extent of releases of hazardous waste or hazardous waste constituents from identified AOCs. The RFI was broken down into two phases. Phase I of the RFI documented what constituents of concern (COCs) were present in soil and groundwater at the Site above relevant cleanup criteria (Earth Tech, 1996). Phase I was also implemented to determine the physical characteristics of the underlying geology and aquifers of the Site. Phase I RFI included the following tasks:

- Geophysical investigation
- Phase I soil investigation
- Phase I groundwater investigation
- Evaluation of field screening technologies
- Sample the lower clay unit for geotechnical and physical properties.

The Phase I RFI determined that several chlorinated organic compounds were present in soils above the cleanup criteria used in Michigan at that time (Earth Tech, 1996). The groundwater investigation indicated that the upper sand aquifer, south of the Former Fine Chemical Production Area was impacted. The underlying clay unit was documented to be a low permeability unit with a vertical permeability ranging from 5.55×10^{-7} cm/sec to 5.67×10^{-8} cm/sec vertical permeability. No DNAPLs were observed during the Phase I RFI.

The Phase II RFI was performed to further determine the extent of COCs at the Site (Earth Tech, 1999). The work performed under Phase II included:

- White Lake sediment and surface water investigation
- Additional soil investigation
- Additional groundwater investigation with intent to determine vertical extent of contamination
- Evaluate risks and/or hazards posed by complete pathways, if present.

The Phase II RFI confirmed that the upper sand aquifer contained chlorinated compounds at concentrations that exceed 1% of their solubility. Monitoring well sampling performed during Phase II indicated that the upper and middle portions of the upper sand aquifer are impacted more so than the

lower portion of the aquifer. The Phase II RFI also substantiated that water from White Lake was flowing to the purge well network which captured impacted groundwater prior to discharge to White Lake. The concentrations of chlorinated organic compounds were present at concentrations that exceeded 1% of their solubility, so the presence of DNAPL was inferred at the Site.

1.4.2.2. Final Decision

On July 18, 2001, U.S. EPA Region 5 issued Final Decision and Response to Comments (U.S. EPA, 2001b). The Final Decision specified eight remedial components:

1. Continued collection and treatment of contaminated groundwater
2. Evaluation and implementation of feasible on-site collection/treatment options for contaminated groundwater and residual waste to expedite groundwater cleanup
3. Implement long term groundwater monitoring
4. Excavate surface soil that exceeds cleanup goals at one area
5. Provide soil cover and seeding over the former burn pit area
6. Dredge sediments in White Lake that exceed 2 mg/kg of PCB and 0.45 mg/kg of hexachlorobenzene
7. Continue appropriate site access controls
8. Provide institutional controls for land and groundwater use

This TI evaluation relates to the second requirement for the evaluation and implementation of feasible on-site collection/treatment options for contaminated groundwater and residual waste to expedite groundwater cleanup. The remaining requirements are all being accomplished, or have been accomplished, under the requirements of the UAO.

1.5 Remedial Actions to Date

Over the course of the last thirty years, the manufacturing operations that created the chlorinated organic compounds have all ceased and been removed from the site. All of the manufacturing operations have been demolished and removed from the site or placed in the on-site landfill. All waste materials at these manufacturing operations and all stored waste material have been removed from the site or placed in the on-site landfill. Soils containing residual waste have been excavated, down to the water table under the Former Fine Chemical Production Area and the Former Primary Disposal Area.

In addition, a groundwater collection and treatment system has been installed and operated with a monitoring program and shows continuous and complete capture of the impacted groundwater for over two decades. The remedial actions performed to date (summarized in **Table 3** and shown in **Figure 5**) have eliminated any unacceptable exposure to impacted environmental media at the site and have also removed the bulk of DNAPL then found entrained within vadose zone soils. Many of these remedial actions are discussed briefly below.

1.5.1. Source Area Removal and (Landfill) Vault Construction

Source area excavation and removal actions were completed under the 1979 Consent Order issued by the State of Michigan. These actions removed the sources of the residual DNAPL at the Site by removing portions of the manufacturing operations, all waste piles, and also the impacted soils.

At the Former Primary Disposal Area, all of the drums and debris have been removed and placed in a secure landfill. In addition, the soil underlying the Former Primary Disposal Pile was excavated down to the water table (approximately 25 feet below grade at the time) and all of this underlying soil was also placed into a secure landfill. The State of Michigan estimated that 153,063 cubic yards of material from the Former Primary Disposal Area were excavated and placed in the secure landfill. Clean soils were then backfilled over this area.

At the Former Primary Ash Disposal Area, where C-56 waste materials were placed into the fly ash, all of the fly ash was removed and placed in a secure landfill. The State of Michigan estimated that the

average depth of the fly ash was 12 feet and covered an area of 22,779 square meters. In addition, visibly impacted soils were removed under the fly ash. The State of Michigan required that approximately 86,776 cubic meters of soil and debris be removed from the Former Primary Ash Disposal Area.

At the Former Fine Chemical Production Area, the entire facility was dismantled. All materials that could not be salvaged were placed in a secure landfill. The underlying soil was excavated down to the water table (approximately 25 feet below the production area) and all of this soil was placed into a secure landfill. An additional 555,000 cubic yards of soil and material were excavated from the third brine sludge disposal area located just north of the Former Fine Chemical Production Area (WW Engineering & Science, 1994).

The equalization pond was sealed off, cleaned and re-lined. The equalization pond was constructed of reinforced concrete walls and floor. As part of the 1979 Consent Order, the pond's discharge pipe was permanently sealed. Standing water remaining in the pond was treated through the facilities on-site carbon treatment system and discharged under an NPDES permitted outfall. Approximately 5 feet of sediments within the impoundment were solidified and removed from the pond and placed in a secure landfill. The State of Michigan estimated that 17,011 cubic meters of sediment were removed. After the sediment was removed, the impoundment was rinsed and power washed, and then the basin was lined with a synthetic liner followed by a clay liner. The lined pond currently holds clean water that has entered the impoundment through natural precipitation (WW Engineering & Science, 1994). The sediments in the equalization pond are not impacted (Earth Tech, 1999).

These source area removals addressed the major unsaturated soils issues at the Site by removing the soils under the Former Primary Disposal Area and the Fine Chemical Production Area down to the water table.

1.5.2. Groundwater Capture and Treatment

The groundwater plume from the DNAPL source areas is fully contained. A system of eight purge wells collects 1 mgd of groundwater; chlorinated organic compounds are removed from the groundwater through treatment with granular activated carbon, and the treated groundwater is discharged through an NPDES permitted outfall into White Lake. This system currently halts the flow of groundwater containing chlorinated organic compounds to White Lake.

Installation of the purge well system was initiated in the 1980s. The groundwater capture system has a performance record from the 1990s to 2008 documenting that it captures the dissolved plume from the DNAPL areas. A summary report is prepared annually documenting the system performance over the previous year (CRA, 2009). The performance data for 2009 is summarized in **Appendix B**. Graphs are included in the 2009 annual report showing groundwater trends over a time period from 1994 to 2008.

1.5.3. Drinking Water Supply

GSH performed a Residential Water Well User Survey (Earth Tech, 1994). In 1994, approximately 36 residences were identified as having residential wells near the site, but no groundwater within the plume was used for drinking water or any residential purpose. Currently, the City of Montague provides potable water services to approximately 40 residents and commercial business' in Montague Township. This service includes all of the houses that are over or proximal to the defined plume (see **Figure 13**) from the GSH Site, along with houses near the impacted groundwater from the DuPont site one mile west of the GSH site. There are currently no uses of site-impacted groundwater. In 2000, the City indicated that they were approaching limitations on the capacity of the current drinking water wells. GSH and DuPont worked together to evaluate and implement a solution to the problem. In 2006, GSH and DuPont covered the costs for a new municipal well which was constructed and is operated by the City. In addition, GSH and DuPont also paid to have a new water line installed to provide a looped water distribution to the area along White Lake south of Old Channel Trail. These system improvements will help assure that there is potable water supplied the area south of Old Channel Trail into the future.

GSH provides municipal water to the following residences:

- Wackernagel, 5800 Old Channel Trail
- Lathrop, 5780 Old Channel Trail
- Toppings, 5725 Old Channel Trail
- Stevens, 5625 McFall Circle
- Neff (Dakin), 5591 McFall Circle*
- Kelley, 5611 McFall Circle
- Hunt, 7040 McFall Circle
- Hanna, 5575 McFall Circle*
- Grinwis, 5585 McFall Circle
- Engblade, 7180 McFall Drive
- Cousino, 7211 McFall Drive***
- Carroll, 7250 McFall Drive***
- Bortell, 5610 McFall Circle
- Grimshaw, 5607 McFall Circle
- Gunter, 7255 Blueberry Ridge
- Jerabek, 7311 McFall Circle
- Tottens, 7030 McFall Circle*

In 2004, GSH performed a well abandonment effort in the Blueberry Ridge/McFall Drive community south of the Site. Wells were abandoned at 7171 McFall Drive, 7030 McFall Circle, 5575 McFall Circle, and 5591 McFall Circle. No wells were present at the Gunter, Hunt, Grimshaw, Engblade, Miller, Roder and Stevens' residences. Two property owners opted not to have their wells abandoned*** including the Cousino's and Carroll's. Both of these residents were notified in September 2003 regarding groundwater quality at the residential wells. The wells are currently not in use, and both of these two residences receive municipal drinking water from the City of Montague system.

Michigan's on-line GIS groundwater mapper indicates a total of one residential drinking water well existing south of Old Channel Trail within the dissolved contaminant plume boundary:

LISTED OWNER NAME	LOCATION ADDRESS	WELL DEPTH (FT BGS)
GEORGE CARROLL	7250 BLUEBERRY RIDGE DR	78

Source: http://gwmap.rsgis.msu.edu/viewer.htm

In September 2009, GSH contacted residents from the Blueberry Ridge subdivision located within the plume boundaries to confirm that potentially existing residential wells are not being used by residents for any purpose. The Carroll well (7250 Blueberry Ridge Circle) exists but is not used for any purpose. The pump and associated piping has been dismantled.

1.5.4. Soil Removal & Capping

Additional soil remediation has been performed since the excavations performed under the MICJ. Soil removals and a soil cover at the former burn pit that were required under the final decision have been completed (Earth Tech, 2002b).

While performing DNAPL investigation activities, seven small areas in the former industrial portion of the Site were identified as having stained soil, bare spots (no vegetation), or stressed vegetation. From July 2002 through April 2005, GSH investigated the nature and extent of impacted surface soils. These investigations concluded that the soil in these areas exceeded Michigan's Part 201 Soil Direct Contact Criteria and Finite Volatile Soil Inhalation Criteria for five meters thickness (FVSIC5m). To address these areas, it was determined that 0.66 feet of cover over each impacted area would sufficiently reduce the ambient air emissions to safe levels at the Site. In June 2005, GSH covered the seven areas with at least

2 feet of topsoil. GSH re-seeded the soil cover locations and currently maintains vegetation at these areas (Earth Tech, 2005b).

Details of the 2005 soil removal and capping activities are provided in "Supplemental On-Site Soil Investigation and Cover at the Former Occidental Chemical Corporation Site in Montague, Michigan" report dated December 2006 (Earth Tech, 2006c.). Capping activities are presented below:

Areas 1 and 2 were covered with approximately 170 cubic yards of clean topsoil on June 2, 2004. The soil cover on Area 1 was measured in five locations and ranged from 1.83 to 2.24 feet thick, with only one location below 2 feet after compaction, and all locations significantly over 1 foot thick. Area 2 is a small area and the soil cover thickness was over 2 feet thick.

In Areas 3 and 4, the off-site source of topsoil was supplemented by clean topsoil that was left on-site after the site restoration work for the dredging project in 2004. On May 31, 2005 approximately 60 cubic yards of stockpiled clean topsoil staged adjacent to Areas 3 and 4. An additional 240 cubic yards of clean topsoil was used to spread 2 feet of soil over Areas 3 and 4. Soil cover was completed for Areas 3 and 4 on May 31, 2005. The soil cover over Areas 3 and 4 ranged from 2.08 to 6.58 feet thick. The thicker cover depths (over 3 feet) represent soil cover measurements over the excavated areas, while the cover depths between 2 to 3 feet represent soil cover thickness outside of the excavated areas.

Areas 5 and 6 were covered with approximately 200 cubic yards of clean topsoil on June 3, 2004. The soil cover over Areas 5 and 6 ranged from 2.00 to 5.75 feet thick.

On June 1, 2005 approximately 300 cubic yards of clean topsoil was distributed over Area 7.

The average soil cover thickness at each area was greater than 2 feet and all measurements exceed the 0.66 feet required to mitigate volatilization. During the summer of 2005, vegetation was established on each soil cover.

Historical remedial actions to date are presented as Figure 5.

1.5.5. White Lake Sediment Dredging

GSH dredged impacted sediments from White Lake and successfully achieved the required cleanup criteria stipulated in the Final Decision. From July 2003 through December 2003, GSH completed a corrective action to remove impacted sediments from White Lake in the areas near Dowies Point. The removal was performed pursuant to the 1993 UAO. Ten thousand five hundred cubic yards of sediments were removed from the area of approximately 1.6 acres located 200 to 450 feet south of Dowies Point in White Lake under 35 to 50 feet of water. At the completion of the dredging, the sediments remaining in the dredge area were sampled at 32 different locations and all the samples met the target cleanup criteria of 2 mg/kg polychlorinated biphenyl (PCB) and 0.45 mg/kg hexachlorobenzene (Earth Tech, Earth Tech, 2004b). The location of the sediments that were dredged from White Lake is presented as Figure 6.

1.5.6. Institutional Controls

Institutional controls are currently being developed, creating deed restrictions for portions of the Site. These restrictions at the site will assure that no impacted groundwater is used in any way that may lead to inappropriate exposure. In addition, the institutional controls will also assure that there will be no inappropriate exposure to impacted soils. The deed restrictions are taken from the templates used by the State of Michigan for compliance with Part 201 of Michigan Public Act 451 of 1994, as amended. A draft deed restriction has been presented by GSH to the U.S. EPA and to the Michigan Department of Environmental Quality (MDEQ) and also the State of Michigan Attorney General for review and comment (Earth Tech, 2008). The State of Michigan and the U.S. EPA are now evaluating the proposed language. It is anticipated that the deed restrictions will be finalized by the end of 2009. When completed, these restrictions will be permanently recorded with the deed for the property.

2.0 GROUNDWATER CLEANUP STANDARDS

The cleanup criteria that must be met for the groundwater are stipulated in the Final Decision (U.S. EPA, 2001b). These are the concentrations that must be achieved to "expedite groundwater cleanup":

Carbon Tetrachloride (CT)	5.0 ug/L
Chloride	125,000 ug/L
Chloroform	100 ug/L
cis-1,2-dichloroethene	70 ug/L
trans-1,2-dichloroethene	100 ug/L
Tetrachloroethene (PCE)	5.0 ug/L
Trichloroethene	5.0 ug/L
Hexachloroethane (C-26)	6.7 ug/L
Hexachlorobutadiene (C-46)	0.053 ug/L
Hexachlorocyclopentadiene (C-56)	50 ug/L
Octachlorocyclopentene (C-58)	50 ug/L
Hexachlorobenzene (C-66)	1.0 ug/L

These criteria are based on drinking water standards with the exception of C-46 and C-26 which were based on surface water discharge criteria.

The Statement of Basis (U.S. EPA, 2001a) for the Montague site suggests that the point of compliance for these groundwater criteria is throughout-the-plume. "The point of compliance for groundwater represents where groundwater cleanup levels should be achieved within a contaminated aquifer. The groundwater point of compliance for RCRA Corrective Action should be through the area where groundwater is contaminated above the cleanup levels, or, when waste is left in place, at and beyond the boundary of the waste management area encompassing the original sources of groundwater contamination." (U.S. EPA, 2001a, p.9)

3.0 SITE CONCEPTUAL MODEL

The Site Conceptual Model (SCM) synthesizes and presents site-specific conditions to illustrate conceptually the relationship of the receptors to the contaminants emplaced within the sub-surface physical setting. The SCM considers physical site setting, geology and hydrogeology, contaminant release history, contaminant chemistry, contaminant distribution, transport and fate, and presence of receptors. The SCM for the Occidental Chemical Site was developed using criteria recommended in "Guidance for Evaluation the Technical Impracticability of Ground-Water Restoration" (U.S. EPA, 1993b). An overview of the SCM is presented in Section 3.1, and more detailed descriptions of the elements within the SCM are presented in the subsequent subsections.

3.1 Overview of Site Conceptual Model

Under TI guidance, decisions regarding the TI of groundwater restoration are based on a thorough characterization of the physical and chemical aspects of the Site (U.S. EPA, 1993b). The TI guidance indicates that characterization data define the contamination and facilitate the analysis of restoration potential. This section presents an overview of the SCM for the presence of residual DNAPL at the OCC Site, transport of constituents off from this residual material, and potential exposures to these constituents.

A graphical Site Conceptual Model (SCM) in **Figure 7** illustrates in a simplified manner the elements present at the Site. The SCM shows the relationship of contaminants, DNAPL and dissolved-phase plume, emplaced within the sub-surface, to potential receptors, including human residents and White Lake. The SCM integrates the physical site setting, geology and hydrogeology, contaminant release history, contaminant chemistry, contaminant distribution, and presence of receptors. The SCM presented in this section reflects OCCs current understanding of the conditions of the Site.

The model in **Figure 7** illustrates a cross-sectional view running roughly north to south through the areas containing residual DNAPL, extending along the dissolved plume, and ending at White Lake in the south. This figure represents a distance of approximately 6,240 feet from end-to-end. Predominant features in the SCM include four "historical DNAPL entry locations" which are the residual DNAPL source areas: 1) Former Primary Disposal Area, 2) Former Primary Ash Disposal Area, 3) Former Fine Chemical Production Area, and 4) Former Equalization Pond Area. In the cross-sectional SCM, areas 1 and 2 are shown as a generalized single source area, although they are geographically separated by several hundred feet from east to west (cross-section based on profile presented in Earth Tech, 2003). The Former Fine Chemical Production Area constitutes the largest bulk of contaminant mass, as graphically illustrated with DNAPL and the C-56 dissolved plume. DNAPL is also present at the south end of the Former Equalization Pond. The release of DNAPL constituents was halted around 30 years ago, and the current DNAPL represents an aged source of residual DNAPL below the zones excavated during previous remedial actions at the site.

Site topography is variable across the Site, with topographic lows at some the former source areas which were excavated and also at White Lake. Surface soils are well-drained sands that support vegetation in most of the areas. The residual DNAPL source areas 1, 2 and 3 are sparsely to non-vegetated surfaces, and consist of wind-blown sand.

The SCM shows a simplified stratigraphic profile of the Upper Sand Unit and the Lower Clay Unit. The contacts, including lower clay and clay and silt sequences found within the Upper Sand Unit are roughly based on documented stratigraphy from borings drilled across the Site. As discussed further below in Sections 3.4, while the upper aquifer is dominantly sand, the stratigraphy within the aquifer is complex, with subtle micro-scale variations in textural composition, grain-sizes, and bedding structure. In general, DNAPL is found entrained within these finely inter-bedded deposits at the groundwater table extending down to 50 feet below water table in some locations.

Dissolved-phase contamination in the groundwater contains CVOCs such as CT, PCE and CSVOC C-56. C-56 is not found significant distances down gradient of the residual DNAPL areas due to the short half-life for hydrolysis of approximately 15 days for C-56, discussed in Section 3.7. Dissolved phase transport is primarily through groundwater advection. Contaminant transport via diffusion appears to be nominal or limited based on observation of the relatively narrow plume shape.

Groundwater recharge is primarily through surface infiltration of precipitation (rainfall or snow). Within the Upper Sand Unit, groundwater flow is to the south-southeast at an estimated flow velocity of 1.8 feet/day (0.27 feet/day Darcy flow velocity). The Upper Sand Unit is an unconfined aquifer. The aquifer is generally aerobic at shallow and middle depths, and anaerobic near the Lower Clay Unit.

A single purge well is shown on **Figure 7** to represent the active purge well gallery of eight wells along the southern limit of the SCM. The purge wells induce capture at the lake boundary, and draw water back from White Lake, preventing dissolved-phased chlorinated CVOCs from entering the lake. Potential receptors presented in the SCM include a residential housing development south of the site and White Lake. Terrestrial wildlife receptors are also present at the Site (not presented in the graphic model). The SCM does not include any use of the groundwater as a source of drinking water, as there is no use of the impacted groundwater as a source of potable drinking water.

In summary, the SCM includes the following elements:

1. An 880-acre site situated in a rural area adjacent to White Lake.
2. Variable surface topography and well-drained, sandy vadose zone soils, where groundwater recharge is through precipitation infiltration into the highly permeable soils and flow from up gradient of the site.
3. An unconfined upper sand aquifer, with heterogeneous horizons of silt and clay, underlain by a low-permeability clay unit.
4. Groundwater flow toward the lake at an estimated flow rate of 1.8 feet/day.
5. Weathered (40 to 50-years old) residual DNAPL located in four source areas.
6. The DNAPL is disseminated within the larger interstitial pore-spaces in sands above thin finer-grained silts and clay layers.
7. The DNAPL is located at the groundwater table extending up to 50 feet below water table at various source areas.
8. Three separate C-56 plumes likely exist and are located proximal to and immediately down gradient from the residual source areas, including the Former Fine Chemical Production Area, the Former Equalization Pond Area, and generally the residual wastes areas within the Northern Exposure Area.
9. A dissolved CVOC plume extends throughout the long-axis of the Site, and is present in the upper and middle portions of the upper sand aquifer, and in the lower portions of the aquifer in the Former Fine Chemical Production Area.
10. The dissolved COC plume is completely captured by a purge well network.
11. Potential receptors including biota in White Lake, humans and terrestrial animals.

3.2 Site Exposure Model

A Conceptual Site Exposure Model (CSEM) for current conditions is presented in **Figures 8** and **9**, showing the primary receptors as human and ecological receptors, including those located in White Lake. This CSEM is built from the exposure model presented in the risk assessment performed during the RFI (Earth Tech, 2000a). Historical remedial actions taken in the course of the RCRA Corrective Action program have mitigated exposure to these receptors. The current groundwater purge wells capture the entire dissolved plume prior to use by humans and prior to exposure to environmental receptors. The soil remedies mitigate exposure to impacted soils. The CSEM in **Figure 8** for current conditions shows that no pathways are complete that would potentially expose receptors at the site. **Figure 9** shows receptors near the Site. Receptors and the CSEM are discussed further below.

Ecological Receptors

The general site area provides habitat for a variety of terrestrial animals, as noted in the risk assessment conducted for completion of the RFI (Earth Tech, 2000a). In instances where animals may be in close proximity to chemicals of concern, contact with chemicals that are associated with saturated soils or chemicals that are emitted from the soils in vapor or particulate phase may result in unacceptable exposures and risk of adverse health effects. Current conditions are protective of these pathways. The potential exposures to these terrestrial animals are discussed in the evaluation of each remediation scenario.

Human Receptors

Two general groups of human receptors have been considered in this evaluation: workers (e.g., personnel working on-site or utilities personnel) and non-workers. The rationale for defining these two general groups is based on measures that typically can be taken to preclude exposure to constituents in the DNAPL. For instance, it has been assumed that workers will generally have the option to employ personal protective equipment which will prevent exposure and thus mitigate risk during remediation activities. Alternatively, non-workers are considered those receptors that may not readily, nor should be expected to, avail themselves of donning personal protective equipment to mitigate risk. For the purposes of this report, non-workers may be considered residents in the area, vacationers using the general area for recreational purposes, and those moving through the general vicinity of the area in order to conduct personal business.

Conceptual Site Exposure Model

Conceptual site exposure models schematically define the exposure pathways between a contaminant source (i.e., residual DNAPL) and potential receptors. The exposure pathway must be complete in order to conclude that the risk of adverse health effects may result for potential receptors.

In order for the exposure pathway to be complete, it must contain a contaminant source, a means of transport to a receptor (i.e., transport mechanism), a toxicological exposure route (i.e., ingestion, dermal, and/or inhalation) and a defined receptor. In the assessment of the remedial alternatives, transport mechanisms are defined as work processes that may result in activities that may facilitate exposure.

Thus for each remedial alternative presented in Sections 6.0, 7.0 and 8.0, the source has been considered the residual DNAPL that exists less than 70 ft bgs while the transport mechanisms are those work processes that are deemed key to completing the remedial action. As such, engineering requirements for each remedial alternative were generally defined and evaluated to understand how they might lead to an uncontrolled release of chemicals which could in turn result in exposures to receptors of concern at the site.

3.3 Physical Site Setting

Site topography ranges from approximately 582 feet above mean sea level (amsl) at the shoreline of White Lake to 730 feet amsl at the apex of the site vault. The highest topographic area not related to the vault is approximately 642 feet amsl near the Former Equalization Pond Area and other areas. Topography ranges from 618 to 640 feet amsl at the Northern Exposure Area; 618 to 640 feet amsl at the Former Fine Chemical Production Area; and 634 to 642 feet amsl at the Former Equalization Pond.

The southern boundary of the Site is the shoreline of White Lake and the elevation of the ground drops off at the bluff by White Lake to approximately 582 feet amsl. A bluff rises up from the shoreline approximately 45 feet to an elevation near 625 feet amsl. A topographic high due to anthropogenic effects are located at the secure landfill vault and several excavated areas (residual source areas) (WW Engineering & Science, 1994). Historic excavations are still reflected at low areas within the boundaries of the site.

Land Use

The property boundaries and surrounding land use near the DNAPL source zones are shown in **Figure 2** which shows the low density residential and industrial land use of the surrounding property. Property use

immediately north of Hancock Road is primarily low density residential in addition to some recreational use. Montague Township Park is located one-half mile from the northern-most source area, north of the Hancock Road and Whitbeck Road intersection and includes sports fields for recreation use.

Property immediate south of Hancock Road but north of Occidental property is low density residential. The property immediately northwest of the Hancock and Lamos Roads intersection is low density residential. An industrial complex and low density residential housing development are located west of Lamos Road. The property immediately southwest of the Lamos Road and Old Channel Trail intersection is industrial. Property use immediately west of the Site (east of Lamos Road) is primarily undeveloped or low residential use. Property use east of Whitbeck Road is low density residential and industrial. Much of the land is undeveloped. A cemetery is located northwest of the Hancock and Whitbeck Roads intersection. Residential property is located northeast of the Old Channel Trail and Whitbeck intersection (*Ibid*).

Land use south of Old Channel Trail consists of both residential housing in the form of Blueberry Ridge development situated on a *cul-de-sac* extending to the shoreline of White Lake. The portion of Occidental-owned property extending to White Lake south of Old Channel Trail is surrounded by low density residential land on the west, White Lake on the south, and both low density residential land use and White Lake on the east. Property southeast of Whitbeck Road and Old Channel Trail intersection is low density residential property (*Ibid*).

Ecological Setting

The ecological setting of the Site was previously presented in the "Current Conditions Report" (WW Engineering & Science, 1994) and the "Human Health and Ecological Risk Assessment" (Earth Tech, 2000a). The Site consists of several terrestrial habitats offering a diverse and varied animal community. The U.S. Department of Agriculture Muskegon County Soil Map of 1968 classifies surface soils of the Site as Rubicon Sand. Rubicon Sand consists of deep well-drained sandy soils. In various portions in the northern limits of the Site Roscommon and Au Gres sands and Granby loam sand is present. These soils consist of deep, poorly-drained, sandy soils.

Sandy soils of the Site and nearby eco-tones support oak-pine forests (primarily on undeveloped areas of the site, where White Pine, Black Oak and White Oak are dominant), pine plantations (consisting of government planting of Red and Scotch Pine, in the northern and eastern portions of Site), deciduous swamp (northern edge of the Site along Hancock Road), black locust/*Ailanthus* communities (general in previously urbanized areas near White Lake), Oak Savannah openings (proximal to the Vault area), and old field habitats. Wet meadow habitats are present proximal to White Lake yielding hydric soils.

GSH has implemented voluntary habitat restoration projects and wildlife re-enforcement activities across the Site. These include introduction of several native Michigan prairie grass species and various native hardwood trees. Habitat restoration Areas are demarcated on **Figure 10**. (*Ibid*).

White Lake

White Lake lies within the greater 509 square mile White River Drainage Basin, and comprises 2,571 acres with mean and maximum depths of 22 and 70 feet, respectively and a mean hydraulic retention time of 56 days. White Lake is classified as a eutrophic and dimictic (seasonally stratified) lake formed from a drowned river mouth. White Lake contains three basins, with the Site being situated on the "upper third" basin of the lake.

As part of the UAO, impacted sediments were removed from an area of approximately 1.6 acres near Dowies Point shown on Figure 6. 10,500 cubic yards of sediment were removed from White Lake, and post-dredging sampling confirmed that the cleanup criteria were met under the entire dredge area. White Lake is not considered to as part of the Site, but is included as a receptor in the SCM.

Regional Aspects

The City and community has a long and interesting history punctuated by the late-19th Century pine logging industry and chemical industrialism in the 1950's. The City of Montague has a population of

2,407 with density of 905 people per square mile. There are 1,075 housing units at an average density of 404 per square mile (2000 census). The City is located in Montague Township, but is politically independent. The average City elevation is 636 feet amsl. The City has a total area of 3.2 square miles, of which 2.7 square miles is land and 0.5 square miles is water. The City is at the southern end of the Hart-Montague trail, a paved cycling and multiuse trail which attracts tourist visitors during the warm months. Major highways of the City include US-31, Business Route 31, B-15 and B-86.

Montague Area Public Schools (MAPS) is the local school district for the City of Montague. Three of the districts five schools are located in the City, and include MHS, Nellie B. Chisholm Middle School, and R.R. Oehrli Elementary School. Other schools include Oceana HS and Rothbury Elementary School and various parochial schools which are all located further from the Site.

Lake Michigan has a moderating effect on the climate of Muskegon County and Montague. Average daily high temperatures in Muskegon County range from 32 degrees Fahrenheit in January to 82 degrees Fahrenheit in July. Average monthly precipitation ranges from 1.78 inches in February to 3.15 inches in September. Yearly precipitation averages 31 inches. The primary wind direction is westerly.

3.4 Geology and Hydrogeology

Regionally, the geology of the Montague area consists of approximately 300 to 350 feet of unconsolidated Quaternary sediments and till overlying the Mississippian age Marshall Sandstone, a bedrock formation consisting of shale and inter-bedded sandstone facies. The Quaternary deposits in the Montague area are primarily dune sands, lakebed, and fluvial sand, silt and clay deposits. These deposits are present at the Site and represent massive dune sequences and lake beds associated with historical Lake Michigan. Since the late 1970's the hydrogeology and quaternary geology of the Site has been extensively evaluated through sub-surface drilling. Over 200 soil borings have been performed with construction of numerous monitoring wells that have contributed to a thorough understanding of Site stratigraphy and delineation of the aquifer systems.

The geology at the site consists of three general units:

- Upper Sand Unit
- Underlying Clay Unit
- Underlying sands

Upper Sand Unit

The upper sand unit is an unconfined aquifer which is continuous across the site. The upper sand unit is the primary unit of concern in this TI Evaluation because both DNAPL and dissolved-phase contamination reside within this unit. The unit is composed of mainly fine to medium grained quartz-rich sands. The sands are associated with a glacial lake near-shore activity and show depositional aeolian and lacustrine features, including bedding planes, sharp depositional contacts, and thin lamellae of variable texture and heterogeneity (Earth Tech, 1996, 1997, and 2003).

Thin (1 cm or smaller) silty and clayey horizons are found throughout the upper sand unit. The genesis of lamellae (also called laminae and corvarvany) in dune deposits is poorly understood and controversial, with suggested origin from both deposition and diagenesis (Schaetzl, 2001). At the OCC Site the presence of these lamellae is significant in retarding the vertical migration of DNAPL at various locations at the site.

Soil Core at CPT-02-40
20-25' Depth Range: Upper Sand Unit
Note Bedding Planes



The upper sand unit also contains thicker (macro-scale <5 m) beds of fine gravel, silt and clay. These sequences are more frequently present in the lower portions of the Upper Sand Unit.

The saturated thickness of the Upper Sand Unit ranges from approximately 35 to 140 feet. Groundwater is encountered from approximately 614 feet amsl at the northern area that contains DNAPL to approximately 578 feet amsl at White Lake. The depth to groundwater across the Site is typically 35 to 50 feet bgs. Groundwater elevations are subject to fluctuation of ± 0.5 feet during the course of a year.

Aquifer tests including both slug-tests and aquifer pumping tests conducted on the Upper Sand Unit show hydraulic conductivities of approximately from 50 to 70 ft/day. Groundwater flow in the Upper Sand Unit is to the south-southeast at an estimated flow velocity of approximately 1.8 ft/day (0.27 ft/day Darcy velocity). The MICJ (State of Michigan, 1979) historically reported a groundwater flow velocity of 1.5 ft/day. A groundwater contour map for the aquifer is presented as **Figure 11**.

The Upper Sand Unit aquifer is generally aerobic. However, groundwater residing in the lower portions of the aquifer, within silt and clay inter-bedded deposits, is generally reducing.

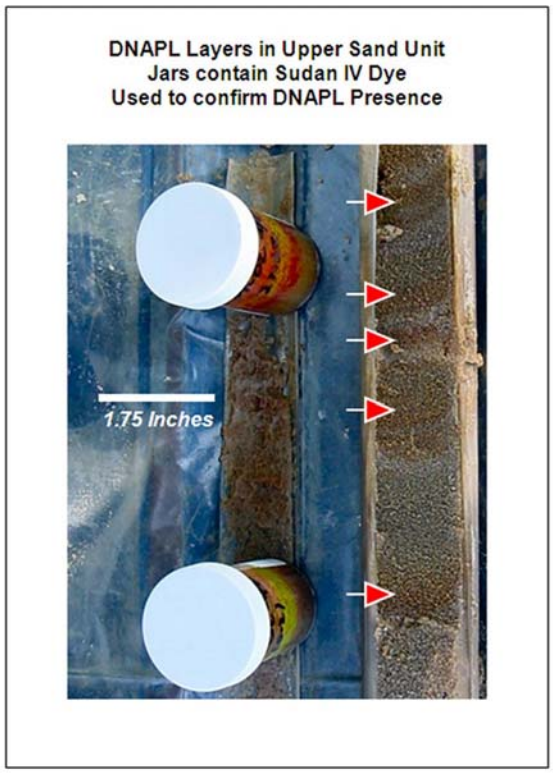
Underlying Clay Unit

The underlying clay unit appears to be continuous across the site and has been encountered at depths ranging from 45 to 200 feet below the surface. When the clay has been completely penetrated, it ranges in thickness from 35 to 140 feet. Vertical permeability of the unit is low and ranges from 5.55 x 10^{-7} cm/sec to 9.11 x 10^{-8} cm/sec, based on falling head permeability analysis of samples collected from the unit. Compositionally the clay unit is frequently classified as till, and is silty clay composed of approximately 40-45% clay, 35-40% silt and smaller fractions of sand.

Inter-bedded layers of sand are present within the clay unit and range in thickness from 10 to 45 feet. The clay unit underlying the upper unconfined aquifer may act as a regional aquitard and appears to separate the upper aquifer from lower, confined saturated sand layers. The MICJ notes that the underlying "till" is clay-rich and is approximately 80 feet thick on the northern portions of the Site and approximately 10 feet thick near the southern edge of the Facility [near Old Channel Trail], and thickens again on the southern limit of the Site.

Lower Sand Units

Limited site-specific information is available regarding lower sand units which form confined units separated from the upper unconfined system by the extensive clay. However, no specific information is known regarding the lateral extent and thickness of the lower sand units. The lower sand unit are not discussed further in this TI Evaluation due to demonstration that no impact resides within the lower sands (State of Michigan, 1979; U.S. EPA, 1993a).



3.5 DNAPL Architecture

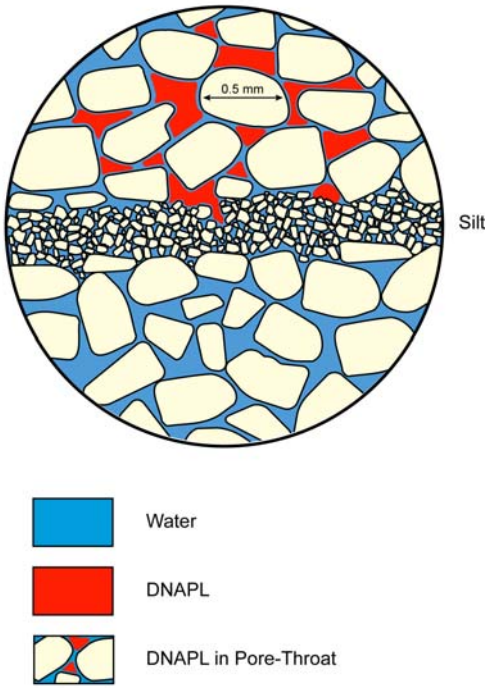
DNAPL architecture refers to the three-dimensional aspect of how immiscible-phase liquids are positioned within a subsurface system. In this TI Evaluation, DNAPL refers to the presence of a liquid in the pore space of the aquifer material that is separate from the aqueous or water phase. DNAPL encountered at the Site is primarily C-56, typically with C-58, and CVOCs. Historically, the DNAPL responded through gravity, groundwater advection and capillary forces by migrating downward and laterally into larger pore throats through the Upper Sand Aquifer. As the

DNAPL migrated into the sand aquifer, multiple DNAPL layers formed due to the effects of subtle pore-size contrasts in the sand induced by finer-grained silty and clayey layers. This is shown in the image to the right, where C-56 DNAPL zones are shown as relatively thin horizons within the sand. Based on observation of cores retrieved near or at residual source areas, DNAPL resides interspersed and "sandwiched" within thin bedded clastic sediment horizons.

Figure 12 shows DNAPL residing in thin inter-bedded sedimentary deposits.

DNAPL does not exist at the Site as pools of free-phase mobile liquids. The groundwater has a higher affinity than the DNAPL for the sand grains that make up the aquifer. In this situation, interfacial tension holds small volumes of DNAPL in the larger interstitial pore throats within the aquifer material. The DNAPL is held in place by interfacial tension and is rendered relatively immobile under static site conditions (Pankow & Cherry, 1996; Cohen & Mercer, 1993).

As shown in the conceptual illustration to the right, sand grains are present with thin laminar horizons of finer grained silt layer. This model is consistent with observations made at the OCC Site. DNAPL resides disseminated within pore throats with boundary conditions established peripherally due to the presence of surrounding groundwater and thin finer grained underlying layers. However, DNAPL may also enter or penetrate the laminae due to the presence of fractures, coarser grains or other secondary porosity features. Mechanically-induced stress to bedding planes or disruption of the interfacial water-to-DNAPL surface tension will also mobilize DNAPL (see discussion in Sections 5.5.3 and 6.3.2).

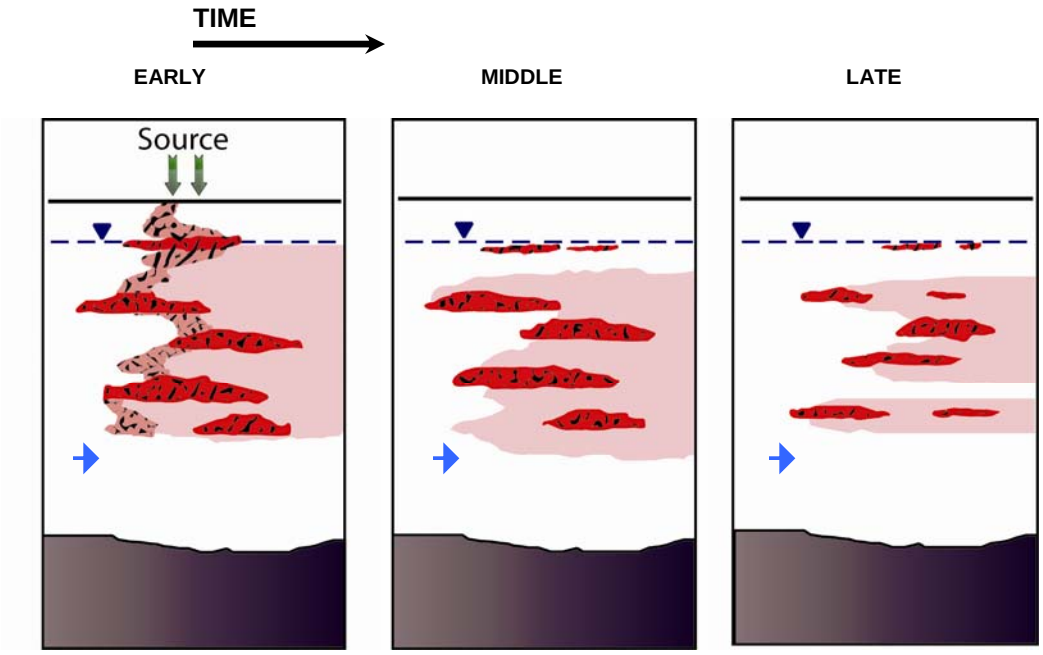


The DNAPL present at the site is at relatively low levels of saturation within the pore space. No pools of DNAPL saturated soils have been identified at the Site. Most of the sands that contain DNAPL have less than 10,000 mg/kg which represents less than 1% DNAPL by dry mass of the soil. In addition, the DNAPL left in these soils is held up in the upper portion of the aquifer by interfacial tension. Capillary barriers such as thin fine sand, silt and clay layers have prohibited the migration of the DNAPL to the bottom of the aquifer.

This model is consistent with a "suspended layered DNAPL" model presented by B.L. Parker *et al*., 2003. OCCs current understanding of the Site is also consistent with reported case studies for DNAPL distribution in older sites within sandy aquifers, where "DNAPL resides in sporadic thin horizontal layers as a result of a few decades of groundwater flushing" (*Ibid*).

In essence, residual DNAPL present below the water table since 1979 (i.e., after the fine chemical production activities ceased at the site), has been aged and re-distributed through laminar groundwater flow, dissolution and weathering of the DNAPL.

Source Zone DNAPL Weathering in Sandy Aquifers



ABOVE. *Graphical illustration showing weathering of DNAPL source zones over time. Dark red areas represent DNAPL source zones. The lighter shading represents dissolved-phase fractions partitioning from DNAPL. Blue arrows represent groundwater flow direction. The weathering components include chemical dissolution and reduction of DNAPL zones mediated by groundwater flushing. The OCC Site represents late stages in DNAPL evolution where residual DNAPL is present as relatively narrow layers within bedding planes of the sedimentary deposits of the Upper Sand Aquifer. Adapted from B.L. Parker, et al., 2003.*

The residual DNAPL areas have been investigated and delineated through focused DNAPL investigations performed after the Final Decision (Earth Tech, 2002a and 2003). The residual DNAPL areas that were delineation are presented in **Figure 4**. Each of these residual DNAPL areas are described below:

3.5.1. Former Primary Disposal Area

DNAPL was observed in the aquifer directly under the Former Primary Disposal Area at the north end of the industrialized portion of the site. The source of the DNAPL is suspected to be the Former Primary Disposal Area that is described in the Current Conditions Report (WW Engineering & Science, 1994). This area contained fly ash, drums of C-56 residue, C-56 catalyst, asbestos, empty barrels, various construction debris (lumber, cement blocks, bricks), rubber gaskets, fiberglass piping, and other miscellaneous debris. Old concrete cells from the chlor-alkali process were used to construct west sidewall for the pile. This area received wastes from the Former Fine Chemical Production Area. In the 1979 Consent Order, the Michigan Department of Natural Resources estimated the depth of material in this area to average approximately 10 feet and cover an area of 146,588 sq ft. The Michigan Department of Natural Resources required that debris and underlying soils within this area were excavated to the depth of the water table (approximately 25 feet below grade for a total estimated volume of 200,513 cubic yards). This material was placed into the on-site Secure Landfill Vault. With the removal of this material, the source area for the DNAPL was removed, and the impacted soils were removed down to the water table. Clean soils were backfilled into this area from the sandy soils excavated during the construction of the on-site landfill.

During the Phase II investigation, field testing confirmed the presence of DNAPL in the several borings. Borings confirmed the presence of DNAPL generally at the local water table and extending into the upper portion of the aquifer.

The Former Primary Disposal Area is a source of both dissolved CVOCs and C-56. In addition, C-58 and C-66 are also present but reside within the C-56 plume. Figure 13 shows that plume boundary for CVOCs, C-56, C-58 and C-66. Four borings in this area contained DNAPL that stained red using Sudan IV dye: 02-33, 02-40, 02-41, and 02-43. Analytical results from soil samples show that primarily chlorinated compounds in this DNAPL are C-56 and C-58, typically with detectable concentrations of CT and PCE frequently between 100 and 400 mg/kg. The sands are not fully saturated with DNAPL, but instead, the DNAPL is at partial saturation and there is a significant ratio of water in the pore spaces. The combined mass of these compounds makes up only 3% of the total dry soil mass in the most impacted sample (02-40 from 6.4 m to 6.7 m (20.99 to 21.98 feet) and from 7.6 m to 7.9 m (24.93 to 25.91 feet). A sample of the DNAPL was collected and analyzed for a broad scan of volatile and semi-volatile compounds. This analysis confirmed that C-56 and C-58 are the dominant chlorinated compounds from the volatile organic compound (VOC) and SVOC scans in the DNAPL that was submitted to the laboratory.

The chemical analyses of samples that contained visible DNAPL using the dye test documents that the DNAPL in this area is horizontally and vertically heterogeneous. While C-56 and C-58 are the dominant constituents in boring 02-40, CT and PCE are the dominant constituents in the sample from boring 02-42. The DNAPL at location 02-40 was observed from the water table from 11.5 to 13 feet depth, and also below the water table from a depth of 15 to 27.5 feet.

3.5.2. Former Primary Ash Disposal Area

The Former Primary Ash Disposal Area is located due east from the Former Primary Disposal Area. While DNAPL was observed within this area, the DNAPL in this does not significantly contribute to the plume of CVOCs dissolved in the groundwater apparently because of the low concentration of CVOCs in the DNAPL and because of the low relative saturation of the pore space with the DNAPL. The DNAPL at the Former Primary Ash Disposal Area contains C-56 and C-58, and these compounds are being transported in the groundwater in a very limited extent due to the hydrolysis half life and the very low solubility in water (high Koc). Figure 13 shows that plume boundary for CVOCs, C-56, C-58 and C-66.

From the early 1950's to the late 1960's, the Former Primary Ash Disposal Area was primarily used for the disposal of fly ash from the facility's boiler house. Fly ash was not generated after the facility was converted from coal power to natural gas in the early 1970's. It was also reported that Area 2 contained several barrels of C-56 residue (WW Engineering & Science, 1994). The MDNR estimated the depth of material in Area 2 to average approximately 12.5 feet and covered an area of 246,013 sq ft. In the 1979 Consent Order, the MDNR required that debris and soil be removed; this included all of the debris and underlying soils within this area which were visibly impacted with chlorinated hydrocarbons. This material, with an estimated volume of 113,677 cu yds of was placed into the on-site Secure Landfill Vault. The source of the DNAPL appears to be from the use of this area for waste disposal within the fly ash landfill. With the removal of the fly ash and with the removal of visually impacted soil and all debris from the area, the source of the DNAPL has been removed.

The data collected during Phase II of the DNAPL investigation documents that DNAPL is present at the Former Primary Ash Disposal Area. The data also document that the DNAPL in this area does not significantly contribute to the plume of CVOCs dissolved in the groundwater because of the low concentration of CVOCs in the DNAPL such as CT, PCE, and C-26 and because of the low relative saturation of the pore space with the DNAPL. The DNAPL at the Former Primary Ash Disposal Area contains C-56 and C-58, but these compounds are not being transported in the groundwater.

Eight soil borings were drilled in this area, and borings 02-83, 02-84, and 02-90 all contained DNAPL. Soil samples were analyzed from within and below the observed DNAPL zones in borings 02-83, 02-84, and 02-90. Visual inspection of the dye test on the soil samples indicated that the DNAPL is at partial saturation with a significant ratio of water filling the pore spaces in this area, and the maximum concentration observed in the DNAPL zone was 180 mg/kg of C-56 and 140 mg/kg of C-58, indicating that the sum of the chlorinated organic compounds equates to less than 10,000 mg/kg which represents less than 1% of the total mass. Therefore, the DNAPL is at a low residual saturation in this area.

Volatile chlorinated organic compounds were not detected in the soil samples collected that contained DNAPL (including CT, PCE, and C-26). The DNAPL in this area does not provide a major source for PCE and CT to the groundwater (Earth Tech, 2003).

3.5.3. Former Fine Chemical Production Area

The Former Fine Chemical Production Area is where C-56 production occurred from 1957 through 1977, and DNAPL was observed in soils sample from under this area. From 1957 to 1977, the Former Fine Chemical Production Facility Area was used to produce C-56, muriatic acid and anhydrous HCL. Pursuant to the 1979 consent order, the facility was dismantled and the contents were salvaged to the extent possible. All of the non-salvageable materials, along with the underlying soil down to the depth of the water table (approximately 26 feet below grade) was excavated and placed into the Secure Landfill Vault. Activities associated with C-56 production are considered the source area for the DNAPL in this area. No specific operations are identified as the release points, since the entire C-56 production facility and all underlying soil down the water table was placed into the on-site landfill. In addition, a pipe that discharged directly to the northwest into a former impoundment (all removed) is a second source area located just northwest of the production area.

During the Phase II investigation, thirty-eight soil boring locations were installed to investigate the presence of DNAPL in the Former Fine Chemical Production Area. Locations 02-21 02-22, 02-36, 02-37, 02-38, 02-50, 02-51, 02-52, 02-53, 02-54, 02-59, 02-60, 02-62, 02-64, 02-66, 02-67, and 02-73) were found to contain DNAPL (refer to **Appendix A**). The soil samples identified two areas containing DNAPL in the Former Fine Chemical Production Area: the historic discharge pipe location and the production area. Thirty-nine soil samples were collected from the borings and chemically analyzed for site-specific chlorinated organic compounds.

The major chlorinated constituents present in the DNAPL-impacted soil samples were C-56 and C-58. The concentration of C-56 was typically 3 to 6 times higher than the concentration of C-58. PCE, C-26, and C-46 were frequently detected. PCE was detected in one sample, 02-52 (38 to 40 feet), at 6,600 mg/kg, though PCE was typically present at less than 10 mg/kg. The analytical scan performed on sample 02-52 (34 to 38 feet) identified other chlorinated compounds containing 5 or less carbons.

Soil Boring SB-02-73 was installed at the location where a sewer line historically discharged into the impoundment north of the production area. Boring SB-02-73 contained visible DNAPL during the dye tests down to a depth of 31.5 feet, over 3 feet below the water table. The main chlorinated organic constituent present in the DNAPL in this area was C-56 (410 mg/kg), and 2.5 mg/kg of PCE were also detected. Since the concentration of chlorinated compounds in this sample was less than 0.1% of the mass of the dry weight of the sample, the DNAPL observed at this location only partially fills the pore space in the sand. Boring locations 02-74, 02-24, 02-23, and 02-57 surround this location and delineate the extent.

The second area that contained DNAPL is the Former Fine Chemical Production Area. The highest concentrations of chlorinated organic compounds were observed under the Former Fine Chemical Production Area where the DNAPL was also the thickest (locations 02-22, 02-36, 02-51, 02-52, 02-53, and 02-54). The concentration of C-56 was between 1,000 to 5,000 mg/kg in seven samples collected in this area, and there was frequently over 1,000 times more C-56 than PCE. Monitoring wells MW-95-02A, B, and C and MW-02-04 are located within this zone. The sands in this area are not fully saturated with DNAPL, rather, the DNAPL is at partial saturation with a significant ratio of water in the pore spaces. Analyses of the samples taken from this area showed that the sum of the chlorinated organic compounds only equates to about 3% of the total dry mass of the sample.

Farther from the production area, the maximum concentrations of C-56 in the DNAPL-soil samples were lower, and the ratio of C-56 to PCE was less than 100 (locations 02-60, 02-62, 02-66, and 02-67). Monitoring wells MW-95-03A, B, and C are located within this zone.

The Former Fine Chemical Production Area is a source of dissolved CVOC and CSVOC compounds, including C-56, C-58 and C-66. Figure 13 shows that plume boundary for CVOCs, C-56, C-58 and C-66. Sample locations 02-70, 02-71, and 02-76 are listed as having trace amounts of DNAPL based on field observations to the dye tests. Soil samples were collected from the intervals in each core that correlated with the faint red stain. Laboratory analyses of the samples from these three borings indicate that only very low concentrations of chlorinated organic compounds were present at these locations. The combined concentration of all of the chlorinated organic compounds detected were 5 mg/kg (0.0005%) in SB-02-70; not detected in SB-02-71; and less than 3.9 mg/kg (0.00039%) in SB-02-76. This concentration indicates that these samples contained very little DNAPL present as a separate phase non-aqueous phase liquid.

An additional eleven soil borings (02-35, 02-55, 02-56, 02-57, 02-58, 02-61, 02-65, 02-72, 02-74, 02-75, 02-77) were found to have no DNAPL present based on field Sudan IV observations. MW-95-04A, B, and C and MW-02-06A and B are located immediately adjacent to, and outside, the projected extent of the DNAPL.

3.5.4. Former Equalization Pond Area

The Former Equalization Pond Area is the former wastewater equalization pond for the chemical plant. DNAPL was observed in a single boring at this area during the Phase II Investigation. The equalization pond was originally constructed of reinforced concrete and had a total volume of approximately 12 million gallons. From approximately 1954 to 1978, wastewaters from the fine chemical production and the chlor-alkali production were discharged into this concrete basin via the process sewer line. The source of the DNAPL on the south side of the impoundment could have been the former outfall sump that resided on the south side of the former equalization pond, or the pond itself. The wastewater treated in this unit was neutralized, cooled, and allowed to equalize and settle prior to its discharge.

Pursuant to the 1979 Consent Order, the pond's discharge pipe was permanently sealed. Standing water in the basin was then treated in the facility's activated carbon absorption system and discharged through the facilities NPDES-permitted outfall. Approximately 5 feet of sediments were solidified, scraped from the concrete-lined basin, and placed into the on-site Secure Landfill Vault. The MDNR estimated that the pond contained approximately 22,284 cu yds of sediment. After removal of the sediments, the pond was flushed clean with water and the concrete basin was lined with clay and a synthetic (Hypolon™) layer. The pond then filled up with clean rain water.

The Former Equalization Pond Area is a source of dissolved CVOC and CSVOC compounds, including C-56, C-58 and C-66. Figure 13 shows that plume boundary for CVOCs, C-56, C-58 and C-66. Soil boring SB-02-78 was completed to the south of the Former Equalization Pond Area to investigate if DNAPL was present. DNAPL was observed in this boring, and analytical results from the soil samples collected from this boring show that C-56 and C-58 are the primary chlorinated compounds found in the DNAPL in this area. The DNAPL in this area is at partial saturation with a significant ratio of water in the pore space. The sum of the chlorinated organic compounds equates to less than 10,000 mg/kg which represents less than 1% of the total mass. Additional borings around the impoundment and to the south delineated the extent. No borings were drilled through the former equalization pond itself (Earth Tech, 2003).

Presently, the Former Equalization Pond Area is a restored shallow wetland area that serves as habitat for various water fowl, wading birds, amphibians and reptiles.

3.6 Contaminant Chemistry

As noted in Section 2.0, contaminants of concern at the Site include two general groups of chemicals: 1) CVOCs which include various chlorinated solvents (e.g., CT), and 2) chlorinated semi volatile organic compounds (SVOCs; e.g., C-56 and C-58).

While some chlorinated organic compounds are found in nature, they are usually in very small amounts. These compounds are mainly derived from man-made sources which are synthetically produced. The

carbon-chlorine bond is frequently difficult to break and the presence of chlorine also lessens the reactivity of other bonds in organic molecules.

While these properties may be useful for many applications, such as fire retardants, pesticide derivation, plastics, and electronics, these same properties often lead to slow degradation rates once the compound has entered the environment. Also, these compounds are generally hydrophobic, meaning they do not readily dissolve in water and are dissolved in hydrocarbon like media such as oils or fatty tissue (Baird, 1999).

Below is a summary of some physical properties of the COCs at the site.

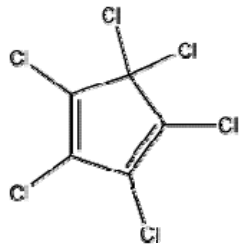
Summary of Physical Properties of COCs

Name	Molecular Formula	Molecular Weight (g/mol)	Density (g/mL)	Water Solubility (mg/L)
CT	CCl_4	153.82	1.58	793
PCE	C_2Cl_4	165.83	1.62	200
C-26	C_2Cl_6	236.74	2.09	50
C-46	C_4Cl_6	260.76	1.66	3.2
C-56	C_5Cl_6	272.77	1.70	1.8
C-58	C_5Cl_8	343.68	Not Available	Not Available
C-66	C_6Cl_6	284.78	2.04	6.2

(Dean, 1992; http://cameochemicals.noaa.gov/chemical/3558; MDEQ, 2006)

These seven compounds all have relatively low solubility in water and are denser than water.

C-56 is presented here in more detail than other site COCs due to it's toxicity, primary occurrence as DNAPL and as dissolved phase, and relatively infrequent occurrence at environmental sites of contamination. C-56 is a highly reactive and volatile substance that is used as an intermediate in chemical manufacturing processes. The main structure of C-56 is a five carbon ring with six chlorine atoms bonded to the carbons (hence the C-56 nomenclature referring to 5 carbons and 6 chlorine atoms). There are 2 double bonds between the carbons in the ring. There is no hydrogen present in this compound. A graphical representation of the structure of C-56 is shown to the right. (Cameo Chemicals website, NOAA).



C-56 is an acutely potent irritant of mucus membranes and the lungs when the vapors are inhaled. When contacted with skin, C-56 can cause burns and blisters. It also will irritate the eye if contact is made. Ingestion of the liquid is expected to cause damage to the mucosa of the esophagus and stomach. The U.S. EPA does not classify C-56 as a human carcinogen (Cameo Chemicals website, NOAA).

C-56 was produced at the site through the direct chlorination of a five carbon ring. During this reaction, a series of fully chlorinated by products also appear to have been produced. These fully chlorinated by products include the list of constituents in Section 2, all of which are completely composed of carbon and chlorine with no hydrogen atoms. These fully chlorinated compounds all have low solubilities in water, with the solubility generally decreasing with increasing molecular weight from CT being the most soluble, lightest molecule to C-56 being a much heavier molecule with solubility 440 times lower than CT. All of the fully chlorinated compounds will be soluble in non-polar solvents including a DNAPL composed dominantly of C-56 and C-58 (*Ibid*; Baird, 1999).

3.7 Contaminant Fate & Transport Modeling

The contaminant fate and transport of five of the contaminants of concern at the Site was evaluated using the U.S. EPA analytical model REMChlor (for Remediation Evaluation Model for Chlorinated Solvents) (Falta et al., 2007). These five compounds include three CVOCs – PCE, CT, and C-26 – along with two chlorinated semi-volatile organic compounds (CSVOCs) – C-56 and C-58. The evaluated areas include the four identified DNAPL residual source areas at the Site:

- Former Primary Disposal Area (within the Northern Exposure Area)
- Former Primary Ash Disposal Area (within the Northern Exposure Area)
- Former Fine Chemical Production Area (within the Central Exposure Area)
- Former Equalization Pond Area (within the Southern Exposure Area)

REMChlor is a combination of two models: a source model and a plume model. The source model serves as a time-dependent mass flux boundary condition relative to the analytical plume model, where flow is assumed to be one-dimensional. The plume model simulates first order sequential decay and production of daughter products. The decay rates and parent/daughter yield coefficients are variable functions of time and distance. This approach allows for flexible simulation of enhanced plume cleanup that may be temporary in time, limited in space, and which may have different effects on the various daughter products generated.

Model input parameters associated with the current conditions (assuming no remediation) of the Site's Upper Sand Aquifer properties, chemistry and decay rates are presented in **Appendix C** as **Tables M1**, **M2** and **M3**, respectively. These tables include parameters that are related to the aquifer (Darcy velocity and effective porosity), and are chemical specific (retardation coefficient, dispersion, decay rate). For the baseline evaluation a gamma (Γ) of 1 was assumed since a Γ of 0.5 is for DNAPL located in clean sand at a young site and a Γ of 2 represents DNAPL in clay at an older site. A Γ of 1 represents DNAPL in fine to silty sand at an average age site. Location specific parameters including source mass and concentration are presented in **Table M4** (**Appendix C**). The receptor for each of the modeling scenarios was modeled from the source area down to White Lake.

Due to the low decay rates for the CVOCs (e.g., PCE in aerobic environment) and relatively high velocity of the groundwater at the Site, the concentrations within the CVOC plumes remain relatively constant from the source areas to the receptor, White Lake. This indicates that little natural attenuation is occurring, as observed in the monitoring well data. The model output confirms the low decay rate observed for the CVOCs because the modeled concentration within the plume remains fairly constant from the source area to the receptor. This is consistent with the current conditions that are observed at the Site.

A significant input variable in the model to predict dissolution of the DNAPL is the actual mass of DNAPL present at each location. The mass estimates used are from the Phase II DNAPL Investigation (Earth Tech, 2003). These estimates include uncertainty. The estimates were developed by calculating the volume of the aquifer where DNAPL is present and assuming that these volumes had the concentrations of constituents present in the samples of the aquifer material that were analyzed during investigations at the site. The controls on the volume of aquifer are presented in the Phase II report, which documents the borings that define the boundaries of the DNAPL areas and also the estimated extent of DNAPL used for these estimates. It should be noted that, while the extent of DNAPL has been defined by perimeter borings, the estimated extent of DNAPL could have been drawn at a number of alternate boundaries, and the estimates of the extent of DNAPL, and therefore the mass of DNAPL, are subject to significant uncertainty.

A discussion of DNAPL dissolution modeling is presented for each residual source zone. Graphs of the model output for each of the contaminants of concern at the 4 residual source areas are provided as attachments within **Appendix C**. A summary of the results is presented as **Table M5** in **Appendix C**. A discussion of the REMChlor Model and model calibration is presented in Section 3.7.5 and also included

in **Appendix C**. Please also refer to the Table of Contents explaining sub-appendices within **Appendix C**.

3.7.1. Former Primary Disposal Area

Gamma (Γ) of 1 was assumed as base line for modeled scenarios presented below. The calculated maximum time for the plume generated from the Former Primary Disposal Area to reach the required cleanup criteria is over 10,000 years. Individual compounds ranged from 308 years for CT to greater than 10,000 years for C-56 and C-58. The maximum mass of these three compounds also occurred in the Former Primary Disposal Area compared to the other three identified DNAPL source areas. C-26 (hexachloroethane) and PCE required 355 and 1540 years, respectively to reach their respective cleanup criteria. Due to the large retardation coefficients and rapid decay rates for C-56 and C-58, the plumes for these two compounds were limited to within several hundred meters of the source area.

3.7.2. Former Primary Ash Disposal Area

Gamma (Γ) of 1 was assumed as base line for modeled scenarios presented below. The calculated maximum time for the plume generated from the Former Primary Ash Disposal Area to reach the required cleanup criteria is 1480 years. Individually, the source of C-56 and C-58 was estimated to reach cleanup criteria in 1,365 and 1,480 years, respectively. As discussed previously, the large retardation coefficients and rapid decay rates for C-56 and C-58 limited the plume lengths for these two compounds to within several hundred meters of the source area. No source mass was observed for the CVOCs (PCE, CT and C-26), therefore, no calculations were performed for these compounds in this area.

3.7.3. Former Fine Chemical Production Area

Gamma (Γ) of 1 was assumed as base line for modeled scenarios presented below. The calculated maximum time for the plume generated from the Former Fine Chemical Production Area to reach the required cleanup criteria is 6,900 years. The Former Fine Chemical Production Area is one of the largest DNAPL areas and contains the maximum mass for PCE and C-26. The calculated time for the plume to reach the cleanup criteria from the Former Fine Chemical Production area ranged from 174 years for PCE to 6,900 years for C-56. The *sigmav* parameter was increased to produce a higher dispersivity (x/20) for PCE to determine the sensitivity in the model to this parameter. The result was only an increase of 2 years, from 174 to 176 years, indicating that the model is not sensitive to dispersivity for this solution. C-26 and C-58 required 810 and 2,090 years, respectively to reach their respective cleanup criteria. CT was not calculated due to the small source mass (less than 1 kg).

3.7.4. Former Equalization Pond Area

Gamma (Γ) of 1 was assumed as base line for modeled scenarios presented below. The calculated maximum time for the plume generated from the Former Equalization Pond Area to reach the required cleanup criteria is 1,220 years. In the Former Equalization Pond Area the cleanup times were only calculated for PCE (440 years) and C-56 (1,220 years). The concentration of C-58 did not exceed the cleanup criteria and there was little to no source mass (less than 1 kg) to calculate cleanup times for CT and C-26. The estimated mass at the Former Equalization Pond Area has significant uncertainty due to the uncertainty on the exact location of the extent of DNAPL under the Former Equalization Pond. As discussed in Section 3.7, the extent of DNAPL is directly related to the estimate of the mass of DNAPL under the Former Equalization Pond Area. As presented in the Phase II DNAPL report (Earth Tech, 2003), borings surround the Former Equalization Pond that document that the extent of DNAPL is defined – given that information, an estimate of the extent of DNAPL was provided in the figures in the DNAPL Phase II report, and this estimated area was used to calculate the mass of DNAPL and, therefore, the time required to meet cleanup time frames. At the Former Equalization Pond Area, there is significant uncertainty that the DNAPL area could be larger than the estimated area due to the lack of borings under the impoundment which is still present at the site. This uncertainty would lead to longer estimated time frames for the baseline, and all alternate scenarios evaluated for the Former Equalization Pond Area.

3.7.5. Model Calibration and Sensitivity Analysis

A sensitivity analysis was performed for the model. The gamma and dispersivity were evaluated. In general, REMChlor modeling simulated that CVOC plumes would quickly reach White lake with similar concentrations extending from the residual source areas towards the lake due to little retardation and degradation. C-56 is predicted to not travel far due to degradation (due to fast hydrolysis half-life), while C-58 moves slower, but also decays rapidly resulting in limited plumes developing. These predicted behaviors are confirmed with field observations. Likewise, PCE and CT exhibit classic elongate plume morphology as seen in observed field data (CRA, 2009). The model calibration and in-depth sensitivity analysis summary is included in **Appendix C.**

4.0 GROUNDWATER RESTORATION POTENTIAL

GSH has evaluated the potential to restore groundwater at the site by achieving the cleanup criteria throughout the plume. This evaluation of groundwater restoration potential considered how remedies such as treatment or removal of contaminant source areas would potentially improve groundwater quality at a site and was based on a thorough understanding of how contaminants are emplaced at a site and where source areas are located. This section presents GSH's understanding of residual source areas, historical and on-going remedy analysis, and predictive modeling to estimate groundwater cleanup for various remedy alternatives.

4.1 Source Area Delineation Justification

Identified residual sources areas have been fully delineated at the Site. Historically, source areas were identified in the MICJ, UAO and Final Decision, and numerous remedial investigations were performed over a 30 year period to better define the extent of contamination and DNAPL zones at the Site. The "Guidance for Evaluating the Technical Impracticability of Ground-Water Restoration" (September 1993) defines three areas to delineate at a DNAPL site are the (1) DNAPL entry locations, (2) the DNAPL Zone, and (3) the aqueous contaminant plume.

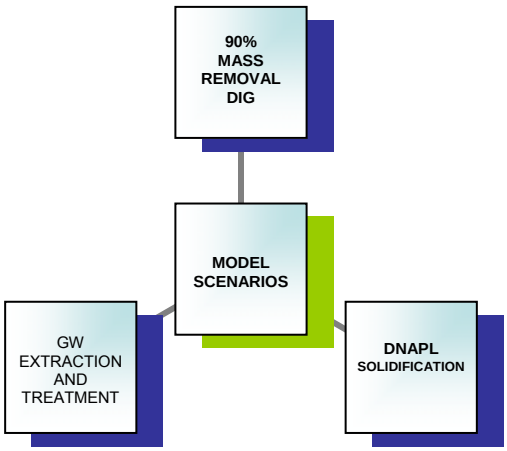
At the Site, the historical DNAPL entry locations from surface spills, near-surface waste disposal and drum disposal (Sections 1.3 and 1.4 of this report) were well-documented in the MICJ, and the DNAPL entry points within the vadose zone were removed through focused excavations performed in the 1980s. Subsequent to those removals, several additional investigations (**Table 2**) were performed to characterize site conditions and to evaluate exposures and risks at the Site.

Two separate investigations performed in 2002 and 2003 specifically focused on defining the extent of DNAPL within the four residual source areas (Earth Tech, 2002a and 2003). Residual DNAPL source areas have been defined both vertically and laterally and are presented as **Figure 4.** Area-specific cross sections are presented in **Appendix A**. These investigations identified the presence of DNAPL through the use of oil-in-soil kits when UV fluorescence and other methods were not effective on the DNAPL at this site. The extent of DNAPL has been defined with borings, though some residual NAPL may still exist in small areas outside of the identified areas.

The aqueous contaminant plume is defined through wells installed specifically for this purpose. The plume is stable and not expanding, and the monitoring system has been developed and deployed for this demonstration. The established plume boundaries are presented as **Figure 13**.

4.2 On-Going Remedy Analysis

This evaluation includes the evaluation of in situ and ex situ remedial alternatives. The in situ remedy types considered to be potentially applicable at the site included chemical, biological, physical, and containment methods. The ex situ remedy considered was excavation and disposal. In situ remedies which were evaluated but not retained for further consideration at the site included Fenton's reaction chemical oxidation, persulfate chemical oxidation, permanganate oxidation, ozone chemical oxidation, zero valent iron (ZVI) reductive dechlorination, enhanced reductive dechlorination (ERD) (biological), surfactant enhanced aquifer remediation, thermal desorption, NAPL extraction, and isolation. Remedies which were not retained for further consideration were screened out due to their apparent lack of effectiveness as described in further detail in Section 5.0. The containment remedy is specifically described in Section 5.5.



The remedies retained for detailed analyses included excavation with landfill disposal, in situ solidification (ISS) (DNAPL remediation) and groundwater extraction and treatment (groundwater treatment). Excavation with disposal is detailed in Section 6 and ISS is detailed in Section 7. Groundwater extraction and treatment is included in Section 8.

4.3 Cleanup Timeframe Analysis

In addition to evaluating baseline conditions at the site using the REMChlor model, discussed previously, alternate cleanup timeframe scenarios were also evaluated.

To simulate the solidification or isolation of the DNAPL at the site, the Γ was increased from 1 to 2 for all five of the compounds to simulate DNAPL within clay or solidified matrix. This simulates a potential source solidification remedy or cutoff where the source permeability is reduced. This scenario represents either source zone isolation or solidification of DNAPL mass.

To simulate the excavation and removal of DNAPL impacted aquifer material at the site, an evaluation was performed by removing 90% of the source DNAPL within a two year period and using a Γ of 1 as was used in the baseline evaluation.

Graphs of the model output for each of the evaluation scenarios of increased Γ, and source removal for each COC at each of the 4 residual source areas are provided in the appendices within **Appendix C**. A summary of the results is presented as **Table M5** in **Appendix C** and discussed below.

4.3.1. Former Primary Disposal Area

The alternate scenarios were evaluated and the time required to achieve cleanup at the Former Primary Disposal Area were calculated:

Years to Achieve Cleanup Criteria	Existing Condition	Solidification	(90%) Removal
Carbon Tetrachloride (CT)	308	1230	210
Tetrachloroethene (PCE)	1540	3800	890
Hexachloroethane (C-26)	355	510	160
Hexachlorocyclopentadiene (C-56)	>10000	>10000	4900
Octachlorocyclopentene (C-58)	>10000	>10000	79

4.3.1.1. Solidification or Reduced Permeability

With the Γ parameter increased to 2 to simulate the solidification of the DNAPL into a less permeable matrix, the overall time to achieve cleanup criteria remains at greater than 10,000 years. The C-56 and C-58 cleanup times remained greater than 10,000 years and the times increased for PCE, CT and C-26 increased to 3,800, 1,230 and 510 years, respectively. This increase is due to the longer time that these residual contaminants will remain in the source area.

4.3.1.2. Source Removal

Even with a removal of 90% of the mass of the DNAPL from the Former Primary Disposal Area, the maximum estimated time frame was still 4,900 years. The cleanup time for C-56 and C-58 was reduced to 4,900 and79 years, respectively. The cleanup timeframes for PCE, CT and C-26 were calculated at 890, 210 and 160 years, respectively.

4.3.2. Former Primary Ash Disposal Area

The alternate scenarios were evaluated and the time required to achieve cleanup at the Former Ash Disposal Area were calculated:

Years to Achieve Cleanup Criteria	Existing Condition	Solidification	(90%) Removal
Carbon Tetrachloride (CT)	NA	NA	NA
Tetrachloroethene (PCE)	NA	NA	NA
Hexachloroethane (C-26)	NA	NA	NA
Hexachlorocyclopentadiene (C-56)	1365	1035	12
Octachlorocyclopentene (C-58)	1480	890	45

4.3.2.1. Solidification or Reduced Permeability

With the Γ parameter increased to 2 to simulate the solidification of the DNAPL into a less permeable matrix, the overall time to achieve cleanup criteria was reduced from 1,480 years to 890 years. An increase in time is typically observed with an increase in the Γ parameter, as seen in the other areas; however, the combination of low contaminant mass/area, rapid decay and relatively low initial concentration of the C-56 and C-58 compounds results in a decrease in time with an increase in the Γ parameter.

4.3.2.2. Source Removal

With ninety percent of the source removed, the timeframe for cleanup was significantly reduced for C-56 and C-58. The cleanup time for C-56 and C-58 was reduced to 12 and 45 years, respectively. Therefore, this reduction will do little to affect the time required for the overall dissolved plume at the site to achieve cleanup criteria. This source area is not a significant contributor to the overall VOC dissolved plume so no modeling was performed for the VOC fractions.

4.3.3. Former Fine Chemical Production Area

The alternate scenarios were evaluated and the time required to achieve cleanup at the Former Fine Chemical Production Area were calculated:

Years to Achieve Cleanup Criteria	Existing Condition	Solidification	(90%) Removal
Carbon Tetrachloride (CT)	NA	NA	NA
Tetrachloroethene (PCE)	174	1700	138
Hexachloroethane (C-26)	810	1720	445
Hexachlorocyclopentadiene (C-56)	6900	8500	1980
Octachlorocyclopentene (C-58)	2090	1200	36

4.3.3.1. Solidification or Reduced Permeability

With the Γ parameter increased to 2 to simulate the solidification of the DNAPL into a less permeable matrix, the overall time to achieve cleanup criteria increased from 6,900 years to 8,500 years. With the exception of C-58, the cleanup timeframe increased from the baseline for all constituents. This increase is due to the longer time that these residual contaminants will remain in the source area. As discussed previously, the combination of low contaminant mass/area, rapid decay and relatively low initial concentration of C-58 results in a decrease in time with an increase in the Γ parameter.

4.3.3.2. Source Removal

By removing 90 percent of the source mass, the maximum cleanup time was reduced from 6,900 years to 1,980 years. However, 1,980 years is still a significant period of time, and this reduction is not significant when establishing remedial objectives for time scale.

4.3.4. Former Equalization Pond Area

The alternate scenarios were evaluated and the time required to achieve cleanup at the Former Equalization Pond Area were calculated:

Years to Achieve Cleanup Criteria	Existing Condition	Solidification	(90%) Removal
Carbon Tetrachloride (CT)	NA	NA	NA
Tetrachloroethene (PCE)	440	440	40
Hexachloroethane (C-26)	NA	NA	NA
Hexachlorocyclopentadiene (C-56)	1220	1440	280
Octachlorocyclopentene (C-58)	NE	NE	NE

4.3.4.1. Solidification or Reduced Permeability

With the Γ parameter increased to 2 to simulate the solidification of the DNAPL into a less permeable matrix, the maximum overall time to achieve cleanup criteria increased from 1,220 years to 1,440 years. This increase is due to the longer time that these residual contaminants will remain in the source area.

4.3.4.2. Source Removal

With ninety percent of the source mass removed, the maximum timeframe for cleanup was reduced from 1,220 years to 280 years.

4.3.5. Cleanup Timeframe Analysis Conclusion

If the remedial technologies were practically implementable, overall the maximum time required to achieve the current groundwater cleanup criteria were estimated to be reduced from over 10,000 years to 4,900 years using the best scenario from the solidification and source removal approaches.

5.0 RELEVANT TECHNOLOGIES

Technologies that have the potential to treat chlorinated DNAPL were evaluated for use at the Site to determine if it was feasible and practical to expedite achieving the groundwater cleanup goals at the Site. The highest inputs to the dissolved groundwater plume are the DNAPL zones discussed above. To expedite groundwater cleanup, these DNAPL areas must be treated, removed, or isolated from the groundwater.

GSH presented a preliminary review and screening of the viable remedial approaches in the Phase I DNAPL Report (Earth Tech, 2002a) and the Phase II DNAPL Report (Earth Tech, 2003). The screening addressed the unique composition of the DNAPL (mostly C-56 and C-58) and the distribution of the DNAPL in the upper third of a sand aquifer. Technologies with the potential to treat the DNAPL in-situ were further evaluated through a series of bench and pilot studies. In addition, fundamental characteristics of C-56 and C-58 were also further documented during the second phase of bench studies.

Following the screening activities, GSH conducted bench tests for four technologies on DNAPL impacted materials obtained from the Site. Nationally recognized leaders in the treatment of DNAPL were utilized to screen individual technologies and perform bench studies on materials from the Site to determine if the technologies would be effective in removing C-56 and C-58 DNAPL in the soil and also if the technology would be feasible to implement at the Site. Dr. Frank Loeffler at Georgia Institute of Technology was contracted to conduct the bench study on bioremediation and evaluated biostimulation and bioaugmentation. Kerfoot Technologies, Inc. performed bench studies on the use of ozone to treat the DNAPL. Toxicological & Environmental Associates, Inc. conducted bench tests evaluating the use of ZVI – the method used the emulsified zero valent iron (EZVI) technology developed and patented by the National Aeronautics and Space Administration (NASA). Dr. Richard Watts, a professor in the Department of Civil and Environmental Engineering at Washington State University, performed bench studies on the use of hydrogen peroxide using Fenton's Reagent on samples from the Site. The methods, results and conclusions from these studies are presented in Earth Tech, 2005a.

Further bench tests were performed to address analytical and mass balance issues identified in the first round of bench tests. Ann Arbor Technical Services (ATS), a specialty chemistry consulting and laboratory firm, was contracted to help design and then to implement the studies. The bench and analytical work performed by ATS addressed basic issues related to C-56 and C-58 such as laboratory repeatability, modification of standard U.S. EPA methods to support the analysis of C-56 and C-58, determination of hydrolysis rates, and an air stripping study. Bench studies on in-situ chemical oxidation (ISCO) evaluated multiple oxidants at different temperatures, including persulfate, peroxide and persulfate, and peroxide with an iron catalyst. The methods, results and conclusions from these studies are presented in Earth Tech, 2006a.

Two parallel pilot tests were performed at the site in 2005 using ISCO to treat the DNAPL in place by adding either ozone and hydrogen peroxide or hydrogen peroxide with an iron catalyst (Earth Tech 2006b). Neither ozone sparging nor hydrogen peroxide with an iron catalyst significantly reduced the amount of the major constituents in the DNAPL (C-56 and C-58).

An additional pilot test for ERD of the DNAPL and the dissolved phase was performed on ERD in 2007 (Brown and Caldwell, 2008). This test included biostimulation and bioaugmentation in the aquifer at the Site.

This section presents an overview of the technologies evaluated and screened in this TI evaluation. The following presentation builds on the work completed over the last eight years since the Final Decision was published. This presentation is not intended to be a complete presentation of this material, and the reader is referred back to the reports on the investigations, bench studies, and pilot studies. A summary of the evaluation of relevant technologies is presented in **Table 5**. Four general technology groups were evaluated and include: 1) chemical methods, 2) biological methods, 3) physical treatment, and 4) containment methods. Technologies are evaluated for effectiveness and feasibility:

1. Effectiveness – The ability of the technology to reduce concentrations of contaminants in groundwater, as well as to reduce residual DNAPL mass, such that Site cleanup criteria can be achieved in a significantly expedited but "reasonable" timeframe.

2. Feasibility – From an engineering perspective, the ability to implement a potentially effective technology at the Site, considering such factors as reliability, complexity, exacerbation potential, and risks to humans and the environment.

5.1 In-Situ Chemical Oxidation (ISCO)

ISCO is a process by which strong oxidizing agents are injected into the subsurface to convert hazardous contaminants into non-hazardous or less hazardous forms. Because oxidizing agents generally degrade very quickly, successful delivery and distribution of oxidizing agents through the treatment zone is a key component to successful ISCO application. While ISCO is an effective means of treatment for many organic compounds, some contaminants are resistant to chemical oxidation (Federal Remediation Technologies Roundtable (FRTR), 2009). Multiple oxidizing agents that create highly oxidizing radicals have been evaluated for potential use at the OCC Site, including Fenton's reagent, ozone, and persulfate.

5.1.1. Fenton's Reagent

Fenton's reagent is a solution of hydrogen peroxide and ferrous iron (Fe^{2+}) in which the iron catalyzes the formation of the hydroxyl radical (OHB). The hydroxyl radical is a very strong oxidant. It is relatively non-selective and capable of degrading most organic contaminants. Reagents are typically introduced to the subsurface by either pressure or gravity injections. Treatment generally involves multiple injection events separated by periods of extended groundwater monitoring (FRTR, 2009; U.S. EPA, 2004a).

Fenton's reaction occurs exothermically and results in increased temperatures, steam production, and a significant increase in pressure induced upon the surrounding formation. In deep vadose zones or in deep monitoring and injection wells, explosive conditions are possible in the presence of significant organic mass. This is a significant safety concern that must be very closely monitored and managed. There have been several incidents involving spontaneous subsurface explosions during treatment with Fenton's reagent (U.S. EPA, 2004a).

Site-specific treatment with Fenton's reagent was evaluated in bench scale and pilot scale applications. Dr. Richard Watts of Washington State University performed bench studies on DNAPL-impacted samples from the Site. Dr. Watts was selected based on his technical background and extensive research on Fenton's reagent. While the concentrations of C-56 and C-58 decreased significantly in the bench tests, the concentration of chloride in the remaining aqueous solution only increased 1% of the expected value to achieve mass balance with the complete mineralization of the total chlorinated organic compounds removed, suggesting that Fenton's reaction was preferential (Earth Tech, 2005a). Additional bench tests using hydrogen peroxide were attempted by Ann Arbor Technical Services (ATS) using closed systems, but the pressure buildup caused the reaction vessels to rupture and the ATS bench tests on Fenton's reagent were terminated early (Earth Tech, 2006a).

Fenton's reagent was further evaluated in the field with a pilot test. The pilot test failed to significantly reduce the amount of C-56 and C-58 in the DNAPL-impacted soils. Furthermore, the Fenton's reagent injections increased the temperature in the aquifer from a baseline temperature around 10°C to over 50°C (Earth Tech, 2006a). The increased temperatures are a concern because the DNAPL can be mobilized at elevated temperatures. The viscosity and surface tension of the DNAPL are expected to change at increased temperature and the DNAPL may be mobilized into the lower portions of the aquifer, exacerbating the current problem. The pilot study concluded that oxidants reached all three of the confirmation borings, indicating that oxidant delivery was not a limitation in the study. Therefore, activities to enhance the permeability of the formation, such as pneumatic or hydraulic fracturing, would not be needed. There were also issues in the control samples that were attributed to mobilization during the pilot study implementation. During the pilot study, a control area was located near the pilot test where no treatment was performed – the concentrations of CVOCs increased in the control plot indicating that

these volatile organic compounds may have been mobilized by the heat generated during the performance of the pilot study.

Based on the negative results of both bench-scale and pilot studies, and the risks associated with the technology, Fenton's reagent is not retained as an effective technology at the Site.

5.1.2. Persulfate

The persulfate anion is a strong oxidant capable of destroying organic contaminants. Persulfate salts dissociate in water to produce the persulfate anion; persulfate salts include ammonium persulfate, potassium persulfate, and sodium persulfate. Potassium persulfate has a low solubility and ammonium persulfate may lead to increased ammonia concentrations in groundwater, so sodium persulfate is the salt most commonly used. The persulfate anion is more stable in the subsurface than either ozone or hydrogen peroxide, and it is not highly sorptive. Therefore, it is able to remain in the subsurface for weeks. Additionally, the density of a sodium persulfate solution may be greater than water, enabling it to be transported in the subsurface by both density-driven and diffusive means, thus increasing its ability to effectively reach target contaminants (U.S. EPA, 2006).

Bench studies performed by ATS also evaluated chemical oxidation using persulfate (Earth Tech, 2006a). The studies evaluated persulfate with no pH buffer, persulfate at buffered pHs and persulfate enhanced with peroxide. Persulfate was not utilized in the pilot test due to the higher reactivity and performance of ozone and Fenton's reagent. Another complication with persulfate is the large mass of salts (sulfate) that would remain after treatment.

5.1.3. Permanganate

Permanganate is an oxidizing reagent that may be used for the in-situ remediation of organic compounds. Permanganate is available as either potassium permanganate or sodium permanganate. Permanganate has been shown to successfully remediate a variety of organic compounds, such as trichloroethene (TCE), tetrachloroethene (PCE), dichloroethene (DCE), and vinyl chloride (VC). However, there are several organic compounds that studies have found to be recalcitrant to permanganate treatment, including 1,1,1-trichloroethane (TCA), 1,1-dichloroethane (DCA), chloroform, methylene chloride, chlorobenzene, benzene, PCBs, some pesticides, and carbon tetrachloride (CT), among others (U.S. EPA, 2006). Carbon tetrachloride is a significant component of the dissolved plume at the Site, and the documented inability of permanganate to treat this COC indicates it would not be an effective technology for the Site.

Permanganate has a relatively slow reaction rate, as compared to other ISCO reagents. This allows the permanganate to remain in the subsurface longer and may increase delivery effectiveness (U.S. EPA, 2006). However, pilot studies conducted for Fenton's Reagent at the Site indicated that delivery was not a limitation, so the slower reaction rate of permanganate is not likely to offer any advantage at the Site over the stronger oxidants that were evaluated. Furthermore, solid manganese dioxide is a byproduct of the permanganate reaction, and has been well documented to accumulate at the groundwater-NAPL interface. These accumulations may inhibit mass transfer between reagents and COCs and also may reduce permeability of aquifer media (U.S. EPA, 2006).

Another concern with permanganate application is the potential addition, oxidation, and mobilization of metals in the subsurface. Both sodium permanganate and potassium permanganate contain impurities, with chromium and arsenic generally being the impurities of greatest concern. Furthermore, oxidation of trivalent chromium to the more toxic form of hexavalent chromium, as a result of permanganate treatment, has been demonstrated in the laboratory. In addition, other heavy metals that are sensitive to pH or redox conditions may be mobilized under the altered conditions (U.S. EPA, 2006). Although these conditions have been shown to return to pre-treatment conditions through natural attenuation, the increase or mobilization of metals during permanganate application is a risk that would need to be closely monitored.

In summary, it has been documented that permanganate oxidation does not effectively treat carbon tetrachloride, which is a significant COC in the dissolved plume at the Site. Permanganate offers no distinct advantage over the other oxidizing agents that have been evaluated in bench studies and pilot studies at the site, so it is highly unlikely that permanganate would result in complete mineralization of C-56 or C-58, the primary constituents of the DNAPL source material. Furthermore, the possible addition, transformation, or mobilization of metals as a result of permanganate application would introduce new risks at the Site. For these reasons, permanganate oxidation is not retained as an effective or feasible technology.

5.1.4. Ozone

Ozone may be used for the in-situ remediation of impacted material in aquifers by sparging ozone gas through the aquifer into or below the AOC. Ozone oxidizes contaminants as it passes through the impacted material. Because ozone is highly reactive and corrosive to most delivery systems, it must be generated on-site. This is accomplished using electrical generators to produce ozone from ambient oxygen (U.S. EPA, 2006). In order to reach contaminants before decomposing, sparge wells typically must be closely spaced. A vapor control system generally must be implemented in conjunction with ozone treatment to prevent gasses or byproducts from damaging subsurface utilities or escaping to the surface as fugitive emissions (U.S. EPA, 2004a).

Ozone was evaluated for use at the Site in bench scale and pilot scale tests. Kerfoot Technologies, Inc. performed the initial bench tests on the DNAPL-impacted material using procedures they had evaluated on other impacted soil columns. These results were difficult to interpret due to the reduction in C-56 and C-58 in the control samples. There was a decrease in C-56 and C-58 in the actual samples, and paired comparisons showed more reduction with higher dose. However, the lack of a stable control sample made the results questionable, and the lack of adequate chloride produced in the system indicated that ozone may not remove significant chlorine atoms from the chlorinated compounds (Earth Tech, 2005a).

Ozone was further evaluated in a full scale field application in combination with the injection of hydrogen peroxide. The ozone sparge system failed to significantly reduce the amount of C-56 and C-58 in the DNAPL zones. While the ozone appears to have reduced the concentrations of CVOCs and chlorinated SVOCs present below a clay layer that retains some DNAPL, the ozone was not able to be applied to the top of the clay layer where the DNAPL is preferentially located (Earth Tech, 2006a). The ability to facilitate contact between gas-phase ozone and DNAPL was a limitation in this study, especially where the DNAPL is preferentially retained or disseminated on thin silt and clay layers. In theory, hydraulic or pneumatic fracturing would not necessarily improve the contact between the gas phase ozone and the DNAPL, and could potentially mobilize DNAPL. If the fractures provide a preferred flow path for the gas phase, the ozone would have a tendency to channel within the fractures. Disruption of the soil fabric would also potentially mobilize DNAPL.

In summary, ozone treatment was evaluated in a bench-scale study and a pilot study at the Site. Results from these studies documented that ozone was unable to treat DNAPL compounds at the Site. Therefore, ozone is not retained as an effective treatment technology.

5.1.5. ISCO Conclusion

Multiple strong oxidants have been evaluated as potentially applicable treatment technologies, including Fenton's reagent, hydrogen peroxide, persulfate, and ozone. In bench-scale and/or pilot-scale studies at the Site, each of these strong oxidants has failed to effectively treat the DNAPL constituents in a safe manner. While a significant decrease in the parent compounds (C-56 and C-58) was observed in some of the evaluations, chloride concentrations measured before and after treatment are not consistent with these reductions in the parent compounds if complete mineralization was achieved. This strongly suggests that the compounds are not completely mineralized, and are instead converted to intermediate degradation products. As such, a significant concern in attempting to implement these technologies is the creation of intermediate degradation products of which the fate, transport, and associated risks cannot be fully assessed (Earth Tech, 2005a).

Based on these studies, ISCO application at the Site is not likely to result in a significant decrease in the mass of source material, and would consequently fail to significantly reduce the clean-up timeframe at the Site. For these reasons, ISCO is not retained as an effective technology.

Because ISCO reactions liberate heat, DNAPL mobilization, both vertically (deeper into the upper sand aquifer or into deeper aquifer zones) and laterally is deemed a potential exacerbation concern, which could potentially induce additional exposure risks at the Site.

5.2 Other Chemical Technologies: Zero Valent Iron (ZVI) Reductive Dechlorination

ZVI is a technology that can be effective in treating some chlorinated organic compounds, especially chlorinated ethenes such as TCE. The technology has also been applied to DNAPL (Geiger, et al., 2001). The National Aeronautics and Space Administration (NASA) has developed a technology using EZVI. EZVI consists of an emulsion of oil in water, with nanoscale iron particles contained within the emulsion droplets. The oil membrane protects the ZVI from contacting the water before it reaches the DNAPL, and then allows the DNAPL to diffuse through metal oxidation. The oxidation reaction produces molecular hydrogen that can be used as an electron donor source to bio-stimulate indigenous microorganisms to reductively dechlorinate aqueous phase solvent contamination (Earth Tech, 2005a).

In 2004, a bench study was performed to evaluate the treatment of the DNAPL with ZVI. Studies on the behavior of C-56 and C-58 in the presence of ZVI were not available prior to the investigations related to this Site. The bench study utilized nano-scale iron particles contained in an oil-water emulsion (EZVI), following the patented method developed by NASA. Toxicological & Environmental Associates, Inc. was the licensed contractor that implemented the pilot study on samples from the Site. The study showed reductions in the concentrations of C-56 and C-58 in the treated samples, though the response to the treatment did not have a consistent response to dose. The dose of EZVI was in excess of the design dose since the samples were not fully saturated with DNAPL, so the dose should not have been a limiting factor. The concentration of chloride generated by the bench test documented that the EZVI did not completely dechlorinate the C-56 and C-58, but instead created intermediate chlorinated products. A mass balance of chloride ions in the treatment systems suggested that an average of only one chlorine molecule was liberated from each molecule of C-56 and C-58 removed. Incomplete reaction byproducts are documented in ZVI systems on smaller molecules such as CT, and this incomplete mineralization of C-56 and C-58 suggested that other chlorinated byproducts remained in the samples (Earth Tech, 2005a).

As with ISCO technologies, results from testing strongly suggest that C-56 and C-58 are not completely mineralized by EZVI, and are instead converted to intermediate degradation products. A significant concern in attempting to implement this technology is the creation of these intermediate degradation products of which the fate, transport, and associated risks cannot be fully assessed (Earth Tech, 2005a).

Based on the documented inability of ZVI to mineralize DNAPL compounds, ZVI is not retained as an effective treatment technology.

5.3 Biological: In Situ Enhanced Reductive Dechlorination (ERD)

Biological treatment techniques refer to technologies by which microorganisms are stimulated to use contaminants as a food source, thereby degrading them. The process involves providing favorable conditions for the microorganisms by supplying them with oxygen or nutrients, or by adjusting local environmental conditions such as pH, temperature, or moisture. Biodegradation may be further enhanced by augmenting the local microbial populations with microorganisms specifically adapted to degrade the applicable contaminants of concern (FRTR, 2007).

ERD is an in-situ remediation technology that has been successfully applied in the treatment of lower molecular weight chlorinated organic compounds, such as chlorinated ethenes (e.g., PCE). This approach exploits naturally occurring bacteria that utilize the chlorinated organic compounds as favorable electron acceptors for energy generation (chlororespiration). The rate and extent of dechlorination that can be accomplished by chlororespiration depend on the Site geochemical conditions, a sustained and

adequate supply of reducing equivalents, and the density of suitable dechlorinating microbial populations. Little is known about the microbial populations that use C-56 and C-58 as growth-supporting electron acceptors (Earth Tech, 2005a).

In 2004, Dr. Frank Loeffler of Georgia Institute of Technology performed bench studies on the DNAPL-impacted soil from the Site. These bench studies included both biostimulation and bioaugmentation. The study showed that dehalococcoides are present in low numbers in soil from within the aquifer. PCE and TCE were not degraded by indigenous organisms in microcosm spiked with PCE and TCE, even when nutrients were added. The Site soil also inhibited degradation of PCE in a bioaugmentation and contaminant-spiked sample. Additionally, degradation gases ethene and ethane were not observed. C-56 and C-58 were lost in the autoclave control samples and all other reactors including controls, so no analytical data was available for C-56 and C-58. These bench studies concluded that a combination of the Site constituents and conditions were not appropriate for ERD (Earth Tech, 2005a).

A pilot study was performed for ERD by Brown and Caldwell in 2007. Studies were performed both in a source area and in an immediately down gradient portion of the dissolved groundwater plume. Although proper conditions were maintained throughout the test for oxidation potential and nutrient concentrations, there was no degradation of CT or PCE in the source zone. There was evidence of partial reductive dechlorination of CT and PCE in the dissolved phase down gradient of the source zone; however, results indicated that full degradation was not achieved. The 2007 field pilot studies concluded that site conditions preclude reductive dechlorination from occurring in source areas, and that ERD is unlikely to meet the clean-up goals for the dissolved portion of the plume (Brown and Caldwell, Inc., 2008).

Based on the results of these studies, ERD is not retained as an effective technology.

5.4 Physical

Physical methods refer to a wide variety of technologies by which contaminates are physically removed or treated. These technologies may involve altering the physical properties of contaminates to facilitate more effective removal, such as thermal desorption or surfactant enhance technologies. Physical methods also include any method by which contaminants are removed by more conventional means, such as excavation and disposal.

5.4.1. Excavation, Ex-Situ Treatment and Removal

Ex-situ remediation technologies refer to any method by which contaminated soil is removed and treated above ground and/or disposed. This includes such processes as landfill disposal, ex-situ thermal treatment, ex-situ stabilization/solidification, and soil washing. Excavation and disposal would offer a potentially effective means for the remediation of source areas at the Site. The practicability of implementing this technology is further evaluated in Section 6.

5.4.2. Surfactant Enhanced Aquifer Remediation (SEAR)

Surfactant Enhanced Aquifer Remediation (SEAR) is a technology in which soils containing DNAPL are flushed with a surfactant to increase the solubility of the DNAPL in groundwater, thereby enabling it to be recovered through a pump and treat system. SEAR has been most widely used to remediate chlorinated hydrocarbon DNAPL, such as TCE and PCE, and has also been used to treat contaminants such as creosote, gasoline, jet fuels, and polychlorinated biphenyls (Navel Facilities Engineering Command NAVFAC, 2002).

Surfactant enhanced aquifer remediation (SEAR) was identified in the Phase I DNAPL investigation report (Earth Tech, 2002a) as a potentially feasible technology. Based on the distribution and composition of the DNAPL presented in the Phase II DNAPL investigation report (Earth Tech, 2003), SEAR was eliminated as a potential remedial approach. One consideration in the removal of SEAR as a feasible alternative was the very low solubility of C-56 and C-58. If the solubility of C-56 was increased 1,000 times in the surfactant flood, then the effective solubility of C-56 in the surfactant would be 1,800 mg/L. This is still a very low solubility – similar to the solubility of TCE in groundwater without a surfactant (1,100 mg/L).

At these low solubilities, it would be difficult to remove sufficient DNAPL from the aquifer through flushing to significantly reduce the time required to achieve groundwater cleanup. In addition, the position of the DNAPL on thin silt and clay layers within the aquifer also increases the risk of mobilization of the DNAPL. Surfactants change the surface tension of the DNAPL in solution and can increase the mobility of the DNAPL in the sandy aquifer. Since there is still a significant thickness of clean sands underneath the DNAPL zones, the increased risk of spreading the DNAPL must be balanced against any potential gain in expediting cleanup. The current groundwater collection and treatment system has the dissolved plume contained – spreading the DNAPL may alter this capture (AECOM, 2008a). Therefore, SEAR is not retained as an effective remediation technology for the Site.

5.4.3. Thermal Technologies

In-Situ Thermal technologies apply heat to impacted soil to increase volatilization of volatile organic compounds, such that they can be concurrently recovered and treated with a soil vapor extraction (SVE) system. In order to heat soils to temperatures exceeding 100°C, any groundwater present must first be evaporated. If the target treatment area is below the water table, as is the case at the OCC Site, dewatering is required. In 2008, AECOM conducted a detailed evaluation of the feasibility of implementing ISTD at the Site (AECOM, 2008b).

When C-56 is treated with ISTD or otherwise thermally altered, it results in a significant production of HCl and chlorine gas. Exposure to hazards in the breathing zone are a risk and safety concern for ISTD treatment of C-56 DNAPL at the Site. C-56, as well as other constituents in the DNAPL, have restrictions on the concentration in the ambient air that is safe to breath. There are potential scenarios, such as failure of the dewatering pumps, where large volumes of gas would pressurize the subsurface, forcing gas out of the subsurface and also through the SVE system. There are potentials for exposure to gaseous HCl and chlorine gas, as well as volatilized DNAPL constituents.

ISTD may also mobilize DNAPL into the lower, unimpacted portion of the lower sand aquifer. During the dewatering process, the interfacial tensions holding the DNAPL in the top third of the aquifer would change, resulting in considerable risk for DNAPL migration both laterally and vertically. Furthermore, during the temperature ramp-up period, the surface tension of C-56 is projected to decrease significantly. Therefore, the tension holding C-56 in the larger pore throats would decrease and DNAPL would be expected to flow downward in the aquifer. One method for mitigating increased DNAPL mobility during the temperature ramp-up period is to first create a “hot floor” zone below the target treatment zone. However, a greater dewatering depth would subsequently be required; this would add to the complexities and risks of the project, and still does not address DNAPL migration that may occur during the dewatering process (AECOM, 2008b).

There has been one large scale pilot study conducted for ISTD on C-56. The pilot study was conducted in March 2002 at the Rocky Mountain Arsenal Hex Pit near Denver, Colorado. HCl gases generated during the degradation of C-56 corroded the system, causing it to fail and forcing the study to be terminated. The pilot study was unable to document even 50% treatment of impacted soil. Furthermore, notes regarding vapors during the study strongly suggest that workers were present in work zones where concentrations exceeded safe levels. The Rocky Mountain Arsenal Hex Pit consisted of much simpler stratigraphy than the OCC Site, so risks and complexities involved with ISTD implementation would be even greater at the OCC Site (AECOM, 2008b).

Based on the complexities and risks associated with implementing ISTD at the Site, it is not retained as a feasible technology.

5.4.4. Solidification Methods

ISS is a process by which a cementing agent is mixed into impacted soil to solidify the AOC. This greatly reduces the permeability of the treated area. As a result, groundwater will preferentially flow around the area, limiting constituents from leaching. The ISS process does not directly result in a reduction of constituents. Instead, the goal of in-situ solidification is to contain the impacted area and limit migration of constituents. A thorough examination into the practicability of implementing ISS as a containment technology is presented in Section 7, based on the request of EPA Region V to provide further evaluation of applicable containment methodologies.

5.4.5. NAPL Extraction and Pump and Treat Methods

In some cases, is it possible to directly extract DNAPL using purge wells or a similar system. Recovered DNAPL may subsequently be separated from recovered groundwater using an oil-water separation system, and the DNAPL can then be disposed at a licensed disposal facility. As discussed in Section 3.4 of this report, the DNAPL is held in place by interfacial tension within the pore throats of aquifer material. DNAPL is not pooled within the aquifer material or on silt and clay lenses. Based on these Site conditions, it would not be possible to overcome the interfacial tension and recover a significant volume of DNAPL using extraction methods, and no significant reduction in the clean-up timeframe is likely to be achieved. Therefore, DNAPL extraction is not retained as an effective technology for the Site.

Pump and Treat methods are currently being deployed successfully to capture dissolved phase constituents at the Site (Section 1.5.2; also CRA, 2009).

5.5 Physical Containment

Section 5.5 refers to physical containment methods. This section was added at the request of EPA Region V to provide further evaluation of applicable contaminant containment methodologies, including use of barrier walls, sheet piling, or slurry walls.

5.5.1. Overview

Physical containment would require the installation of impermeable barriers around impacted aquifer sediments where DNAPL is present. The concept is to prevent future migration and dissolution of DNAPL constituents into surrounding groundwater. In order to reliably contain the soils from groundwater, it would be necessary for the barrier to key into a continuous and relatively impermeable layer. At the Site, the uppermost layer into which a containment wall could be keyed is a clay layer, the top of which ranges in depth from approximately 100 to 130 feet bgs. This would constitute a very deep containment wall, beyond the practical depth limitation of barriers such as sheet pile. An alternative method would require injection of a flowable grout wall or grout floor introduced through jet-grout means. This technique is also deemed unfeasible due to requirement to perform drilling and injection within DNAPL source areas. In addition, an impermeable cap would be required above the containment zone to mitigate precipitation from infiltrating into the contained soil.

5.5.2. Groundwater Flow Alteration

The groundwater plume is currently hydraulically contained through the existing pump and treat system. The addition of barriers for containment would alter the current groundwater flow and the groundwater plume would widen as it is forced to flow around the containment barriers. By changing the groundwater flow path, the groundwater plume could be driven outside of the current containment zone, resulting in the risk of possible uncontrolled discharge into White Lake. In order to counter that risk and achieve adequate physical containment, it would be necessary to install one continuous containment barrier around all four DNAPL areas and further extend this containment zone to include all portions of the groundwater plume that would be redirected by the barrier. Even if such a barrier were constructed, this

technology would only contain the impacts and would not result in any overall treatment or reduction of the DNAPL or dissolved constituents. Because the containment zone must encompass such a large area, physical containment would provide little to no gain in terms of reducing potential exposure or reducing the cleanup timeframe.

5.5.3. Risk of DNAPL Mobilization

As mentioned previously, DNAPL is present in the upper third of the aquifer at the Site and is partially held on thin clay and silt lenses and laminae. Driving sheet pile through these lenses presents a high risk for mobilizing the DNAPL into the lower portion of the aquifer, which is currently not impacted. The gaps created by driving temporary sheet pile to the depths required would create flow pathways through the relatively impermeable lenses and pore-spaces that contain DNAPL (see Section 3.5 on DNAPL Architecture). Disruption of interfacial tensions and site stratigraphy would potentially mobilize DNAPL below the targeted treatment zone into portions of the aquifer that were not previously impacted.

Furthermore, the vibrations caused by the installation of barrier walls risk mobilizing the DNAPL deeper into the aquifer. At the OCC Site, residual DNAPL is present within the soil pore spaces in a saturated soil medium and remains trapped there by strong capillary forces between the DNAPL and water. This entrapped residual DNAPL provides a continuing source of contamination to the surrounding aquifer. Mobilization of this trapped DNAPL is accomplished if external forces exist that can overcome the capillary force caused by the interfacial tension between the DNAPL and water. In addition to capillary forces acting on the DNAPL, there are buoyancy forces resulting from the difference in density between the DNAPL and water, and viscous forces resulting from the flow of water around the DNAPL. Pore structure and size distribution of the soil medium also have an effect on potential mobilization of DNAPL.

Vibratory pile driving equipment used during installation of steel or PVC sheet piling, concrete piles and/or piping and various other types of construction equipment produce vibrational frequencies or waves which are transmitted through the subsurface. Research studies have investigated the use of vibrations applied to the soil-NAPL-water medium to enhance mobilization of NAPL ganglia (Reddi and Challa, 1994). These studies investigated lighter than water LNAPL, in non-cohesive soils (sand). General findings in these studies concluded that locally applied vibrations can cause recovery of high percentages of NAPL. In general, higher vibration amplitudes resulted in higher NAPL mobilization. Tests were conducted with a vibration frequency of 3600 vibrations per minute, or 60 Hertz (Hz), at vibration amplitudes ranging from 0 to 0.6 millimeters (mm). Further study postulated that mechanisms involved during vibratory destabilization of the soil pore structure in sands may either result in compaction or expansion of the sand. In cases where compaction existed, viscous forces tend to split up the NAPL ganglia, while buoyancy forces cause the maximum sustainable lengths of ganglia to increase. The role of viscous and buoyancy forces are reversed where expansion of the sand existed. In any case, significant recoveries of trapped NAPL were accomplished (Reddi and Wu, December 1996).

Research has also been conducted on vibration effects on denser than water NAPL, or DNAPL, which exists at the OCC Site. One study (Roberts et al., 2001) investigated the effect of low frequency vibrations (100 Hz or less) on enhancement of DNAPL recovery. This study postulated that, while little research had been conducted on DNAPL, the same scientific principals that apply to LNAPL mobilization should apply to DNAPL. Tests were conducted on trichloroethylene (TCE) at vibration frequencies of 25 to 100 Hz and vibration amplitudes of up to 40 micrometers (µm). At amplitudes below 12 µm, no significant DNAPL mobilization occurred. The study showed mobilization of DNAPL occurred with varying vibration frequencies and amplitudes, as well as differing water flow rates. Additional studies have also observed significant TCE mobilization at vibratory frequencies between 0 and 285 Hz (Vogler and Chrysikopoulos, 2004).

Most typical equipment used during installation of piling and/or piping operates in the frequency range of 7 to 50 Hz, depending on the machine (Rausche, 2002). Recommended vibration amplitudes for sandy soils for the driving of sheet pile range from 4 mm to 10 mm at frequencies of 25Hz and 16 Hz, respectively (Erofeev et al., 1985). Resonant pile drivers, of which the Bodine-Guild resonant driver is the most significant, operate at higher frequencies (90 to 120 Hz); however, due to the mechanical complexity, are generally not used extensively (Warrington, 1992).

A review of other types of commonly used construction equipment revealed that most construction equipment induces vibration frequencies ranging from 7.2 Hz to 64.3 Hz at amplitudes ranging from 0.1 to 18.3 mm (King and DeMarco, 2003). Equipment cited includes various types of vibratory compactors, haul trucks, hoe rams, scrapers, and rollers, amongst others.

It has been shown that vibration mechanisms essentially disrupt the forces keeping DNAPL ganglia in a stable state in order to mobilize NAPL. Chrysikopoulos and Vogler (2004) showed that acoustic waves significantly enhance ganglia dissolution to the surrounding water due to the imposed oscillatory interstitial water velocity acting at the NAPL-water interface. This dissolution enhancement was shown to be directly proportional to the acoustic wave frequency, and the greatest enhancements were realized with NAPLs of lower equilibrium aqueous solubility. This enhancement increases dissolved-phase constituent proportions and their migration.

An increase of mobilization of DNAPL through vibration also leads to an increase in interfacial area of DNAPL contact with water in the aquifer. This mechanism will also increase dissolved-phase constituent proportions and their migration. Consider that it is also possible that vibration effects imposed during sheet pile installation and heavy equipment mobilization and operation could potentially mobilize DNAPL into the lower portions of the Upper Sand Aquifer or into underlying stratigraphic units at the OCC Site.

Considering that the operating vibration frequencies of typical vibratory pile driving equipment and various other types of construction equipment exist in the lower frequency range (50 Hz and below), and have been shown in the literature to enhance both LNAPL and DNAPL mobilization, it is reasonable to assume that the operation of such equipment in the vicinity of DNAPL-containing saturated soils will mobilize the DNAPL at the OCC Site to some extent. However, the magnitude of the mobilization is unknown based on the limited research data available and lack of understanding of the physical mechanisms responsible for the observed phenomenon.

5.5.4. Conclusion

Physical containment would not expedite cleanup of residual waste and contaminated groundwater, as is stipulated in the U.S. EPA Final Decision (See Section 1.3). It is documented that the existing groundwater pump and treat system is effectively containing the groundwater plume and preventing discharge of compounds into White Lake. Installing physical barriers would alter that groundwater capture and risk mobilizing DNAPL into unimpacted portions of the aquifer. Physical containment would introduce significant new environmental risks at the Site, and would provide little to no gain in terms of reducing cleanup timeframe or reducing potential exposure at the Site. For these reasons, physical containment is not retained as an effective or feasible technology.

6.0 EXCAVATION AND DISPOSAL EVALUATION

6.1 Process Overview

Excavation of the aquifer to remove DNAPL involves the removal of source material and subsequent disposal at a licensed landfill. The Site conditions, safety requirements, and distribution of DNAPL (DNAPL architecture) would require a complex excavation scenario. The DNAPL source material ranges in depth at the Site from approximately 25 to 70 feet below the ground surface and is located up to approximately 25 feet below the water table. An overview of the excavation and disposal process is presented schematically in **Figure 14**, and is discussed below.

As excavation progresses and DNAPL impacts are exposed to the atmosphere, chlorinated organic compounds in the DNAPL would volatilize. These compounds have the potential to migrate off-site and become an exposure risk for human or ecological receptors both on-site and off-site (see Section 6.2). To manage this exposure, the excavation would be fully contained within a structure. Temporary enclosure sprung structures are available to enclose the excavation and mitigate the migration of fugitive vapors. Workers within the structure would perform work in Level B personal protective equipment, including supplied air respirators. Exposure risks to workers, non-workers (residents), and ecological receptors are discussed in Section 6.2.2.

Reviewing available alternatives, the dimensions of the sprung structure would be approximately 132 feet by 118 feet, and it would be approximately 45 feet tall. This is the largest air-tight sprung structure available that is readily movable. The air within the sprung structure would be cycled and treated with vapor-phase activated carbon systems. Within a sprung structure of this size, an area of approximately 100 feet by 100 feet could be excavated. Because some of the targeted excavation areas exceed these dimensions, it would be necessary to separate the excavation areas into sub-sections (or “cells”). Once excavation of a sub-section is complete, the sprung structure would be moved over the next before excavation proceeds. To facilitate movement of the sprung structure, it would be skid-mounted by a system of I-beams attached to the structure at ground level, such that it could be pulled along the beams. It would be necessary that the ground be leveled and graded prior to the erection of this beam network (topographic variations of up to 15 to 20 feet exist across residual sources areas). A conceptual grading plan is presented in **Figure 15**.

In order to reach the required excavation depths within each enclosed sub-area, it would be necessary to install temporary sheet pile shoring around each 100’ by 100’ excavation sub-section. Sheet pile would be installed at the ground surface and would be installed to an approximate depth of 150 percent of the excavation depth. A conceptual sprung structure plan is shown in **Figure 16**. Before beginning deep excavation, the sub-section would be dewatered to below the target excavation depth at an estimated maximum flow rate of 1,200 gallons per minute. It is anticipated that the groundwater would contain high levels of dissolved chlorinated organic compounds and would be treated on-site with liquid-phase activated carbon systems. Treated water would be discharged under a permit.

Through the process of installing sheet piling and dewatering the target DNAPL areas, it is likely that DNAPL would be mobilized and would be drawn deeper into the aquifer. Both the installation of the piling to isolate the excavation cells and the dewatering activities are likely to cause downward mobilization of the DNAPL.

As excavation proceeds, clean overburden would be staged on-site for later use as backfill. Although the target of excavation would be soil that contains DNAPL, some of the soil that would be excavated as overburden may be residually impacted in the Former Primary Ash Disposal Area, the Former Fine Chemical Production Area, and the Former Equalization Pond Area. Both soil containing DNAPL and soil containing residual impacts would be hauled from the site in trucks designed to carry hazardous waste, and would be disposed as hazardous waste at a licensed landfill.

Once all impacted soil is removed from the excavation sub-section, the section would be backfilled with clean overburden material, the sprung structure would be relocated over the next sub-section, the temporary sheet pile would be removed, and the dewatering system re-established in the new cell. This

process would proceed until all source areas have been addressed, and Site restoration would follow. It is estimated that it would take approximately 24 months to complete this excavation.

6.2 Health and Safety Concerns

Removal and disposal of source material at the Site would not reduce either short-term or long-term exposure to the contaminants, as baseline exposure under the existing conditions is already within acceptable exposure guidelines and standards. Previous remediation activities at the site include excavation of the waste material and impacted soils with placement in a secure landfill, the cover of isolated soil areas, and the implementation of a groundwater collection and treatment system. With these remedial activities, there is no unacceptable exposure to the contaminants in the DNAPL (Earth Tech, 2000a; Earth Tech, 2002a). However, the risk of exposure to contaminants would increase during this potential remediation process.

6.2.1. Air Quality Dispersion Model

An air quality dispersion model (EPA WATER9) was used to assess potential exposure to compounds through the inhalation exposure pathways during excavation of residual DNAPL areas. WATER9 is traditionally used to evaluate emissions from wastewater processes, conveyances and applications. At this Site it is being used to evaluate partitioning of compounds from wet soils or ponded water potentially present in excavated soils.

Air quality modeling was conducted for the largest onsite excavation area (the Former Fine Chemical Production Area). The dimensions at the top of this pit are approximately 643.2 feet long, 383.3 feet wide and 20 feet deep. Modeling was conducted to evaluate the emissions of C-56.

The first step in determining C-56 concentrations emitted from the top of the pit (excavation) was to run EPA's WATER9 to determine the C-56 emission rate (grams per second) from the groundwater at the bottom of the pit. WATER9 is a wastewater treatment model that is used to estimate emissions of individual waste constituents from units at facilities that collect, store, treat or dispose of wastewater. For this case, two scenarios were run for comparison purposes. It was assumed that the pit functioned as both a lagoon, with wet soils and an open trench, both default units within WATER9. The default lagoon and open trench variables were used when applicable and site-specific data was not available. The following WATER9 variables were adjusted with provided site-specific information that was converted to appropriate units for the model:

Flow (liters per second)	10.07
Temperature (degrees Celsius)	10
Pollutant Concentration in Water (mg/L)	0.800
Length of Impoundment (meters)	196.05
Depth of Impoundment (meters)	13.716
Width of Impoundment (meters)	116.83
Time within Lagoon (months)	12

The flow in liters per second (volumetric flow rate) was determined by first assuming that the groundwater flow velocity of approximately 650 feet per year flowed along the long end of the pit, which was provided as 643.2 feet (or 196.05 meters). The 643.2 feet dimension was assumed to be the length of the pit. The groundwater flow velocity was thus multiplied by the width of the pit (383.3 feet or 116.83 meters) and the depth to calculate the volumetric flow per year. As a conservative estimate, the depth was assumed to be the maximum provided 45 feet (or 13.716 meters). The resultant cubic feet per year flow was then converted to liters per second.

For the lagoon scenario, resident time was required. Since the project would be expected to take over a year, the time in the pit (or "lagoon") was assumed to be 12 months.

Once all variables were added to the WATER9 program for each scenario (lagoon and open trench), the resultant emission rate of C-56 from the groundwater surface in grams per second was computed (result: 0.00796 grams per second for a lagoon, 0.00806 grams per second for an open trench). This emission rate is dependent on depth of groundwater and will increase with increased depth.

To determine the ground level C-56 concentration, dispersion modeling was conducted using a series of parallel line sources at ground level to represent the entire area at the top of the pit. Total emissions from the pit were evenly divided among each line source. There were 196 line sources modeled, each line source spaced one meter apart. Assuming a level of equilibrium occurs in the pit, the emission rate (grams per second per meter) at the top of the pit (at ground level) was set equal to the emission rate (grams per second per meter) of C-56 at the bottom of the pit (groundwater surface). A one-hour average concentration of C-56 was conservatively calculated at a receptor located 0.5 meters from the edge of the pit, at the center of the short side of the pit. A very low speed wind, less than 1 meter per second, was directed across the pit perpendicular to the 196 line sources. The contribution of each line source was then added together for the receptor modeled at the edge of the pit.

A one-hour concentration of 142.3 micrograms per cubic meter of C-56 was calculated at the edge of the pit for the lagoon scenario, 144.1 micrograms per cubic meter of C-56 for the open trench scenario. This greatly exceeds the initial threshold screening level (ITSL) of 0.2 ug/m3 that was developed by the MDEQ (MDEQ, 2009), which is deemed to be protective of continuous exposure to residential receptors.

This model provides a conservative estimate of the emission of C-56 from a pond surface. Contaminant concentrations and vapor-phase partitioning of C-56 DNAPL residing in excavated soils is expected to generate higher emissions values than predicted by WATER9 for emissions from a dissolved water source.

WATER9 model output is presented in **Appendix D**.

6.2.2. Exposure Potential

If not controlled, compounds in the DNAPL exposed through excavation would volatilize, resulting in an unacceptable exposure risk to workers and non-worker receptors through inhalation. The risk to non-workers was evaluated quantitatively by comparing calculated potential exposure concentrations against the risk based ITSL developed by the MDEQ under its Air Toxics program. The value is protective of residential exposures averaged over a 24 hour period. The ITSL is developed in accordance to Michigan Rule 366.1229(2). The potential concentration of C-56 in air was calculated to be 142.3 ug/m3. When compared to the MDEQ established ITSL of 0.2 ug/m3 (MDEQ, 2009), the calculated concentration suggests that risk to non-worker receptors will exceed MDEQ permitted risk by over 700 times.

Based on comparison of the modeling results to acceptable levels of C-56 in air, the foregoing assessment suggests that control measures should be taken to mitigate exposures to receptors. Such exposure controls are anticipated to include enclosures to reduce the release of chemical emissions beyond the area of excavation and mitigate exposure to non-worker receptors. It is anticipated that these control measures will significantly reduce, but not completely eliminate, emissions to the environment and associated risk to receptors.

It is expected that the containment structure will be erected over a work area with estimated dimensions of 100 ft x 100 ft (i.e., 10,000 sq ft). Therefore, each DNAPL area will require multiple excavation mobilizations to complete residual removal and disposal. The following evaluation considers exposures associated with only one excavation mobilization. The underlying assumption of the overall assessment is that each excavation mobilization will result in additive exposures, such that risks to receptors of concern will tend to increase in proportion to the number of 10,000 sq ft sub-units remediated.

The associated exposure scenarios, separated by work process, are discussed below and are depicted schematically in **Figure 17**.

Soil Overburden Removal – Worker Exposures

DNAPL exists at depth and is overlain by, on average, approximately 20 to 40 feet of partially impacted overburden material. Therefore, in order to gain access to residual DNAPL, overburden material must be excavated, resulting in the creation of a 20- to 25-feet deep excavation pit. Because some chemical impacts exist in lower portions of the overburden material, exposure are pathways are deemed potentially complete for the worker receptor group.

Residual DNAPL Excavation – Worker Exposures

After removal of the overburden material, excavation of DNAPL will proceed. It is anticipated that workers will be potentially exposed to DNAPL material associated with saturated soils, resulting in direct contact, leading to exposures via the ingestion and dermal exposure routes. In addition, the relatively high degree of volatility of the DNAPL chemicals also allows worker exposure through the inhalation route. Thus, workers are expected to be potentially exposed to chemicals in DNAPL material during the excavation process. Due to this exposure potential, it is anticipated that workers will use Level B personal protective equipment to mitigate unacceptable exposures during DNAPL excavation. Pathways leading to worker exposures are considered potentially complete.

Residual DNAPL Excavation – Non-Worker and Ecological Receptor Exposures

The excavation of DNAPL material from the area under the containment is expected to greatly mitigate exposures to non-worker and ecological receptors. Although some amount of chemical vapor may be released during the excavation process, emission control is expected to result in acceptable emissions outside of the containment structure. Therefore, pathways leading to potential exposure to non-worker and ecological receptors are considered incomplete assuming the use of these engineering controls.

Waste Loading – Worker Receptors

It is anticipated that soils saturated with DNAPL will be loaded into trucks for shipment off site to a permitted disposal facility. During the loading operations, workers will potentially be exposed to saturated soils, resulting in contact via ingestion, dermal, and inhalation exposure routes. As a result of this potential exposure, it is anticipated that workers will use personal protective equipment to mitigate the risk associated with chemical contact. Pathways leading to worker exposures are considered potentially complete.

Waste Loading – Non-Worker and Ecological Receptors

Chemical emissions from material that is being loaded into waste transport vehicles and moved outside of the containment for subsequent transport to permitted disposal facilities may result in emissions of DNAPL chemicals outside of the control structure. While emissions outside of the containment structure are thought to be limited in magnitude, potential exposure to non-workers and ecological receptors cannot be ruled out. Thus, it has been assumed that non-worker and ecological receptors may potentially be exposed to vapors that escape during waste loading and transport staging. Thus, pathways leading to non-worker and ecological receptor exposure are considered complete.

Waste Transportation – Worker, Non-worker, and Ecological Receptors

The waste material is expected to be hauled in trucks that are intended for the use of hazardous waste shipping. Despite such precautions, the shipping vehicles are not hermetically sealed and, as such, a finite (though limited) quantity of volatile emissions is anticipated. Such emissions are anticipated to result in limited exposures to workers, non-workers, and ecological receptors via the inhalation pathway. Thus, pathways leading to worker, non-worker and ecological receptor exposure are considered complete during waste transportation.

Transportation Accident – Worker, Non-worker, and Ecological Receptors

Hazardous waste transportation accident is expected to be very low; however, the risk to receptor populations and valued resources in not zero. For instance, the average annual exposure frequency has been estimated to be greater than 1 in 100,000, assuming transport over an approximate 300 mile transport route (Assante Duah, D.K. 1993 Hazardous Waste Risk Assessment, Lewis Publ., Boca Raton, FL)). In a study conducted to evaluate risk reduction occurring as a result of differential hazardous waste

transportation scenarios, accidents threatening groundwater resources were determined to potentially occur once in a 68 year period over a 40 mile hauling route (Lovett, et. al, 1997). The specific results of this case study should not be applied to the OCC Site. However, they do illustrate that the finite probability of exposure is not zero for purposes of this TI Evaluation.

In the event of such an incident, workers (i.e., truck drivers) may inadvertently contact waste material directly, and be exposed via the ingestion, dermal and inhalation exposure routes. Emergency response procedures are expected to result in rapid containment of the spilled waste material, but the potential exists for emissions of chemicals to the air. Such emissions may potentially contact non-worker and terrestrial ecological receptors via the inhalation route. Thus, pathways leading to worker, non-worker and ecological receptor exposure are considered complete in the event of a transportation accident.

6.2.3. Worker Safety

Performing work within or on the banks of the excavation pit shored by sheet pile would present significant safety concerns to workers. This is due to low cohesive strength of soils and weak slope-stability of dune sands found at the Site.

6.3 Environmental Concerns

There is no current unacceptable exposure to the environment to the constituents in the DNAPL (Earth Tech, 2000a). Impacted groundwater migrating through the DNAPL is captured by a purge well system and treated prior to discharge into White Lake under an NPDES permitted outfall. All surface soil exposures are incomplete. Potential surface soil exposures identified at the site was previously addressed (Earth Tech, 2002b). Therefore, the removal and disposal of source material will not decrease the risk of exposure to constituents in the environment.

6.3.1. Risk of DNAPL Mobilization During Dewatering

Prior to excavating the DNAPL-impacted portion of the aquifer, the aquifer must be dewatered. Dewatering the aquifer will change the interfacial tensions that are holding the DNAPL in the upper third of the aquifer. Water in narrower throats will drain out. The remaining water held in the aquifer will be at a much lower capillary pressure. As the water is drained from the water-wetted narrower pore throats that hold the DNAPL in its current location, the capillary pressure in these pore throats will decrease and DNAPL may be mobilized downward under the force of gravity and through capillary pressures. This effect will be more pronounced at aquifer locations where the DNAPL is present at residual saturation or is perched on strata or laminae that can be partially de-saturated by gravity drainage. This effect will occur less in the clay strata that may not readily drain and de-saturate during aquifer dewatering, but may be significant for silt strata or those lithologies exerting higher capillary pressures.

6.3.2. Risk of DNAPL Mobilization During Sheet Pile Installation

DNAPL is present in the upper third of the aquifer at the Site and is partially retained on thin clay and silt lenses and laminae. Driving sheet pile through these lenses presents a high risk for mobilizing the DNAPL into the lower portion of the aquifer, which is currently not impacted. The gaps created by driving temporary sheet pile to the depths required would create flow pathways through the relatively impermeable lenses on which much of the DNAPL is currently perched. This risks expanding the impacts below the targeted excavation zone into portions of the aquifer that were not previously impacted.

In addition to compromising the lenses on which much of the DNAPL is currently retained, vibrations produced in the process of sheet pile installation are likely to further increase DNAPL mobilization. As presented in Section 5.5.3, review of multiple studies has demonstrated that vibrations produced during sheet pile installation and other construction activities are likely to mobilize DNAPL, which is currently held in place by strong capillary forces between the DNAPL and water. If DNAPL were mobilized into portions of the aquifer that are not currently impacted, this would exacerbate the current Site conditions. Furthermore, the impacts could be driven outside of the capture zone of the existing groundwater pump and treat system, resulting in a potential release of DNAPL compounds to White Lake.

6.4 Clean-up Timeframe

The contaminant fate and transport of contaminants of concern was evaluated using the USEPA analytical model, REMChlor (See Section 3.7). The model was used to estimate cleanup timeframes, by source area, for five predominant COCs. A scenario in which 90% of source material is removed through excavation and disposal was run, and the estimated cleanup timeframe under this scenario was compared to baseline conditions. The results for each of the source areas are summarized in **Table M5** of **Appendix C**.

Although the estimated cleanup timeframe was reduced from baseline conditions, the estimated cleanup timeframe under the excavation scenario is still thousands of years for C-56 and hundreds of years for PCE. From a practical standpoint, this would not significantly expedite groundwater cleanup, as is mandated by the U.S. EPA Final Decision (see Section 1.3). The percentage of DNAPL left behind after excavation would serve as a continuing long-term source of DNAPL compounds to groundwater. The current groundwater pump and treat system would still need to remain active indefinitely, and a substantial improvement in groundwater quality would not be achieved within a reasonably expedited timeframe.

6.5 Cost Estimate

This excavation scenario is estimated to cost approximately $145 million dollars to complete. This inordinately high cost is a result of the large scale, long duration, and high level of complexity associated with this project. It is important to note that this cost estimate only incorporates costs for implementation of the project. There would be additional pre-implementation design costs. Typically, at this level of evaluation, design costs are estimated to be about five percent of the total cost, or about seven million dollars.

The most costly items encountered during the scope of the excavation project are anticipated to include dewatering, removal and disposal of soil, and sheet pile shoring for the excavation pit. Costs associated with maintaining a dewatering system over the 24 month duration of the project would total nearly $15 million. The sheet pile necessary to properly shore the excavation pit is estimated to cost approximately $25 million. Costs associated with removal, transportation, and disposal of soil are estimated to total over $90 million. Oversight costs over the 24 month excavation period are estimated to exceed $2 million. See **Table 7** for a more complete breakdown of estimated costs.

6.6 Remedy Analysis Conclusion

In the preceding analysis, the practicability of implementing excavation and disposal was evaluated for the OCC Site. The potential of excavation and disposal to reduce the timeframe for groundwater restoration was estimated, and associated environmental and human exposure risks were considered.

DNAPL is currently held in the upper third of the aquifer both by thin silt and clay lenses and by capillary forces associated with the DNAPL-water interface. During the dewatering process, these interfacial tensions would change, and there is significant risk of mobilizing DNAPL into the lower unimpacted portion of the aquifer. Additionally, in order to successfully excavate the DNAPL to required depths, it would be necessary to install a matrix of temporary sheet pile shoring throughout these residual DNAPL bodies. These would compromise the thin lenses on which DNAPL is perched, while also producing vibrations that have the potential to overcome the capillary forces that are currently holding the DNAPL in place. This process has a high likelihood to mobilize the DNAPL into the lower unimpacted portion of the aquifer. As such, there is a high likelihood to exacerbate Site conditions through the excavation process.

C-56 as well as other constituents in the DNAPL have restrictions on the concentration in the ambient air that is safe to breath. Excavation of soils impacted with DNAPL would produce high concentrations of these chemicals in the surrounding air. Although control measures could potentially eliminate exposure to unsafe levels of COCs, an unanticipated breach of these protective measures is still a significant concern, given the high level of complexity and long duration of the project.

Even after 90% of the DNAPL is excavated, the time necessary to reach the Site cleanup criteria would be approximately 4,900 years (Former Primary Disposal Area) for C-56. Therefore, excavation and disposal would not significantly expedite the cleanup of contaminated groundwater at the Site, as is stipulated in the U.S. EPA Final Decision. Furthermore, at an estimated cost of approximately $145 million, excavation and disposal would be inordinately costly.

There are currently no unacceptable risks associated with the Site. Excavation and disposal has a high potential to exacerbate site conditions, and would result in little or no overall gain in terms of reducing the cleanup time fame or Site exposure risks. Instead, excavation and disposal would introduce considerable new environmental and exposure risks during the remediation process. Therefore, excavation and disposal of residual DNAPL is not an effective or practicable technology to expedite groundwater cleanup at the OCC Site.

7.0 IN-SITU SOLIDIFICATION (ISS) EVALUATION

7.1 Process Overview

ISS involves the use of a large vertical auger, 6 to 10 feet in diameter, to mix soil with solidification reagents to create a homogeneous solid mass of greatly reduced permeability. As a result, groundwater would preferentially flow around the area, limiting further leaching from source material. The technology is used to render a contaminant mass less mobile by reducing the intrinsic permeability of the impacted soil or aquifer material. However, the technology is typically used for inorganic contaminants and is generally not effective for VOCs, as are present at the Site (FRTR, 2009). An overview of the site specific ISS process is presented schematically in **Figure 18**, and is discussed below.

Based on the type of soil present at the Site, it would be possible for the auger to reach depths of approximately 30 to 35 feet bgs. As described previously, there are four separate DNAPL source areas identified at the Site. The maximum depths of these source areas range from approximately 25 to 70 feet below the ground surface, and the impacted regions range in vertical thickness from approximately 7 to 25 feet. In order for the auger to reach the treatment depths necessary, the overburden above the soils containing DNAPL source material must first be removed. This would also eliminate unimpacted soil from being solidified unnecessarily. However, because dewatering is not anticipated, it is assumed that saturated overburden will be left in place and will be solidified, even if it is unimpacted.

Once overburden is removed, some impacted soil will be exposed to the atmosphere. It is expected that compounds will volatilize into surrounding air in areas where impacted soils are exposed. Mixing the solidification admixture into the soil with the auger is expected to result in additional volatilization. Fugitive emissions from these volatilized compounds have the potential to migrate off-site, creating an exposure risk for human or ecological receptors (See Section 6.2.1). Therefore, the ISS treatment area would need to be fully contained within an air-tight structure prior to overburden removal. Temporary enclosure “sprung structures” are available to enclose the ISS treatment area and mitigate the migration of fugitive vapors. Workers within the structure would be expected to conduct work in Level B Personal Protective Equipment, including supplied air respirators. Exposure risks to workers, non-workers (residents), and ecological receptors are discussed further in Section 6.2.1.

The dimensions of the sprung structure would be approximately 132 feet by 118 feet, and it would be approximately 45 feet tall. This is the largest air-tight sprung structure available that is readily movable. The air within the sprung structure would be cycled and treated with vapor-phase activated carbon systems. Within the sprung structure, ISS treatment could be conducted for an area with dimensions of approximately 100 feet by 100 feet. Because some of the targeted treatment areas exceed these dimensions, it would be necessary to separate the treatment areas into sub-sections (or “cells”). Once ISS treatment of a sub-section is complete, the sprung structure would be moved over the next sub-section before the treatment proceeds. To facilitate movement of the sprung structure, it would be skid-mounted by a system of I-beams attached to the structure at ground level, such that it could be pulled along the beams. It would be necessary that the ground be leveled and graded prior to the erection of this beam network (topographic variations of up to 15 to 20 feet exist across residual sources areas). A conceptual grading plan is presented in Figure 15.

In order to reach the required overburden excavation depths within each enclosed sub-area, it would be necessary to install temporary sheet pile shoring around each treatment sub-section. Sheet pile would be installed at the ground surface and would extend to an approximate depth of 150 percent of the overburden excavation depth. A conceptual sprung structure plan is shown in Figure 16.

Some of the overburden soil that would be excavated is residually impacted in the Former Primary Ash Disposal Area, the Former Fine Chemical Production Area, and the Former Equalization Pond Area. Clean overburden would be staged on-site for use as backfill. Soil containing residual impacts would be hauled from the site in trucks designed to carry hazardous waste and would be disposed as hazardous waste at a licensed landfill.

Once ISS treatment of a sub-section is complete, the section would be filled with clean overburden material, the sprung structure would be relocated over the next sub-section, and the temporary sheet pile

would be removed. This process would proceed until all source areas have been addressed, and Site restoration would follow. It is estimated that it would take about 24 months to complete this process.

7.2 Health and Safety Concerns

Implementing ISS at the Site will not reduce exposure to the contaminants. Baseline exposure under the existing conditions is within acceptable exposure guidelines and standards. Previous remediation activities at the site include excavation and placement in a secure landfill, the cover of isolated soil areas, and the implementation of a groundwater collection and treatment system. With these remedial activities, there is no unacceptable exposure to the contaminants in the DNAPL (Earth Tech, 2000a and Earth Tech, 2002b). However, the risk of exposure to contaminants would increase during the potential remediation process.

7.2.1. Exposure Potential

As stated previously, overburden must be removed prior conducting ISS treatment. If not controlled, chlorinated organic compounds in the DNAPL that are exposed through excavation of overburden and through the solidification by the augers would volatilize, resulting in an unacceptable exposure risk to non-worker receptors through inhalation. The risk to non-workers was evaluated quantitatively by comparing calculated potential exposure concentrations against the risk based ITSL developed by MDEQ (see Section 6.2.1). The potential concentration of C-56 in air was calculated to be 142.3 ug/m3. When compared to the MDEQ established ITSL of 0.2 ug/m3 (MDEQ, 2009), the calculated concentration suggests that risk to non-worker receptors will exceed MDEQ permitted risk by over 700 times.

Based on comparison of the modeling results to acceptable levels of C-56 in air, the foregoing assessment suggests that control measures should be taken to mitigate exposures to receptors. Such exposure controls are anticipated to include enclosures to reduce the release of chemical emissions beyond the treatment area and mitigate exposure to non-worker receptors. Although the control technology is anticipated to help mitigate exposure to non-workers and ecological receptors, the potential still exists for exposure pathways to be complete during application of this technology. **Figure 19** schematically shows the exposure pathway evaluation that has been performed for this remedial alternative. The associated exposure scenarios, separated by work process, are discussed below.

Installation of Sheet Piling and Placement of Sprung Structure

Prior to solidification, sheet piling must be installed around a 100-foot by 100-foot area, which would be covered by a temporary sprung structure before beginning work. Neither the installation of sheet piling nor the placement of the sprung structure would result in complete exposure pathways.

Overburden Removal

DNAPL exists at depth and is overlain by, on average, approximately 20 to 25 feet of partially impacted overburden material. Therefore, in order to gain access to residual DNAPL, overburden material must be excavated, resulting in the creation of a 20- to 25-foot deep excavation pit. Because some chemical impacts exist in portions of the overburden material, exposure are pathways are deemed potentially complete for the worker receptor group.

Augering

A 10-foot diameter auger will be used to emplace injection ports to a depth of the residual DNAPL. During the augering process, soil impacted with DNAPL residual material will be generated in the vicinity of workers. Workers will be potentially exposed to impacted soils via incidental ingestion, dermal contact, and inhalation. Thus, exposure pathways are deemed potentially complete for the worker receptor group.

Injection and In-situ Mixing

Contact of the solidification agent with DNAPL residual impacted soil may be exothermic. Though the rate of heat generation will be controlled by the rate of injection, workers will be potentially exposed to DNAPL residuals via inhalation. Thus, exposure pathways are deemed potentially complete for the worker receptor group.

Moving the Sprung Structure

As described earlier in this report, the work area encompassed by the sprung structure (100 ft x 100 ft) is less than some of the DNAPL areas. Therefore, once a 10,000 sq ft area is remediated via solidification, the sprung structure must be moved to another location within the DNAPL area. Although the DNAPL residual within a 10,000 sq ft area is anticipated to be remediated before moving the sprung structure, the process of footer modification required to move and re-position the structure may result limited volatile emissions. These emissions may potentially expose workers, non-workers, and ecological receptors. Therefore, the air pathway must be considered potentially complete for these receptors.

Waste Transportation

A significant amount of waste material is expected to be generated during in-situ solidification. Impacted soil will require off-site transportation and disposal. The waste material is expected to be hauled in trucks that are intended for the use of hazardous waste shipping. Despite such precautions, these shipping vehicles are not hermetically sealed. As such, a finite (though limited) quantity of volatile emissions are anticipated. Such emissions are anticipated to result in limited exposures to workers, non-workers, and ecological receptors via the inhalation pathway. Pathways leading to worker, non-worker and ecological receptor exposures are considered complete during waste transportation activities.

Transportation Accident

The likelihood of an accident occurring that would result in significant release of waste chemicals is expected to be low. Regardless, there is a finite potential that a transportation accident may occur, which would result in a release of waste material. In the event of such an incident, workers (i.e., truck drivers) may inadvertently contact waste material directly and be exposed via the ingestion, dermal and inhalation exposure routes. Emergency response procedures are expected to result in rapid containment of the spilled waste material, but the potential exists for chemical emissions to be released to the air. Such emissions may potentially contact non-worker and terrestrial ecological receptors via the inhalation route. Therefore, pathways leading to worker, non-worker, and ecological receptor exposures are considered complete in the event of a transportation accident.

7.2.2. Worker Safety

A combination of the depth limitation of the auger and height limitations of sprung structure would require that ISS rig be positioned within the overburden excavation pit. A thorough geo-technical would be needed to evaluate load-bearing of wet soils at the base of the pit. As presented, groundwater would be lowered through use of a dewatering well network. Potential worker safety concerns would include potential failure of underlying soils of low cohesive strength.

7.3 Clean-up Timeframe

The contaminant fate and transport of contaminants of concern was evaluated using the U.S. EPA analytical model, REMChlor (see Section 3.7). The model was used to estimate cleanup timeframes, by source area, for five COCs. A scenario representative of ISS, in which the source area permeability is reduced, was run. The estimated cleanup timeframe under this scenario was compared to baseline conditions, and results are summarized in **Table 8**.

Implementation of ISS would increase the timeframe necessary to reach cleanup criteria at the Site. ISS does not chemically bind organic compounds and therefore will not significantly reduce the extent to which organic compounds can leach when exposed to water. Rather, ISS would greatly reduce the permeability of the treated area and, as such, would greatly reduce groundwater flow through the treated area. In effect, DNAPL compounds would leach into groundwater at reduced concentrations, but for a longer period of time. In reducing the rate at which natural groundwater flow can attenuate residual DNAPL, the cleanup timeframe is ultimately expected to increase, as demonstrated by the fate and transport model.

Therefore, implementation of ISS would not expedite cleanup of residual waste or contaminated groundwater, as is mandated by the U.S. EPA Final Decision (see Section 1.3). After ISS treatment, the

current groundwater pump and treat system would still need to remain active indefinitely, and a substantial improvement in groundwater quality would not be achieved within in an expedited timeframe. Similarly, ISS does not address remediation of "residual source areas" as stipulated in the Final Decision.

7.4 Cost Estimate

This ISS scenario is estimated to cost approximately $88 million dollars to complete. This inordinately high cost is a result of the large scale, long duration, and high level of complexity associated with this project. It is important to note that this cost estimate only incorporates costs for implementation of the project. There would be additional pre-implementation design costs. Typically, at this level of evaluation, design costs are estimated to be about five percent of the total cost, or about four and half million dollars. It is expected that the full-scale pilot evaluation will cost more than a million dollars.

The most costly items encountered during the scope of the ISS project are anticipated to include the ISS treatment, removal and disposal of overburden soil, and sheet pile shoring for the overburden excavation pit. The sheet pile necessary to properly shore the overburden excavation pit is estimated to cost nearly $17 million. Excavating the overburden soils would cost approximately $3 million, and it is estimated that it would total over $33 million to transport and dispose the impacted portion of overburden soils. Implementation of the ISS treatment on DNAPL-impacted soil would cost an estimated $21 million. Oversight costs over the 24 month implementation period are estimated to exceed $2 million. See **Table 9** for a more complete breakdown of estimated costs.

7.5 Remedy Analysis Conclusion

In the preceding analysis, the practicability of implementing ISS was evaluated for the OCC Site. The potential of ISS to reduce the timeframe for groundwater restoration was estimated, and associated environmental and human exposure risks were considered.

DNAPL is currently held in the upper third of the aquifer both by thin silt and clay lenses, and by capillary forces associated with the DNAPL-water interface. In order for the ISS auger to reach the targeted treatment depths, it would be necessary to install a matrix of temporary sheet pile shoring throughout these residual DNAPL bodies in order to facilitate excavation of overburden soils. These would sever the thin lenses on which DNAPL is perched, while also producing vibrations that have the potential to overcome the capillary forces that are currently holding the DNAPL in place. This process has a high likelihood to mobilize the DNAPL into the lower un-impacted portion of the aquifer. As such, there is a high likelihood to exacerbate Site conditions.

C-56 as well as other constituents in the DNAPL have restrictions on the concentration in the ambient air that is safe to breath. Excavation of overburden soils would expose DNAPL compounds and would produce high concentrations of these chemicals in the surrounding air. Although control measures could potentially eliminate exposure to unsafe levels of COCs, an unanticipated breach of these protective measures is still a significant concern, given the high level of complexity and long duration of the project.

After soils are solidified by ISS, the time necessary to reach the Site cleanup criteria is estimated to increase. Because ISS does not chemically stabilize organic compounds, DNAPL constituents would continue to leach from the solidified mass, but at a slower rate. However, despite the decreased leaching rate, it is estimated that DNAPL compounds would leach from the ISS solidified region above cleanup criteria for a period exceeding 10,000 years. Therefore, ISS would not expedite the cleanup of contaminated groundwater at the Site, as is stipulated in the U.S. EPA Final Decision. Furthermore, at an estimated cost of approximately $88 million, ISS would be inordinately costly.

There are currently no unacceptable risks associated with the Site. ISS has a high potential to exacerbate site conditions, and would result in little or no overall gain in terms of reducing the cleanup time fame or Site exposure risks. Instead, ISS would introduce considerable new environmental and exposure risks during the remediation process. Therefore, in-situ solidification of residual DNAPL is not an effective or practicable technology to expedite groundwater cleanup at the OCC Site.

8.0 GROUNDWATER EXTRACTION AND TREATMENT

8.1 Process Overview

Groundwater extraction and treatment involves the placement of purge wells to collect impacted groundwater and the treatment of the collected groundwater prior to discharge to a surface water body or back into the ground. The objectives of groundwater extraction include removal of dissolved contaminants from the subsurface, and containment of contaminated ground water to prevent migration. The dissolved plume of chlorinated organic compounds is currently collected and treated down gradient of the DNAPL zones at the GSH site.

The groundwater plume from the DNAPL source areas is fully contained by the current groundwater collection and treatment system. A system of eight extraction wells collects 1 million gallons per day (mgd) of groundwater; chlorinated organic compounds are removed from the groundwater through treatment with granular activated carbon; and the treated groundwater is discharged through an NPDES permitted outfall into White Lake. This system currently completely and effectively halts the flow of groundwater containing chlorinated organic compounds to White Lake. The current groundwater extraction and treatment system has proven effective. A monitoring program documents that the impacted groundwater is completely captured and that no unacceptable exposure occurs to human or ecological receptors. The treated groundwater is monitored to comply with an NPDES permit, and the discharge to White Lake meets the applicable criteria. In addition, the current extent of the plume is stable. Monitoring of perimeter wells at the site documents that the plume boundary is not expanding and that the current groundwater collection system adequately captures the entire plume (e.g., CRA, 2009).

An alternate remedial strategy could include the placement of more groundwater extraction wells at the site. This section evaluates further remediation of approximately the lower one-third portion of the groundwater contaminant plume, roughly extending from the southern limit of the southern-most residual source area at the Former Equalization Pond Area, south of Old Channel Trail to the existing groundwater extraction well network.

Installation of the current extraction well system was initiated in the 1980s. The groundwater capture system has a performance record from the 1990s to present documenting that it captures the dissolved plume from the DNAPL areas. A summary report is prepared annually documenting the system performance over the previous year (e.g., CRA, 2009). The purge wells induce capture at the lake boundary, and draw water back from White Lake, preventing dissolved-phase chlorinated VOCs from entering White Lake.

As an enhancement to the current extraction well system, six additional extraction wells could be installed up gradient of the current extraction wells, in order to internally capture the plume and reduce contaminant concentrations prior to reaching the barrier extraction wells at White Lake. The generalized location of a potential enhanced groundwater extraction system is presented conceptually and schematically in **Figure 21**, and is discussed below.

The new wells could be located south of known DNAPL areas at the site (Earth Tech, 2003). In addition, the purge wells shown in Figure 21 are also down gradient of other potential impacted soil areas identified in the Phase II DNAPL Report (Earth Tech, 2003) and the RCRA Facility Investigation (Earth Tech, 1999): south of the former chemical sewer going from the Former Fine Chemical Production Area to the Former Equalization Pond Area; south of the Former Equalization Pond Area; and south of the Southern Exposure Area.

Achieving cleanup criteria in the southern portion of the plume would allow GSH to turn off the purge wells adjacent to White Lake. With the implementation of the deed restrictions and the shut-off of the purge wells along White Lake, the lakefront property owned by GSH would likely become developable shoreline.

The new extraction wells could be installed to a depth of 110 feet bgs with 20-foot long screens set from 90 to 110 feet bgs. Each well could be individually plumbed through underground piping to a new treatment system building, with separate controls for each well.

The current groundwater treatment system uses granular activated carbon to treat the extracted groundwater. The system is capable of treating up to 700 gpm of groundwater total or 350 gpm through each set of carbon units. It is assumed groundwater from the additional extraction wells could be treated in a new, similarly arranged, granular activated carbon treatment system. A conceptual layout of the location of the conceptual extraction well system enhancement is presented in **Figure 21**.

8.2 Health and Safety Concerns

Implementing additional groundwater extraction and treatment at the Site will not reduce exposure to the contaminants. Baseline exposure under the existing conditions is within acceptable exposure guidelines and standards. Previous remediation activities at the site (Section 1.5.4) included excavation and placement in a secure landfill, the cover of isolated soil areas, and the implementation of a groundwater collection and treatment system. With these remedial activities, and continued operation of the existing groundwater collection system, there is no unacceptable exposure to the contaminants in the DNAPL (Earth Tech, 2000a and Earth Tech, 2002b). However, the risk of exposure to contaminants would increase during additional groundwater extraction and treatment.

8.2.1. Exposure Potential

The construction of an additional groundwater extraction system increases the exposure of the chlorinated organic compounds in the DNAPL that exist at the site through direct contact to workers during construction and operation of the system.

Installation of Extraction Wells

During drilling of the six new extraction wells, workers may be exposed to drilling cuttings and groundwater contaminated with chlorinated VOCs. Workers will be potentially exposed to impacted soils via incidental ingestion, dermal contact, and inhalation. Thus, exposure pathways are deemed potentially complete for the worker receptor group.

Trenching for Transmission Piping

Trenching to place transmission piping for the new extraction wells will be relatively shallow (less than 6 feet of overburden). It is unlikely the overburden is extensively impacted, but some areas of impact may exist. Because some chemical impacts may exist in portions of the overburden material, exposure are pathways are deemed potentially complete for the worker receptor group.

Waste Transportation

Waste materials (soils and/or groundwater produced during trenching, drilling, decontamination, well development activities and spent carbon) are expected to be generated during construction of the extraction and treatment system. Impacted soil and/or water will require off-site transportation and disposal. The waste material is expected to be hauled in trucks that will be covered with tarps to minimize dust and fugitive emissions. Despite such precautions, a finite (though limited) quantity of volatile emissions and dust are anticipated. Such emissions are anticipated to result in limited exposures to workers, non-workers, and ecological receptors via the inhalation pathway. Pathways leading to worker, non-worker and ecological receptor exposures are considered complete during waste transportation activities.

Transportation Accident

The likelihood of an accident occurring that would result in significant release of waste chemicals is expected to be low. Regardless, there is a finite potential that a transportation accident may occur, which would result in a release of waste material. In the event of such an incident, workers (i.e., truck drivers) may inadvertently contact waste material directly and be exposed via the ingestion, dermal and inhalation exposure routes. Emergency response procedures are expected to result in rapid containment of the

spilled waste material, but the potential exists for chemical emissions to be released to the air. Such emissions may potentially contact non-worker and terrestrial ecological receptors via the inhalation route. Therefore, pathways leading to worker, non-worker, and ecological receptor exposures are considered complete in the event of a transportation accident.

8.2.2. Worker Safety

Worker safety concerns typical for trenching, drilling, and general construction activities exist during the construction of a groundwater extraction and treatment system. A Health and Safety Plan would be prepared to address potential worker safety concerns.

8.3 Clean-up Timeframe

While the period of time required to treat the groundwater at the DNAPL areas would not be decreased by treating the dissolved plume down gradient of the DNAPL zones, the period of time required to achieve cleanup criteria within a portion of the dissolved plume (roughly the lower one-third portion of the plume) could be reduced. The contaminant fate and transport of contaminants of concern was evaluated using the U.S. EPA analytical model, REMChlor (see Section 3.7). The model was used to estimate cleanup timeframes of groundwater between the conceptual six purge wells located south of the Former Equalization Pond Area and the existing purge well network located along White Lake. In the evaluated scenarios, the source areas were removed, since the groundwater collection system would isolate the down gradient portions of the aquifer from the DNAPL source areas. This is similar to the 90% removal, but in this scenario, the source area is assumed to be eliminated from any impact on the down gradient portion of the aquifer. The core of the PCE plume is located west of the Former Equalization Pond Area; so a simulation was run which used the maximum observed PCE concentration as an initial concentration with no source since the proposed six purge wells are assumed to cut off the plume. The estimated cleanup timeframe for this simulation is 18 years. The modeled outputs are provided in **Appendix C**.

DNAPL compounds from the source area would leach into groundwater at the DNAPL source zones, and the period of time required to achieve cleanup criteria under the DNAPL source areas of the former industrial site area would not change.

8.4 Cost Estimate

This groundwater extraction and treatment scenario is estimated to cost approximately $1.91 million to complete, including pre-implementation design costs.

The most costly items encountered during the scope of the groundwater extraction and treatment project are anticipated to include the construction of the carbon treatment vessels, drilling and construction of the extraction wells, and trenching and installation of transmission piping. Construction of the carbon treatment system is estimated to cost approximately $835,000. Drilling and construction of the extraction wells would cost approximately $491,000 and it is estimated that it would cost approximately $402,000 to complete the trenching and installation of transmission piping. Additional costs of approximately $175,000 constitute design and construction labor costs. See **Table 10** for a more complete breakdown of estimated costs.

8.5 Carbon Emission Evaluation

One additional element in the review of treating the dissolved phase plume is an analysis of the environmental impact of the energy usage and subsequent carbon footprint produced during operation of the groundwater extraction and treatment system. Since Michigan obtains approximately 60% of its electricity from coal fired power plants (www.dleg.state.mi.us), the production of this energy would create significant CO_2 emissions. A cursory analysis has been performed to quantify the magnitude of these CO_2 emissions, and these emissions have been further related to a comparable carbon footprint in terms of natural woods or agricultural land.

The groundwater extraction and treatment system uses a number of groundwater extraction pumps and a transfer pump running constantly to accomplish its goal. The system would use four (4) 6-inch, 10 Hp submersible pumps, two (2) 4-inch, 5 Hp submersible pumps, and one (1) 700 gpm, 30 Hp transfer pump for the carbon treatment system. The total energy usage calculated to be required to operate these pumps on an ongoing basis is approximately 1,432 kWh per day.

A carbon footprint for the system was calculated on a yearly basis. At an assumed operation level of 100% for the year, approximately 522 megawatt-hours (MWh) will be required for the remediation system to operate over the period of one year. It is assumed that a portion of this energy will be obtained from the closest coal-fired plant, which is the BC Cobb plant located in Muskegon. This plant is a 500 MW plant (www.consumersenergy.com), which produces 4,380,000 MWh per year. Total CO_2 emissions from this plant in 2007 amounted to 2,278,267 tons (www.environmentalintegrity.org) Therefore, for every MWh produced, approximately 1,040 pounds of CO_2 is produced. At the usage and CO_2 production rates listed above, and assuming 60% of the remediation system's energy is obtained from the BC Cobb coal-fired plant, a total of approximately 163 tons of CO_2 will be emitted during one year of operation of the system. Converting these CO_2 emissions to a carbon footprint, we would require 9 hectares (ha) of natural woods or 12 ha of agricultural land to offset the CO_2 produced.

In conclusion, it is technically possible to expedite cleanup of a portion of the plume using groundwater capture and treatment. However, the treatment area constitutes approximately the lower one-third portion of the plume which is already captured by an existing ground water treatment system. The additional cost, additional potential worker exposure, and impact to the environment would not be off-set by any gain in reduced exposure for human health and the environment over conditions as they exist with operation of the current groundwater treatment system. In addition, the EPA would be requiring additional remediation to reduce constituents to levels in the groundwater in portions of the aquifer where no groundwater will be used as a source of drinking water. Since there is no environmental benefit to expediting groundwater clean-up, only a future use benefit for a prohibited use, it is not practicable to require additional treatment of the dissolved phase plume.

8.6 Remedy Analysis Conclusion

Groundwater collection and treatment is already used. The existing system has proven to be effective and capable of prohibiting the expansion of the plume, and no unacceptable exposure is occurring. Additional extraction wells can be used to isolate a limited areas of the plume, but this method will have no impact on the overall time required to achieve cleanup levels in groundwater at the DNAPL source zones and overall at the GSH Site. The area potentially treated comprises the lower one-third portion of the plume in an area where there is no current use of the groundwater and future use will be restricted by institutional controls.

GSH is in the process of placing a institutional controls in the form of deed restrictions on their property to prohibit the use of ground water as a source of drinking water or other private usages. The deed restriction was reviewed by U.S. EPA and the Michigan Department of Environmental Quality. Since it will be restricted that this groundwater will not be used as a source of drinking water or other use, treatment of the groundwater in this portion of the plume is not needed to achieve clean up levels that are based upon drinking water criteria.

There is a small portion of the plume that flows under adjacent off-site properties. The aquifer is not used as a source of drinking water under these off-site portions of the plume. In this area, GSH has provided the homes with a source of drinking water in the form of City water, and pays for the drinking water at these residences. In addition, GSH contributed to the cost to upgrade the distribution system for the drinking water in this area and also contributed to the cost of a new municipal drinking water well for the City of Montague to assure a reliable and continued source of drinking water to these residences. Therefore, there are no drinking water wells in the down gradient area of the plume, and there is no anticipated future use of the groundwater as a source of drinking water.

9.0 APPLICABLE TI ZONE

To comply with the current Statement of Basis (U.S. EPA 2001a) and Final Decision (U.S. EPA, 2001b), the cleanup criteria presented earlier in Section 2 need to be achieved throughout the plume at the Montague site. These cleanup criteria were established to protect the groundwater resource for use a source of drinking water and for discharge to surface water with no dilution. EPA has established a goal of restoring contaminated groundwater within a reasonable timeframe at RCRA Corrective Action sites. Since the available technical review, bench studies, and full pilot studies document that it is technically impracticable to achieve the cleanup criteria throughout the plume in a reasonable time frame, this document is requesting that EPA's modify the goal of restoring the contaminated groundwater to drinking water standards within a reasonable timeframe. This modification includes two elements: first, an alternate remedial strategy to assure protection of human health and the environment, and second a TI zone where the technical impracticability waiver will apply.

9.1 Alternate Remedial Strategy

The alternate remedial strategy will be implemented to assure protection of human health and the environment during the period during which the TI waiver would apply. The alternate remedial strategy consists of the elements of the Final Decision which have already been implemented and have been proven to be protective of human health and the environment and also been proven to maintain the dissolved groundwater plume within stable boundaries. This includes the removal of source areas and impacted soils which has already occurred, maintaining the existing groundwater collection and treatment system, and continued mechanisms to assure that the impacted groundwater is not used as a source of drinking water.

The process for developing the alternate remedial strategy for the Site is described in Section 5 of the *Guidance for Evaluating Technical Impracticability of Ground-Water Restoration* (U.S. EPA, 1993b). The guidance document states that "alternative remedial strategies typically will address three types of problems at contaminated ground-water sites: prevention of exposure to contaminated ground water; remediation of contamination sources; and remediation of contaminant plumes.' (page 19, Section 5.1)

There is no current or future anticipated use of the groundwater as a source of drinking water under any portion of the plume. GSH is implementing an enforceable deed restriction for the plume under the site. This deed restriction follows the standard deed restriction used in the State of Michigan by the MDEQ for contaminated property, and has been reviewed by attorneys representing both the MDEQ and the U.S. EPA. GSH is providing drinking water for the limited area where the groundwater plume flows off-site and then back on-site. GSH contributed financial support for a new municipal water well to assure a stable source of drinking water for these residences and pays the water bills for these residences.

Source control has been accomplished at the site to the extent practicable. The DNAPL sources have been removed from the site. Operations that utilize the chemicals originally released have been eliminated at the site. No chemical manufacturing has occurred at the site for over 25 years. In addition, the impacted soils under the major source areas where excavated and placed in a landfill. The residual, secondary sources of DNAPL within the aquifer still remain and are technically impracticable to remove.

The dissolved aqueous plume is currently being remediated. The U.S. EPA states that "plume containment offers the potential advantages of preventing further spreading of the contaminated ground water, thereby limiting the size of the plume, and preventing the plume from encroaching on water-supply wells or discharging to ecologically sensitive areas." The existing groundwater collection system accomplishes all of these potential advantages. Ecological receptors are present in White Lake, and the current purge wells prohibit the discharge of impacted groundwater to White Lake at concentrations that are not protective of receptors in White Lake. The current system also has an established and proven method to monitor the effectiveness of the system, both at maintaining a gradient back toward the purge wells from White Lake and also at maintaining the groundwater plume within stable boundaries. There are no water supply wells in the plume, and the plume is not encroaching on any water supply wells. Furthermore, the environmental indicator completed by the U.S. EPA has documented that the plume is not spreading but is stable based upon the current remediation system already in place for the dissolved plume.

9.2 TI Zone

Part of developing an alternate remedial strategy is to define the area where the technical impracticability waiver will apply – this area is referred to as the TI zone. The Guidance for Evaluating the Technical Impracticability of Ground-Water Restoration (U.S. EPA, 1993b page 12, Section 4.4.2) states that "the TI evaluation should specify the horizontal and vertical extent of the area for which the TI determination is sought. Where EPA determines that the ground-water restoration is technically impracticable, the area over which the decision applies (the 'TI zone') generally will include all portions of the contaminated groundwater that do not meet the required cleanup levels (contaminated ground-water zone), unless the TI zone is otherwise defined by the EPA." GSH has delineated the TI zone spatially, both horizontally and vertically, and this section presents the precise boundaries requested for the TI zone.

A plan view of TI zone is presented in Figure 14. The TI zone for the Site is delineated spatially and is based on the following factors:

1. The established plume boundary representing concentrations of compounds above established cleanup criteria for the site.
2. Established perimeter groundwater monitoring boundary that can document compliance with the TI zone.
3. Known hydraulic boundary conditions established at purge well network near White Lake.
4. Known vertical aquifer boundaries (contact between the upper sand aquifer and the lower clay).

On the north side of the TI zone, the boundary is based on three related factors. First, the northern boundary is based on the extent of the AOCs which were source areas for the DNAPL: AOC 3 – the Former Primary Disposal Area and AOC 5 – the Former Primary Ash Disposal Area. Second, the northern boundary is based on the known extent of residual DNAPL in the aquifer. Third, the northern boundary is based on the existing up gradient monitoring wells that can be used to document compliance with groundwater criteria for the Site.

The western edge of the TI zone shown in **Figure 14** is based on three factors. First, the western extent of AOCs that were related to DNAPL source areas, including the Former Primary Disposal Area and the Former Fine Chemical Production Area. Second, the western extent is based on the western extent of DNAPL present at the site. Finally, the western extent of the TI zone is also consistent with the extent of impacted groundwater related to the DNAPL residual areas.

The southern edge of the TI zone that is presented in **Figure 14** is based on the hydraulic boundary with White Lake. At this boundary, the current purge well network captures all impacted groundwater and prohibits the discharge of chlorinated organic compounds into White Lake. This known hydraulic boundary at the lake also represents a boundary based on receptors, as there are no receptors in the plume until the groundwater would discharge to White Lake if the purge well network were not in place.

The eastern boundary is based on three factors. First, the eastern extent of the TI zone is based on the eastern extent of the Former Primary Ash Disposal Area. In addition, the eastern extent is also based on the eastern extent of the Southern Exposure Area discussed in the Phase II RFI (Earth Tech, 1999) and the human health and ecological risk assessment for the facility (Earth Tech, 2000a).

The vertical aspect of the TI zone extends from the groundwater surface to the Lower Clay Surface which is established as a site hydraulic boundary. The vertical extent or depth of the TI zone is defined in relative terms as a definable geological boundary consistent with Section 4.4.2 of U.S. EPA, 1993b, where the lower geological boundary is the boundary between the Upper Sand Unit and the Lower Clay Surface. The vertical extent of the TI zone is not defined in absolute terms (e.g., measured elevations), due to the size of the site and variation of the absolute measurement of the geologic boundary.

The TI zone at the OCC Site corresponds to the plume boundary, and has an area of approximately 300 acres with a thickness of approximately 100 feet (see Figure 7). Other TI zones already approved by U.S.

EPA range from 640 square feet to 28,000 acres, with an average depth of 200 feet at reviewed sites (U.S. Army Environmental Center, 2004).

9.3 Precedence & TI Zone Justification

The recommended TI zone is protective of human health and the environment. While U.S. EPA may consider alternate TI zones which reduce the size of the area covered by the TI zone by requiring additional dissolved phase treatment, these alternate TI zones do not offer any additional protection to human health and the environment. The additional aqueous plume remediation also provides no additional advantages to the current system as defined by U.S. EPA in Section 5.1.3 of the TI guidance (U.S. EPA, 1993b) as discussed above.

GSH reviewed a total of 48 CERCLA sites that have obtained TI Waivers through the EPA or a state-level supported TI review process (U.S. Army Environmental Center, 2004). Of these 48 sites, 20 of these sites received waivers prior to the implementation of the EPA OSWER Guidance of 1993. One site, (the Continental Steel Corporation Site, in Kokomo, Indiana) was granted a TI Waiver through Region 5 EPA, with regulatory support from Indiana Department of Environmental Management.

The TI Waiver at Continental Steel was based on 1) inferred presence of DNAPL, 2) contaminant fate modeling suggesting that groundwater pump and treat remediation not being practicable within a reasonable timeframe, and 3) emplacement of groundwater use deed restrictions. The TI zone for the Continental Steel Site was based on contaminant plume boundaries and defined hydrogeological vertical boundaries or aquifer zones (EPA/ROD/R-05-98/091).

Of the 48 sites, the majority of TI zones in approved TI waivers were based on DNAPL source areas or plume boundaries (U.S. Army Environmental Center, 2004). TI zones defined on plume areas were influenced by technical inability to remove source areas and presence of containment systems (e.g., pump and treat systems) installed to control plume migration (as is the case at the GSH Montague Site).

The G.E. Moreau Site, Saratoga County, New York is an example of a site with a several thousand foot long chlorinated VOC plume that constitutes a TI zone. The G.E. Moreau Site is a former chemical plant site with an estimated 4,800-foot long chlorinated VOC plume that vents to a down gradient surface water body. Contaminated groundwater was treated through a stripper tower located at the surface water body. Estimates for cleanup were modeled to be >200 years to reach ARARs. Based on models of natural gradient flushing versus pump and treat scenarios that indicated that “doing nothing” was more cost-effective than treatment, a TI Waiver was granted.

G.E. Moreau Site is similar to the GSH Montague Site in having:

- Long operational histories with multiple source releases
- Presence of long diffuse and co-mingled chlorinated VOC plumes
- Presence of residual DNAPL source areas
- TI zones based on technically impracticable restoration of groundwater due to presence of residual DNAPL areas
- Existence of an operating groundwater pump and treat barrier system

10.0 CONCLUSIONS

The combinations of remedial actions that have been performed at the site over the last 30 years have successfully eliminated any unacceptable risks to human health and the environment from residual contamination remaining at this former chemical manufacturing facility. GSH has evaluated methods to expedite achieving the groundwater cleanup criteria in the aquifer where DNAPL is present. At this time, no technically feasible options are available to effectively and safely expedite achieving groundwater cleanup criteria throughout the aquifer. This section presents the conclusions on the current remedial actions, then discusses the technologies that were reviewed further, and concludes with a commitment to continue a regular review of the effectiveness of the existing system.

10.1 Current Remedial System Potential

Under the current remedial system, there is no unacceptable exposure to constituents present at the site. All impacted groundwater is captured by the purge well system. The impacted groundwater is not used as a source of drinking water. No unacceptable exposure is present from the constituents present at the site.

GSH currently operates a pump and treat system in which groundwater is pumped from eight purge wells, treated with activated carbon vessels, and discharges into White Lake under and NPDES permit. The system is operated in conjunction with a Groundwater Monitoring Program, which was approved by the U.S. EPA and MDEQ in January 2002. The following objectives are established for the Site under the Groundwater Monitoring Program:

- Demonstrate that the groundwater collection system halts any unacceptable discharge of chlorinated organic compounds to White Lake.
- Demonstrate, through monitoring, that the contaminated plume is stable and that impacted groundwater remains within the original “area of contamination”.
- Develop information that will be used for future demonstration that the groundwater collection system is reducing the level of contamination in the aquifer.

The results from 2008 groundwater monitoring are presented in the 2008 Annual Groundwater Report (Conestoga-Rovers & Associates, 2009; see **Appendix B**).

In 2008, over 100 water levels were collected from six water level performance monitoring wells located between the purge wells and White Lake. Results document that an inward hydraulic gradient was maintained at all times in 2008 with surface water from White Lake being drawn toward the purge wells. Furthermore, the yearly average water level differentials between the six wells and White Lake ranged from 0.25 to 0.55 feet, far exceeding the required differential of 0.1 feet drawdown at these monitoring wells. The system has been continuously operative with maintenance upgrades since the early 1980’s.

Analytical results for the 2008 semi-annual boundary demonstration monitoring show that the concentrations of all COCs are below the applicable groundwater protection standards outside of the defined plume boundary. These results confirm plume stability within the boundary of impacted groundwater delineated in the RFI.

The groundwater collection and treatment system is proven, effective and reliable. In 2008, the average monthly flow rate for the purge well system was approximately 633 gallons per minute. A total of approximately 334 million gallons of water were pumped in 2008. A total contaminant mass of approximately 6,800 pounds of chlorinated organic compounds was removed in 2008. 2008 annual data was consistent with past historical monitoring data.

10.2 Evaluated Remedial System Potential

GSH has thoroughly evaluated standard and innovative remedial approaches to treat residual DNAPL and expedite groundwater cleanup. This includes numerous bench studies of reductive and oxidative technologies, a pilot study on two different ISCO technologies, and a separate pilot study on ERD. These efforts have failed to identify a solution that can affectively treat the residual DNAPL to expedite groundwater cleanup.

GSH further evaluated two remedial alternatives as potentially feasible at the Site: Excavation of residual sources areas, and Solidification of residual source areas. A summary of these evaluated remedial options is presented below.

10.2.1. Excavation

Excavation would involve the removal of over 750,000 cubic yards of soil. Approximately 550,000 cubic yards of this soil would be disposed as hazardous waste at a licensed landfill, while the rest could be used as backfill. To mitigate potential exposure, the work would be conducted in "cells" under a moveable temporary structure. The excavation pit would be shored with temporary sheet pile. The placement of this shoring is expected to cause the DNAPL to mobilize deeper into the aquifer during the placement of the shoring and cause the excavation to be ineffective at removing the DNAPL.

To evaluate this process, GSH assumed that 90% of the residual DNAPL could be removed (approximately 511 tons). After the excavation activities, DNAPL retention in aquifer would be attributed to several factors, including mobilization of DNAPL through pumping and vibrational shock, potential that unidentified stringers of DNAPL are still present, technical limits to attaining target excavation depths, and potential for DNAPL to be present in areas not identified. The remaining DNAPL would continue to act as a source area of DNAPL compounds to groundwater.

It is estimated that, after 90% of residual DNAPL is removed, the time necessary to meet the target cleanup criteria would still be approximately 4,900 years (see Section 6.4). Therefore, excavation and disposal would not result in a significantly expedited cleanup timeframe for contaminated groundwater, as is stipulated in the U.S. EPA Final Decision (U.S. EPA, 2001b).

10.2.2. In-Situ Solidification

ISS is a process that would use a large vertical auger to mix a cementing agent into soils containing residual DNAPL, resulting in a solidified mass of greatly reduced permeability. To mitigate potential exposure, the work would be conducted in "cells" under a moveable temporary structure.

The ISS process does not chemically bind organic compounds, and would result in no direct removal of the residual DNAPL. It is estimated that there are 568 tons of residual DNAPL at the Site, and all of this would remain after implementation of ISS.

Contaminants would still leach from the solidified mass when exposed to water. Because groundwater would preferentially flow through the un-solidified sands around the treatment area, the rate of leaching is expected to decrease. However, even with a decreased leachate rate, contaminants are still expected to leach into groundwater above the target cleanup criteria. As discussed in Section 7.3, the cleanup timeframe is anticipated to generally increase and the time necessary to meet target cleanup criteria is still more than 10,000 years. Therefore, ISS would not result in an expedited cleanup timeframe for residual DNAPL or contaminated groundwater, as is stipulated in the U.S. EPA Final Decision.

Furthermore, the solidification process poses a significant risk for mobilizing the DNAPL into lower portions of the aquifer that are not currently impacted with DNAPL, thus exacerbating the cleanup of the site. In addition, lowering the permeability of the aquifer at DNAPL locations down gradient from other DNAPL locations (Former Fine Chemical Production Area and the Former Equalization Pond Area) will modify the flow path of the groundwater and is expected to change the size of the dissolved plume, increasing the dissolved plume beyond the current boundaries.

10.3 Cost Evaluation

A cost evaluation was performed to compare the costs of operating the current pump and treat system to relevant remedial technologies. Operating and maintaining the current groundwater pump and treat system costs approximately $1,200,000 annually. This includes operation, maintenance, labor, sampling, upgrades as necessary, and activated carbon purchase and disposal. Costs associated with purchase and disposal of activated carbon total approximately $200,000 of the $1.2 million annual costs.

The cost to excavate and dispose soils containing residual DNAPL is estimated to be approximately $145 million (see Section 6.5). The cost to implement ISS treatment of soils containing residual DNAPL is estimated to be approximately $88 million (see Section 7.4). It is important to note that these costs only include items directly related to the implementation of the respective technology. There would be additional pre-implementation costs, including engineering design, contractor procurement, and permitting; a full scale pilot study would also be necessary before implementing ISS. Since these remedial activities do not significantly reduce the time required to achieve groundwater cleanup criteria, the costs to operate the groundwater collection and treatment system would also be required to continue. The cost evaluation is summarized in the table, below:

	Existing Pump and Treat System	Excavation and Disposal	In-Situ Solidification
Pre-Implementation Design	N/A	$7 million	$5.5 million
Implementation	N/A	$145 million	$88 million
Post-Implementation (Groundwater monitoring and Pump & Treat)	$1.2 million annual (Ongoing)	$1.2 million annual (Ongoing)	$1.2 million annual (Ongoing)

10.4 Additional Groundwater Collection and Treatment

The addition of a second line of purge wells to treat the groundwater at the site will not reduce any current or future risks posed by the site. The recommended TI zone is protective of human health and the environment. While U.S. EPA may consider alternate TI zones which reduce the size of the area covered by the TI zone by requiring additional dissolved phase treatment, these alternate TI zones do not offer any additional protection to human health and the environment. The additional aqueous plume remediation also provides no additional advantages to the current system as defined by U.S. EPA in Section 5.1.3 of the TI guidance (U.S. EPA, 1993b) as discussed above. Deed restrictions will prohibit the future use of the groundwater as a source of drinking water. The remaining area of the plume has a municipal water supply that is provided by the City of Montague and paid for by Glenn Springs Holdings. The plume is proven to be stable and not expanding. The current groundwater collection system prohibits the any impacted groundwater from discharging to White Lake. The additional cost and impact to the environment would not be off-set by any gain in reduced exposure for human health and the environment. Since there is no environmental benefit to expediting groundwater clean-up; only a future use benefit for a prohibited use, it is not practical to require additional treatment of the dissolved phase plume.

10.5 Summary of Technical Impracticability (TI)

This TI Evaluation presented a post-implementation evaluation after 30 years of active remediation, after investigation, after extensive contamination source removals, after additional remedial actions, and after bench and pilot testing of traditional and experimental chemical, biological and physical treatment technologies. Site conditions are well known and understood, and offer unique challenges for residual source area remediation and restoration of groundwater conditions. The inter-bedding of fine silt and clay layers in the sandy aquifer has retained the DNAPL within the upper portion of the thick sand aquifer, leading to complex site DNAPL architecture, and as a result, technically impracticable applied remedial options at this time.

This TI Evaluation centers upon an estimated mass of 568 tons of residual contaminants residing primarily as DNAPL in the upper sand aquifer at the Site. Several remedial options are evaluated in this

TI Evaluation. Innovative chemical and biological methods to address DNAPL have been evaluated through bench and pilot studies and shown to be ineffective at treating the DNAPL. Physical methods to address the DNAPL (excavation and solidification) were evaluated further in this report. From a human exposure perspective, residual contaminant removal/isolation or treatment increases risks compared to leaving the residual material in place due to 1) increased exposure scenarios (excavation) and 2) contaminant mobilization (excavation, isolation and solidification).

This TI Evaluation presented is consistent with and meets the applicable criteria under the TI Guidance (U.S. EPA, 1993b). This TI Evaluation was also based on TI Outline presented to U.S. EPA and approved on February 5, 2009. Technical impracticability of groundwater restoration at the Site is demonstrated by the following factors:

- Based on the preponderance of the evidence, residual DNAPL has been identified in four geographically wide-spread source areas.
- Multiple technologies have been evaluated at the Site through bench or pilot studies, including a variety of ISCO reagents, biological ERD, and ZVI reductive dechlorination. None of these technologies were effective in safely treating DNAPL at the Site.
- Predictive groundwater restoration modeling estimates of 4,900 years to reach target groundwater cleanup goals for C-56, using excavation of DNAPL at Former Primary Disposal Area (worst case example), and >10,000 years for C-56, using ISS of DNAPL at Former Primary Disposal Area (worst case example).
- Inordinately high costs for excavation ($145 Million) and ISS ($88 Million), compared to existing ground water capture costs of $1.2 Million annually.
- Potential and likelihood that excavation and ISS would mobilize both DNAPL-phase and dissolved phase contaminants, driving impact outside of capture system and deeper into upper sand aquifer, or underlying aquifer systems.
- Increased human exposure risks during excavation and ISS options.
- Practical infeasibility that ISS addresses remediation of “residual waste areas” noted in Final Decision (instead, DNAPL would still be in-place in the Upper Sand Aquifer).
- Practical infeasibility that excavation of toxic chemicals (C-56 and related compounds) below water table could be safely performed.
- Lack of any of the potential advantages defined by U.S. EPA for additional aqueous plume remediation.

At this time, after a thorough and on-going analysis of remedial options, no suitable technology or combination of technologies exists to safely remove or treat residual contamination and restore groundwater conditions at the Site. For these reasons, a TI Waiver is warranted for the Site.

10.6 On-Going Technology Review

The determination that groundwater restoration is technically impracticable will be subject to future review by U.S. EPA. Assurance that the existing remedy is maintained and continues to be protective of human health and the environment are already incorporated into the requirements of the UAO and the Final Decision (U.S. EPA, 1993a and U.S. EPA, 2001b). A monitoring program is already established to demonstrate that the groundwater plume is stable and that there is no unacceptable discharge to White Lake.

Each five years, GSH proposes to perform an evaluation of the TI Decision consistent with U.S. EPA guidance (U.S. EPA, 1993b). It may become necessary to modify the requirements for site activities to reflect new information that becomes available during the remedy implementation and monitoring; further, additional measures may be required in the future if subsequent advances in remediation technology

make attainment of groundwater cleanup goals technically practicable (U.S. EPA, 1993b). GSH will present a review of the data that becomes available during the implementation of the site remedy and also an evaluation of advances in remedial technologies in a written report to the U.S. EPA each five years.

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TABLES

TABLE 1. REGULATORY HISTORY
FORMER OCCIDENTAL CHEMICAL SITE; MONTAGUE, MICHIGAN

Year	Activity
1952-1954	Chemical plant constructed in Montague Township, Muskegon County, Michigan
1954	Plant begins operations, using fossil brine for "electrolytic" chemical process Chlorine gas, hydrogen gas, muriatic acid, anhydrous HCl and caustic "soda" produced
1956	Production of C-56 begins
1960's	Full Operation continues
1977	C-56 production ceases Caustic soda and chlorine and hydrogen gas production continues
1979	State of Michigan Consent Order Judgment (MICJ) issued
1979-1981	Occidental Chemical Corporation complies with MICJ Fine chemical production facilities and waste materials placed in secure landfill Approximately 1 million cubic yards of contaminated soil excavated and placed in landfill Purge well groundwater capture system, activated carbon treatment system and monitoring wells installed
1982	Remaing production of caustic soda, chlorine and hydrogen gas ceases
1985	Purge well pumping increased to 1 million gallons per day (mgd) Eight purge wells fully capture contaminant plume upgradient from White Lake
1993	U.S. EPA Region 5 issues a Unilateral Administrative Order (UAO) for RCRA Corrective Action
1994	Description of Current Conditions completed
1999	RCRA Facility Investigation completed
2000	Human Health & Ecological Risk Assessment completed Corrective Measures Study for soil and groundwater completed
2001	U.S. EPA Region 5 issues "Final Decision and Response to Comments" Eight remedial components are specified: 1. Continued collection of contaminated groundwater 2. Evaluate and implement feasible on-site treatment to expedite groundwater cleanup 3. Implement groundwater monitoring to assure long term integrity of remedial action 4. Excavate surface soil that exceeds cleanup goals at the Former Small Disposal Pile area 5. Provide soil cover and seeding at the Former Burn Pit Exposure Area 6. Dredge impacted White Lake sediments near the former outfall 7. Maintain site access controls as necessary 8. Implement institutional controls to restrict land and groundwater use
2002	On-Site Soil Corrective Actions completed
2003	Delineation of DNAPL completed Preliminary evaluation of technology to treat DNAPL completed White Lake Sediment Dredging completed
2004	Initial bench tests on DNAPL treatment using ISCO, ERD, and EZVI completed
2005	Additional bench tests on ISCO completed with improved laboratory controls Fundamental chemical parameters developed in laboratory tests for C-56 and C-58
2006	ISCO Pilot Test Results submitted to EPA Region V Supplemental On-Site Soil Cover completed
2008	ERD Pilot Test Results submitted to EPA Region V

TABLE 2. SUMMARY OF SITE REPORTS
FORMER OCCIDENTAL CHEMICAL SITE; MONTAGUE, MICHIGAN

Date	Investigative Report	Source
January 1979	MDNR Staff Report at the Hooker Chemical Site	Michigan Department of Natural Resources
May 1979	Michigan Consent Judgment (MICJ)	State of Michigan
September 1981	Final Report: Groundwater Monitoring program. Occidental Chemical Corporation	Canonie-D'Appolonia
October 1981	Design Basis for Final Ground Water Pollution Control System at the Montague, Michigan Plant	Walker Wells, Inc.
March 1988	Site Analysis Hooker Chemical Company, Montague, Michigan Vol. 2.	U.S. EPA
March 1993	USEPA Unilateral Administrative Order (Docket V-W-009-93)	U.S. EPA
January 1994	RCRA Facility Investigation: Task I Description of Current Conditions	WW Engineering & Science
January 1994	Occidental Chemical Corporation Montague, Michigan Facility Interim Measures Work Plan.	WW Engineering & Science
September 1994	Residential Water Well User Survey for the Occidental Chemical Corporation Facility located in Montague, Michigan.	Earth Tech
October 1996	Phase I RCRA Facility Investigation Report for the Occidental Chemical Corporation Site in Montague, Michigan	Earth Tech
April 1999	Phase II RCRA Facility Investigation Report for the Occidental Chemical Corporation Site in Montague, Michigan.	Earth Tech
September 2000	Human Health and Ecological Risk Assessment for Soil and Groundwater for the Occidental Chemical Corporation Site in Montague, Michigan.	Earth Tech
October 2000	Results of the Investigation and Evaluation of White lake Sediments: Phase II RFI at the Former Occidental Chemical Corporation Facility, Montague, Michigan.	Earth Tech
December 2000	Corrective Measures Study for Soil and Groundwater for the Former Occidental Chemical Corporation Site Montague, Michigan.	Earth Tech
February 2001	Statement of Basis for Occidental chemical Corporatioon Montague Township, Michigan	U.S. EPA

TABLE 2. SUMMARY OF SITE REPORTS
FORMER OCCIDENTAL CHEMICAL SITE; MONTAGUE, MICHIGAN

Date	Investigative Report	Source
July 2001	Final Decision and Response to Comments for Occidental Chemical Corporation Montague Township, Michigan	U.S. EPA
November 2001	Results of the Investigation and Evaluation of White Lake Sediments During 2001	Earth Tech
February 2002	Documentation and Certification Report for On-Site Soil Corrective measures at the Occidental Chemical Corporation Site in Montague, Michigan	Earth Tech
May 2002	Phase I of the DNAPL Investigation at the Occidental Chemical Corporation Site in Montague, Michigan.	Earth Tech
November 2003	Phase II of the DNAPL Investigation at the Occidental Chemical Corporation Site in Montague, Michigan.	Earth Tech
March 2004	Dredging White Lake Sediment near the Former Occidental Chemical Corporation Site Montague, Michigan	Earth Tech
January 2005	Bench Test Results for Treatment of DNAPL at the Occidental Chemical Corporation Site in Montague, Michigan.	Earth Tech
November 2005	Supplemental Groundwater Characterization Data at the Former Occidental Chemical Corporation Site in Montague, Michigan.	Earth Tech
March 2006	Bench Test Results for Treatment of DNAPL at the Occidental Chemical Corporation Site in Montague, Michigan.	Earth Tech
June 2006	Pilot Test to Treat DNAPL at the Occidental Chemical Corporation Site in Montague, Michigan.	Earth Tech
March 2008	Pilot Test for Treating Chlorinated Compounds in Groundwater with Enhanced Reductive Dechlorination at the Occidental Chemical Corporation Site in Montague, Michigan.	Brown and Caldwell
June 2008	Summary of Deed Restrictions for he Occidental Chemical Corporatioon Site in Montague, Michigan	Earth Tech
December 2008	Evaluation of DNAPL Treatment at the Occidental Chemical Corporation Site in Montague, Michigan.	AECOM
December 2008	Evaluation of In Situ Thermal Desorption to Treat DNAPL as the Occidental Chemical Corporation Site in Montague, Michigan	AECOM

TABLE 3. SUMMARY OF COMPLETED REMEDIAL ACTIONS
FORMER OCCIDENTAL CHEMICAL SITE; MONTAGUE, MICHIGAN

Year Completed	AOC		AOC Description	Remedial Action Completed
1981	MICJ ACTIONS	AOC #1	(6) Barrels of waste oil and misc wastes	Waste Removal and Enclosure within Vault
1981		AOC #2	Brine sludge area	Waste Removal and Enclosure within Vault
1981		AOC #3	Drum Burial (Fly Ash Area)	Waste Removal and Enclosure within Vault
1981		AOC #4	Concrete [electrolytic] cell tops/bottoms	Waste Removal and Enclosure within Vault
1981		AOC #5	Primary Disposal Area	Waste Removal and Enclosure within Vault
1981		AOC #6	Fly ash pile and cell parts	Waste Removal and Enclosure within Vault
1981		AOC #7	Burn pit area	Waste Removal and Enclosure within Vault
1981		AOC #8	Original Brine Sludge Disposal Area	Waste Removal and Enclosure within Vault
1981		AOC #9	Primary Brine Sludge Disposal Area	Waste Removal and Enclosure within Vault
1981		AOC #10	Equalization Basin	Waste Removal and Enclosure within Vault
1981		AOC #11	Dried brine associated with deep wells	Waste Removal and Enclosure within Vault
Early to mid-1980's		Groundwater	Impacted Site groundwater	Installation of Purge Wells; Complete Plume Capture
2002		Burn Pits	Soil Cover, Seeding	On-Site Soil Corrective Action at Burn Pits
2002		Small Disposal Pile	Soil Excavation, Soil Cover, Seeding	On-Site Soil Corrective Action at Small Disposal Pile
2003		White Lake Sediments	Impacted Sediments in White Lake	Sediment Dredging
On-Going		Groundwater	Impacted groundwater	Long-term Monitoring under UAO
On-Going		Groundwater	Impacted groundwater	Complete Plume Capture and Treatment
2006		Miscelaneous Areas	Soil Excavation, Soil Cover, Seeding	Supplemental Soil Covered Areas
2007		AOC 3	DNAPL @ Former Primary Disposal Area	ISCO Pilot Test to Treat DNAPL
2008		AOC 3	DNAPL @ Former Primary Disposal Area	ERD Pilot Test to Treat DNAPL
On-Going		Site Areas	Un-related to AOCs	Re-vegitation of Site

TABLE 4. FACTORS AFFECTING GROUNDWATER RESTORATION POTENTIAL
FORMER OCCIDENTAL CHEMICAL SITE; MONTAGUE, MICHIGAN

	CHARACTERISTICS	Geralized Remediation Difficulty Scale (Increasing difficulty to the right))			COMMENTS
Site Use	Nature of Release	SMALL, SHORT, SLUG	MODERATE	**LARGE, LONG, CONTINUAL**	Historical release of amount of NAPL continued over the operational history of the plant from multiple source areas.
Chemical Properties	Biotic Decay Potential	HIGH	MODERATE	**LOW**	Documented inhibition of biological activity in bench and pilot studies. Documented lack of daughter products in dissolved plume extending away from DNAPL.
	Abiotic Decay Potential	HIGH	MODERATE	**LOW**	CT, PCE, and C-26 have long abiotic half lives; CT, PCE, and C-26 do not show abiotic decay in dissolved plume. C-56 and C-58 do have abiotic hydrolysis pathways.
	Volatility of Contaminants	HIGH	**VARIES**	LOW	C-56 and C-58 are main constituents in DNAPL and have low volatility. CT and PCE have relatively high volatility.
	Contaminant Retardation Potential	HIGH	MODERATE	**LOW**	CT, PCE, and C-26 have low retardation factors and are documented to migrate away from the DNAPL. Sandy aquifer has very low organic carbon content (0.02%).
Contaminant Distribution	Contaminant Phase	DISSOLVED	HIGH DISSOLVED	**NAPL**	NAPL has been documented to be present that is mixture of chlorinated organic compounds. NAPL observed by direct observation of NAPL in a well and also dyed NAPL in bulk aquifer core samples.
	Volume of Impact Media	SMALL	MODERATE	**LARGE**	Large estimated total contaminant mass of 568 tons.
	Contaminant Depth	SHALLOW	MODERATE	**DEEP**	DNAPL located approximately 25 to 70 feet bgs (site ranges) extending down into the sandy aquifer.
	Remedial Exacerbation Potential	LOW	MODERATE	**HIGH**	High potential since DNAPL is hung up in upper third to half of a sandy aquifer, held in place by capillary forces in sand and above silt layers. (Added from U.S. DOE, 1998).
Geology	Stratigraphy	SIMPLE	**MODERATE**	COMPLEX	Moderate to complex stratigraphy. While stratigraphy of the aquifer is mostly sand, there are discontinuous, thin layers of silt and clay that significantly influence DNAPL location and migration.
	Texture and Fabric of Deposits	SAND	**MIX**	CLAY	Primary sand facies with interlayered thin sequences of silt and clay.
	Degree of Heterogeneity	HOMOGENEOUS	**VARIES WITH DEPTH**	HETEROGENEOUS	Aquifer heterogeneity increases with depth. Lower aquifer (»600-660 feet amsl or approx. 100 feet bgs) deposits are increasingly more heterogeneous. Thin silt sequences also exist near water table throughout much of the Site.
Flow	Hydraulic Conductivity of Aquifer	**HIGH**	MODERATE	LOW	14-40 ft/day (Pump Tests Pe, WW-26, WW-27, MW-99-02, Earth Tech, 1999). Also reported values in the range of 50-70 ft/day for water table wells.
	Temporal Variation of Flow Regime	NONE	**MODERATE**	HIGH	Existing purge well system in-place. Regional hydrogeology subject to Great Lakes water level fluctuation. Rapid precipitation infiltration into well-drained soils.
	Vertical Flow	NONE	**VARIES AT SITE**	LARGE DOWNWARD FLOW	Gradient moderately but not strongly downward through DNAPL source areas which are in recharge areas for the aquifer.

Key	NOT SITE MATCH	**SITE MATCH**

TABLE 5. SUMMARY OF RELEVANT TECHNOLOGY EVALUATION
FORMER OCCIDENTAL CHEMICAL SITE; MONTAGUE, MICHIGAN

	Technology	Key References	Significant Risks	Conclusions
In-Situ Chemical Oxidation (ISCO)	**Fenton's Reagent**	-Bench Study *(Earth Tech, 2005)* -Pilot Study *(Earth Tech, 2006)*	-Exothermic Reaction -DNAPL mobilization	-Does not achieve significant reduction of DNAPL compounds -Studies show technology is not effective
	Persulfate	-Bench Study *(Earth Tech, 2006)*	-Salts would remain after treatment	-Studies show technology is not effective
	Ozone	-Bench Study *(Earth Tech, 2005)* -Pilot Study *(Earth Tech, 2006)*		-Does not achieve significant reduction of DNAPL compounds -Studies show technology is not effective
Other Chemical Technologies	**Zero Valent Iron (ZVI)**	-Bench Study *(Earth Tech, 2005)*		-Does not achieve complete mineralization of DNAPL compounds -Studies show technology is not effective
Biological Technologies	**Enhanced Reductive Dechlorination (ERD)**	-Bench Study *(Earth Tech, 2005)* -Pilot Study *(Brown and Caldwell, 2008)*		-Does not achieve complete mineralization of DNAPL compounds -Site conditions preclude effective ERD -Studies show technology is not effective
Physical Technologies	**Excavation and Disposal**	-Air Dispersion Model *(Section 7.2.1)* -GW Restoration Model *(Section 5.3)*	-Non-worker exposure -Worker exposure and safety -DNAPL mob. during dewatering -DNAPL mob. during sheet pile installation	-Exposure is a significant risk -DNAPL mobilization is a significant risk -Would not significantly reduce cleanup time of groundwater -Is inordinately costly ($145 million) -Technically impracticable (high exacerbation potential, exposure/safety risks, highly complex implementation)
	Surfactant Enhanced Aquifer Remediation (SEAR)		-DNAPL mobilization	-DNAPL mobilization is a significant risk -Technology would be ineffective because solubility of DNAPL compounds is too low
	Thermal Technologies	-ISTD Evaluation *(AECOM, 2008)* -RMA Case Study *(U.S. EPA, 2004b)*	-HCl Production -Dewatering failure -DNAPL mobilization -Exposure to vapors	-Exposure is a significant concern -DNAPL mobilization is a significant concern -Only attempted pilot study on C-56 failed with dangerous outcome (Rocky Mountain Arsenal in Denver, CO) -Technology is not feasible (complexities and risks are too great for implementation)
	In-Situ Solidification	-Air Dispersion Model *(Section 7.2.1)* -GW Restoration Model *(Section 5.3)*	-Non-worker exposure -Worker exposure and safety -DNAPL mob. during sheet pile installation -Groundwater flow alteration (out of capture)	-Exposure is a significant risk -DNAPL mobilization is a significant risk -Groundwater flow change (out of capture zone) is a significant risk -Would not reduce cleanup time of groundwater (instead would increase) or residual waste -Is inordinately costly ($88 million) -Technically impracticable (high exacerbation potential, exposure/safety risks, highly complex implementation)
	NAPL Extraction Methods			-DNAPL held by capillary force (not in pools) -Therefore, extraction would not be effective
Containment	**Physical Containment (DNAPL Isolation)**		-DNAPL mob. during sheet pile install -Groundwater flow alteration (out of capture)	-DNAPL mobilization is a significant concern -Groundwater flow change (out of capture zone) is a significant concern -Would not expedite cleanup of residual waste or contaminated groundwater
	Hydraulic Containment	-Documented Performance History	-None	-The current on-going remedy at the site -Has long documented history of effectiveness -Presents no unacceptable risks to humans or the environmental

TABLE 6. CLEANUP TIMEFRAME SUMMARY FOR EXCAVATION
FORMER OCCIDENTAL CHEMICAL SITE; MONTAGUE, MICHIGAN

Cleanup Timeframe Comparison - Baseline Conditions vs. 90% Removal through Excavation and Disposal

	Former Primary Disposal Area		Former Primary Ash Disposal Area		Former Fine Chemical Production Area		Former Equalization Pond Area	
Constituent of Concern	**Baseline**	**90% Removal**	**Baseline**	**90% Removal**	**Baseline**	**90% Removal**	**Baseline**	**90% Removal**
C-56	> 10,000 yr	4,900 yr	1,365 yr	12 yr	6,900 yr	1,980 yr	1,220 yr	280 yr
C-58	> 10,000 yr	79 yr	1,480 yr	45 yr	2,090 yr	36 yr	ne	ne
PCE	1,540 yr	890 yr	na	na	174 yr	138 yr	440 yr	40 yr
CT	308 yr	210 yr	na	na	na	na	na	na
C-26	355 yr	160 yr	na	na	810 yr	445 yr	na	na

na - not applicable because constituent has zero / near-zero mass

ne - not evaluated because baseline concentration of constituent is already below criteria

TABLE 7. REMEDIAL COST ESTIMATE FOR EXCAVATION
FORMER OCCIDENTAL CHEMICAL SITE; MONTAGUE MICHIGAN

Excavation

By: SHM adapted from NGG Rev Date: 5/1/2009

Prime Contractor Costs					10%	20%			
Task ID	Task Descr.	Unit	Quantity	Bare Cost	Contracting Cost	Contingency	Total Cost	Unit Rate	%
1	Mobilization	LS	1	$232,595	$23,260	$46,519	$302,374	$302,374	0%
2	Temporary Facilities	MO	24	$1,445,394	$144,539	$289,079	$1,879,012	$78,292	1%
3	Clearing	LS	1	$48,800	$4,880	$9,760	$63,440	$63,440	0%
4	Dewatering	LS	1	$11,500,000	$1,150,000	$2,300,000	$14,950,000	$14,950,000	11%
5	Sheet Piling	SF	942,000	$19,461,720	$1,946,172	$3,892,344	$25,300,236	$27	18%
6	Sprung Structure	LS	1	$458,546	$45,855	$91,709	$596,110	$596,110	0%
7	Excavation of Overburden	CY	455,000	$2,684,500	$268,450	$536,900	$3,489,850	$8	2%
8	Soil Management Area	MO	24	$1,296,750	$129,675	$259,350	$1,685,775	$70,241	1%
9	Deep Excavation Under Sprung Structure	CY	320,000	$6,400,000	$640,000	$1,280,000	$8,320,000	$26	6%
10	Transportation and Disposal	Ton	891,000	$62,370,000	$6,237,000	$12,474,000	$81,081,000	$91	57%
11	Vapor Control/Scubbing	LS	1	$1,348,000	$134,800	$269,600	$1,752,400	$1,752,400	1%
12	Backfill	CY	250,000	$1,984,050	$198,405	$396,810	$2,579,265	$10	2%
13	Site Restoration	SF	551,484	$275,742	$27,574	$55,148	$358,465	$1	0%
				$109,506,097	$10,950,610	$21,901,219	$142,357,926		100%
Other Contracts & Purchases					10%	20%			
Task ID	Task Descr.	Unit	Quantity	Bare Cost	Contracting Cost	Contingency	Total Cost	Unit Rate	%
1	Perimeter air monitoring	Day	420	$630,000	$63,000	$126,000	$819,000	$1,950	100%
				$630,000	$63,000	$126,000	$819,000		100%
Construction Oversight Costs					10%	20%			
Task ID	Task Descr.	Unit	Quantity	Bare Cost	Contracting Cost	Contingency	Total Cost	Unit Rate	%
1	Temporary Facilities	LS	1	$127,600	$12,760	$25,520	$165,880	$165,880	8%
2	Verification Soil Remediation Sampling	Ea	104	$41,600	$4,160	$8,320	$54,080	$520	3%
3	Personnel	Person Days	1,560	$1,578,000	$0	$315,600	$1,893,600	$1,214	90%
				$1,747,200	$16,920	$349,440	$2,113,560		100%
Grand Total							$145,290,486		

TABLE 8. CLEANUP TIMEFRAME SUMMARY FOR IN-SITU SOLIDIFICATION
FORMER OCCIDENTAL CHEMICAL SITE; MONTAGUE, MICHIGAN

Cleanup Timeframe Comparison - Baseline Conditions vs. In-Situ Solidification (ISS)

	Former Primary Disposal Area		Former Primary Ash Disposal Area		Former Fine Chemical Production Area		Former Equalization Pond Area	
Constituent of Concern	**Baseline**	**ISS**	**Baseline**	**ISS**	**Baseline**	**ISS**	**Baseline**	**ISS**
C-56	> 10,000 yr	> 10,000 yr	1,365 yr	1,035 yr	6,900 yr	8,500 yr	1,220 yr	1,440 yr
C-58	> 10,000 yr	> 10,000 yr	1,480 yr	890 yr	2,090 yr	1,200 yr	ne	ne
PCE	1,540 yr	3,800 yr	na	na	174 yr	1,700 yr	440 yr	440 yr
CT	186 yr	1,230 yr	na	na	na	na	na	na
C-26	355 yr	510 yr	na	na	810 yr	1,720 yr	na	na

na - not applicable because constituent has zero / near-zero mass

ne - not evaluated because baseline concentration of constituent is already below criteria

TABLE 9. REMEDIAL COST ESTIMATE FOR IN-SITU SOLIDIFICATION
FORMER OCCIDENTAL CHEMICAL SITE; MONTAGUE, MICHIGAN

In Situ Solidification

By: SHM adapted from NGG Rev Date: 5/1/2009

Prime Contractor Costs					10%	20%			
Task ID	Task Descr.	Unit	Quantity	Bare Cost	Contracting Cost	Contingency	Total Cost	Unit Rate	%
1	Mobilization	LS	1	$532,595	$53,260	$106,519	$692,374	$692,374	1%
2	Temporary Facilities	MO	24	$1,445,394	$144,539	$289,079	$1,879,012	$78,292	2%
3	Clearing	LS	1	$48,800	$4,880	$9,760	$63,440	$63,440	0%
4	Sheet Piling	SF	628,000	$12,974,480	$1,297,448	$2,594,896	$16,866,824	$27	20%
5	Sprung Structure	LS	1	$458,546	$45,855	$91,709	$596,110	$596,110	1%
6	Excavation of Overburden	CY	455,000	$2,684,500	$268,450	$536,900	$3,489,850	$8	4%
7	Soil Management Area	MO	24	$1,296,750	$129,675	$259,350	$1,685,775	$70,241	2%
8	In-Situ Solidification	CY	320,000	$16,529,300	$1,652,930	$3,305,860	$21,488,090	$67	25%
9	Transportation and Disposal	Ton	363,000	$25,410,000	$2,541,000	$5,082,000	$33,033,000	$91	39%
10	Vapor Control/Scubbing	LS	1	$1,606,100	$160,610	$321,220	$2,087,930	$2,087,930	2%
11	Backfill	CY	250,000	$1,984,050	$198,405	$396,810	$2,579,265	$10	3%
12	Site Restoration	SF	551,484	$275,742	$27,574	$55,148	$358,465	$1	0%
				$65,246,257	$6,524,626	$13,049,251	$84,820,134		100%

Other Contracts & Purchases					10%	20%			
Task ID	Task Descr.	Unit	Quantity	Bare Cost	Contracting Cost	Contingency	Total Cost	Unit Rate	%
1	Perimeter air monitoring	Day	420	$630,000	$63,000	$126,000	$819,000	$1,950	100%
				$630,000	$63,000	$126,000	$819,000		100%

Construction Oversight Costs					10%	20%			
Task ID	Task Descr.	Unit	Quantity	Bare Cost	Contracting Cost	Contingency	Total Cost	Unit Rate	%
1	Temporary Facilities	LS	1	$127,600	$12,760	$25,520	$165,880	$165,880	7%
2	ISS QA Sampling	Ea	320	$128,000	$12,800	$25,600	$166,400	$520	7%
3	Verification of Soil Remediation Sampling	Ea	104	$41,600	$4,160	$8,320	$54,080	$520	
4	Personnel	Person Days	1,560	$1,578,000	$0	$315,600	$1,893,600	$1,214	83%
				$1,875,200	$29,720	$375,040	$2,279,960		98%

Grand Total	$87,919,094	

TABLE 10. REMEDIAL COST ESTIMATE FOR GROUNDWATER EXTRACTION AND TREATMENT
FORMER OCCIDENTAL CHEMICAL SITE; MONTAGUE, MICHIGAN

Upgradient Groundwater Extraction/Treatment

Rev Date: 9/4/09

Prime Contractor Costs

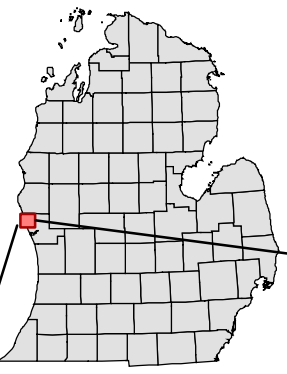
Task ID	Task Descr.	Unit	Quantity	Unit Cost	Extended	20% Contingency	Total Cost	Unit Rate
1	8" Extraction Well	EA	4	$61,013	$244,051	$61,013	$305,064	$76,266
2	6" Submersible Pump for 8" Well w/ controls	EA	4	$6,874	$27,494	$6,874	$34,368	$8,592
3	6" Extraction Well	EA	2	$43,193	$86,386	$21,596	$107,982	$53,991
4	4" Submersible Pump for 6" Well w/ controls	EA	2	$3,128	$6,256	$1,564	$7,820	$3,910
5	Well Enclosures	EA	6	$5,000	$30,000	$6,000	$36,000	$6,000
6	Well Telemetry and Controls	LS	1	$100,000	$100,000	$20,000	$120,000	$120,000
7	20,000 lb Dual Bed Liquid Phase GAC	EA	2	$237,346	$474,691	$118,673	$593,364	$296,682
8	Treatment Building	LS	1	$97,278	$97,278	$24,319	$121,597	$121,597
9	Waste Handling/Disposal	LS	1	$7,603	$7,603	$1,521	$9,123	$9,123
10	Trenching Compaction	LS	1	$10,961	$10,961	$2,740	$13,701	$13,701
11	Underground Electrical Wiring	LS	1	$65,329	$65,329	$16,332	$81,662	$81,662
12	Underground Transmission Piping	LS	1	$245,016	$245,016	$61,254	$306,270	$306,270
				$882,739	$1,395,065	$341,886	$1,736,951	

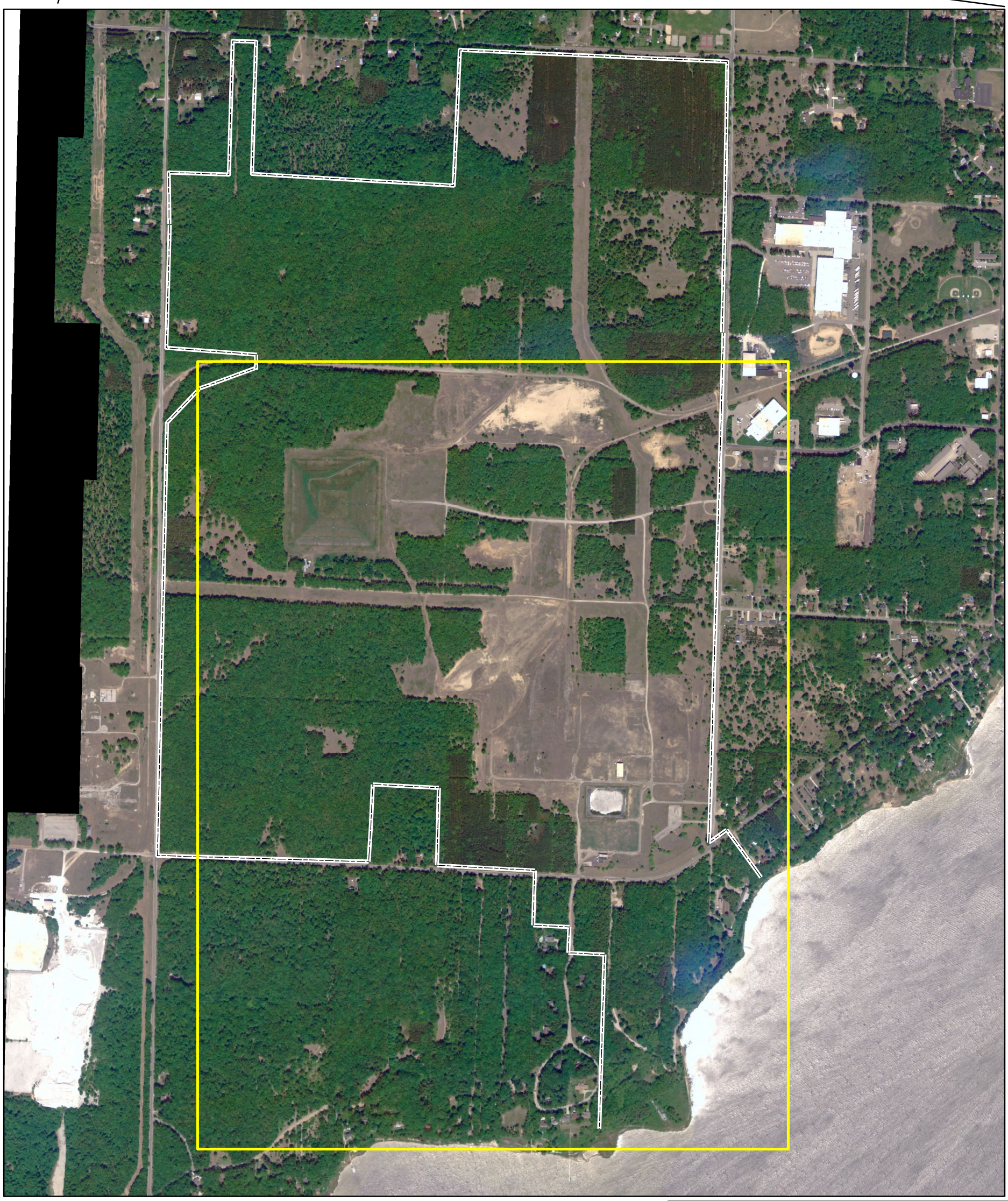
Professional/Construction Management Costs

Task ID	Task Descr.	Unit	Quantity	Bare Cost	Extended Contracting Cost	20% Contingency	Total Cost	Unit Rate
1	Professional Labor (Design and Construction Management)	LS	1	$139,857	$139,857	$34,964	$174,821	$174,821
				$139,857	$139,857	$34,964	$174,821	

Grand Total	$1,911,772

FIGURES





Property Line

Typical Aerial View

N

W E

S

0 750 1,500 3,000 4,500 Feet

1 inch = 1,000 feet

AECOM

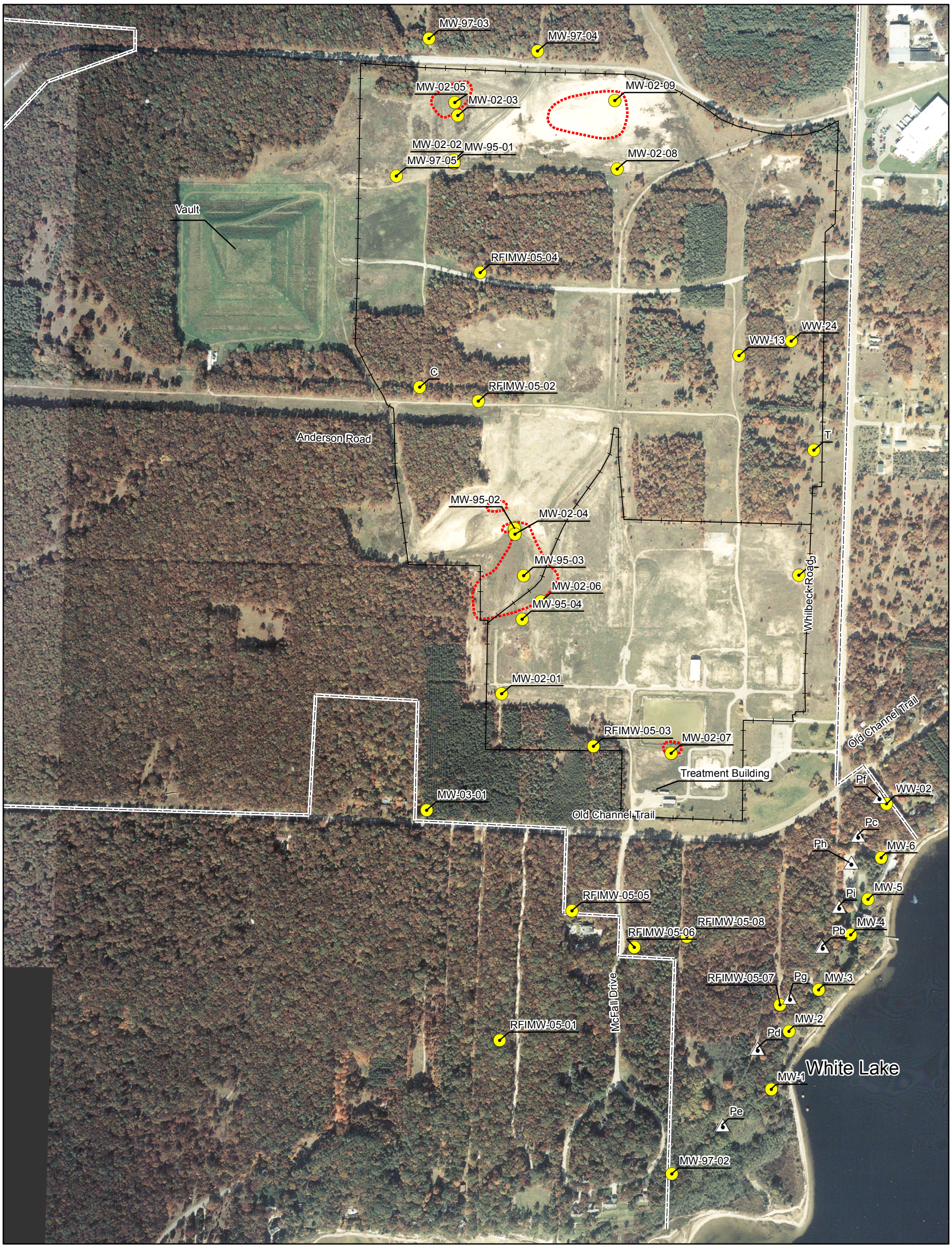
Figure 1

General Site Location Map

Former Occidental Chemical Site
Montague, MI

#98355	April 2009	Creator: ENC040209
		QC: JT

L:\work\GIS\MSRMI\2009 Maps\Site_Map.mxd



Aerial Photo Source: Abrams Aerial Survey Corporation

MW-05-02 — Monitoring Well (Not All Shown)

Ph — Purge Well

Extent of DNAPL Contamination

Property Line

Fence

0 300 600 1,200 1,800 2,400 Feet

N W E S

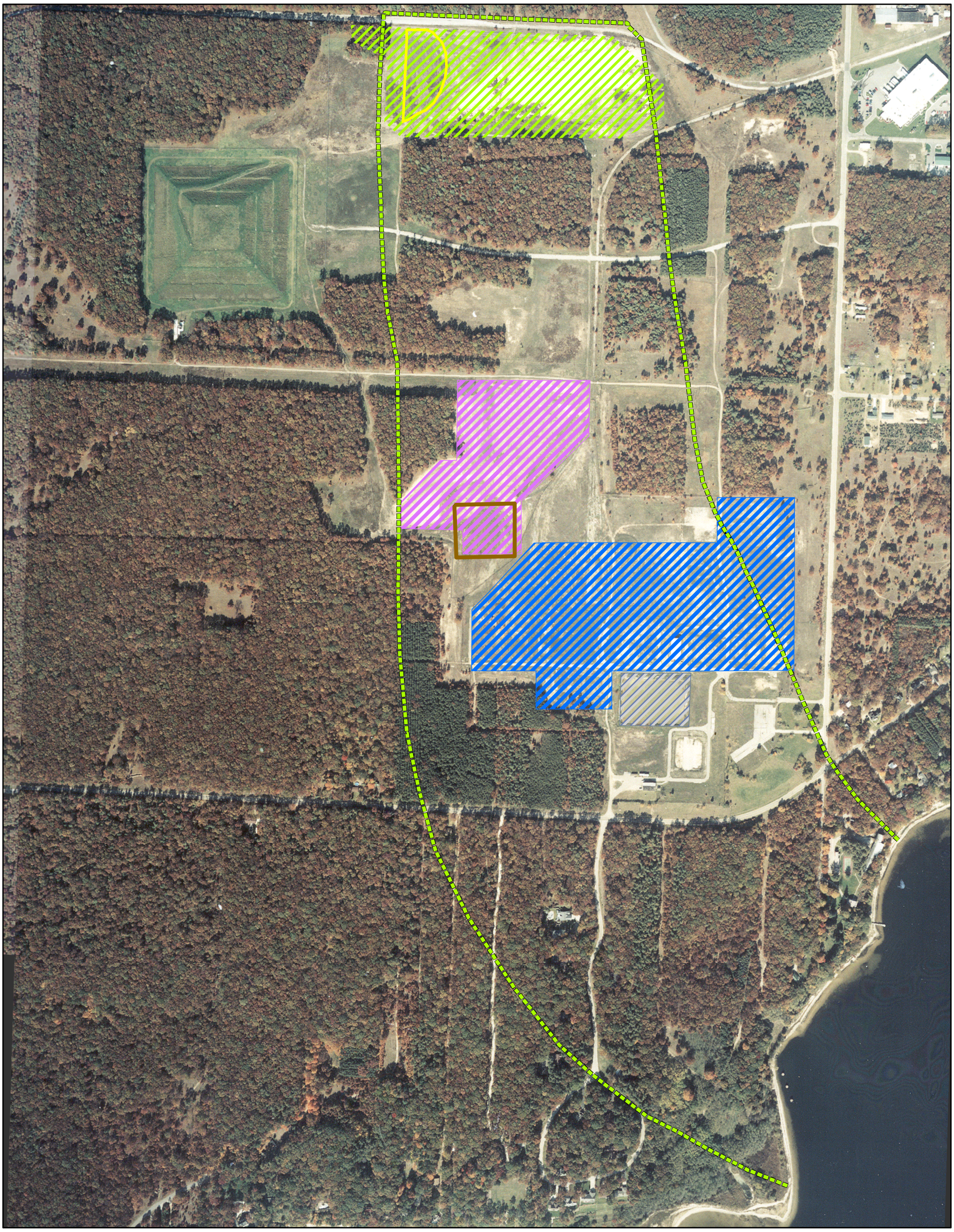
AECOM

Figure 2

Site Features Map

Former Occidental Chemical Site
Montague, Michigan

98355	April 2009	Creator: CPP081809
		Q.C: JT



Aerial Photo Source: Abrams Aerial Survey Corporation

Historical Source Areas

- Former Equalization Pond Area
- Central Exposure Area
- Former Fine Chemical Production Area
- Southern Exposure Area
- Northern Exposure Area
- Former Primary Disposal Area
- Dissolved Groundwater Plume Area

0 300 600 1,200 1,800 2,400 Feet

N W E S

AECOM

Figure 3

Historical Source Areas

Former Occidental Chemical Site
Montague, Michigan

98355	April 2009	Creator: CPP080709
		Q.C: JT



Aerial Photo Source: Abrams Aerial Survey Corporation

MW-05-02 Monitoring Well

Ph Purge Well

Extent of DNAPL Contamination

Property Line

0 300 600 1,200 1,800 2,400 Feet

N W E S

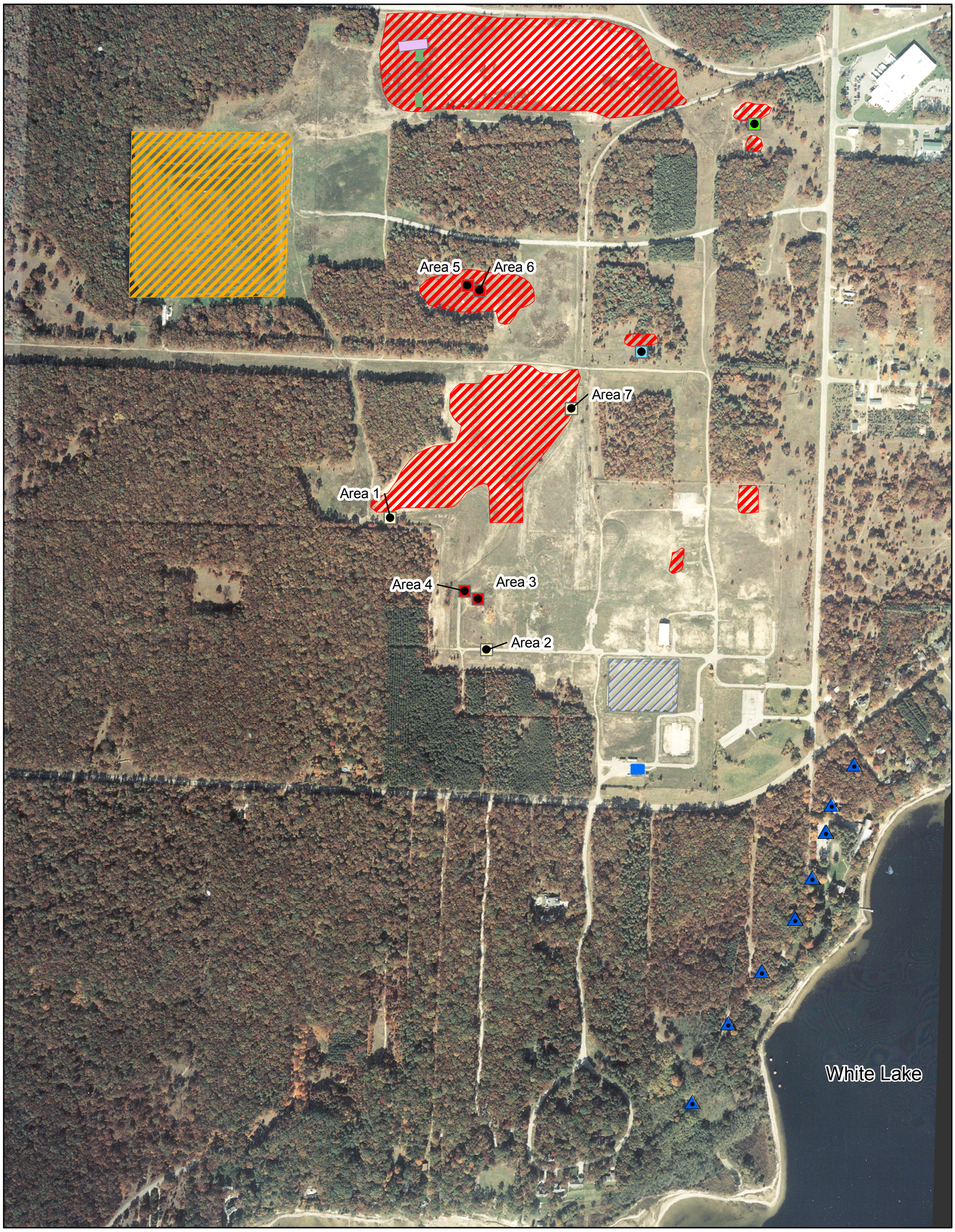
AECOM

Figure 4

Extent of DNAPL

Former Occidental Chemical Site
Montague, Michigan

98355	April 2009	Creator: ENC040209
		Q.C: JT



Aerial Photo Source: Abrams Aerial Survey Corporation

Remediation Actions

- Equalization Pond Excavation and Capping (early 1980's)
- Excavation Areas (1979-1982)
- Localized Excavation Area (2001)
- Localized Soil Capped Area (2001)
- Localized Excavation and Capping (Excavation 2003, capping 2005)
- Localized Soil Capped Area (2005)

Groundwater Treatment

- Purge Wells
- Activated Carbon Absorption System

DNAPL Treatment Pilot Tests

- ISCO Pilot Test (2005)
- ERD Pilot Test (2007)

On-Site Landfill

- Storage Vault/Landfill

Note: Areas 1-7 discussed in Reference "Earth Tech, 2006c"

0 300 600 1,200 1,800 2,400 Feet

N W E S

L:\work\GIS\MSRM\2009Maps\Remedial_Actions_To_Date.mxd

AECOM

Figure 5

Historical Remedial Actions To Date

Former Occidental Chemical Site
Montague, Michigan

98355	April 2009	Creator: CPP090109
		Q.C: JT



Aerial Photo Source: Abrams Aerial Survey Corporation

Area Dredged

Property Line

Fence

0 150 300 600 900 1,200 Feet

N W E S

AECOM

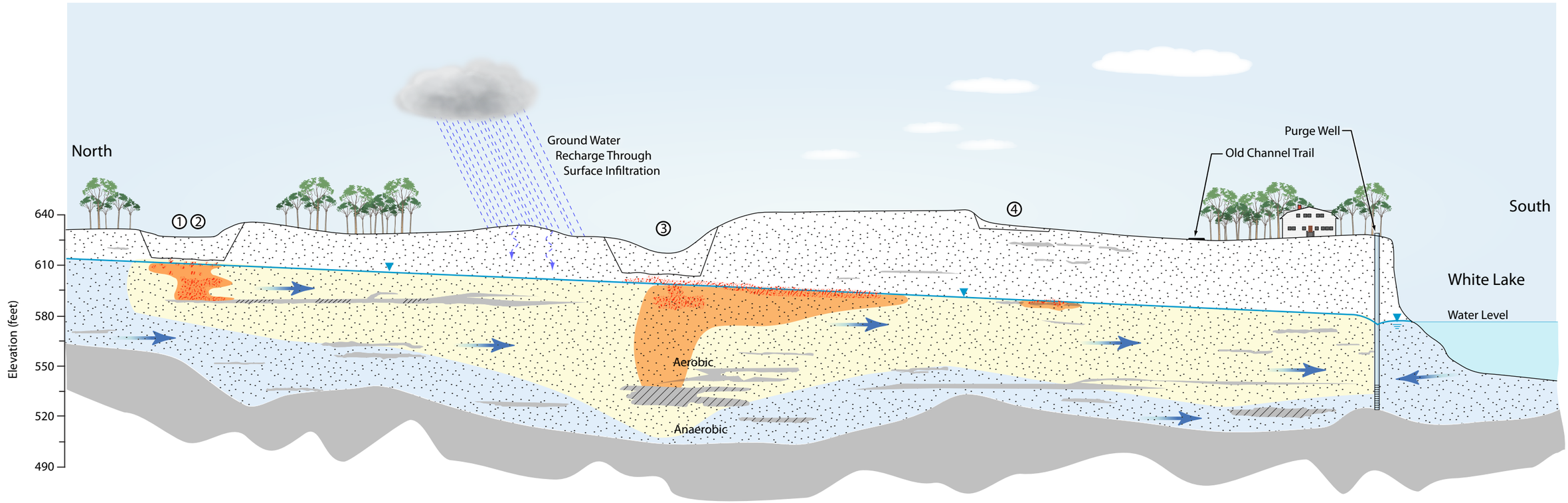
Figure 6

White Lake
Extent of Sediment Removal

Former Occidental Chemical Site
Montague, Michigan

98355	August 2009	Creator: CPP080909
		Q.C: JT

Note: Profile view approximately 6,240 feet.



Note: Scale is Approximate

DNAPL
Dissolved VOC Plume
Dissolved C-56 Plume
Sand Aquifer
Silt
Clay
Water Table Level
Groundwater Flow

Historical DNAPL Entry Locations

① Former Primary Disposal Area
② Former Primary Ash Disposal Area
③ Former Fine Chemical Production Area
④ Former Equalization Pond

Approximate Areas of Initial Excavations

* Note: Only C-56 and VOC's Shown in Site Conceptual Model

AECOM

5555 Glenwood Hills Parkway, SE Suite 200 Grand Rapids, MI 49512 (616) 942-9600

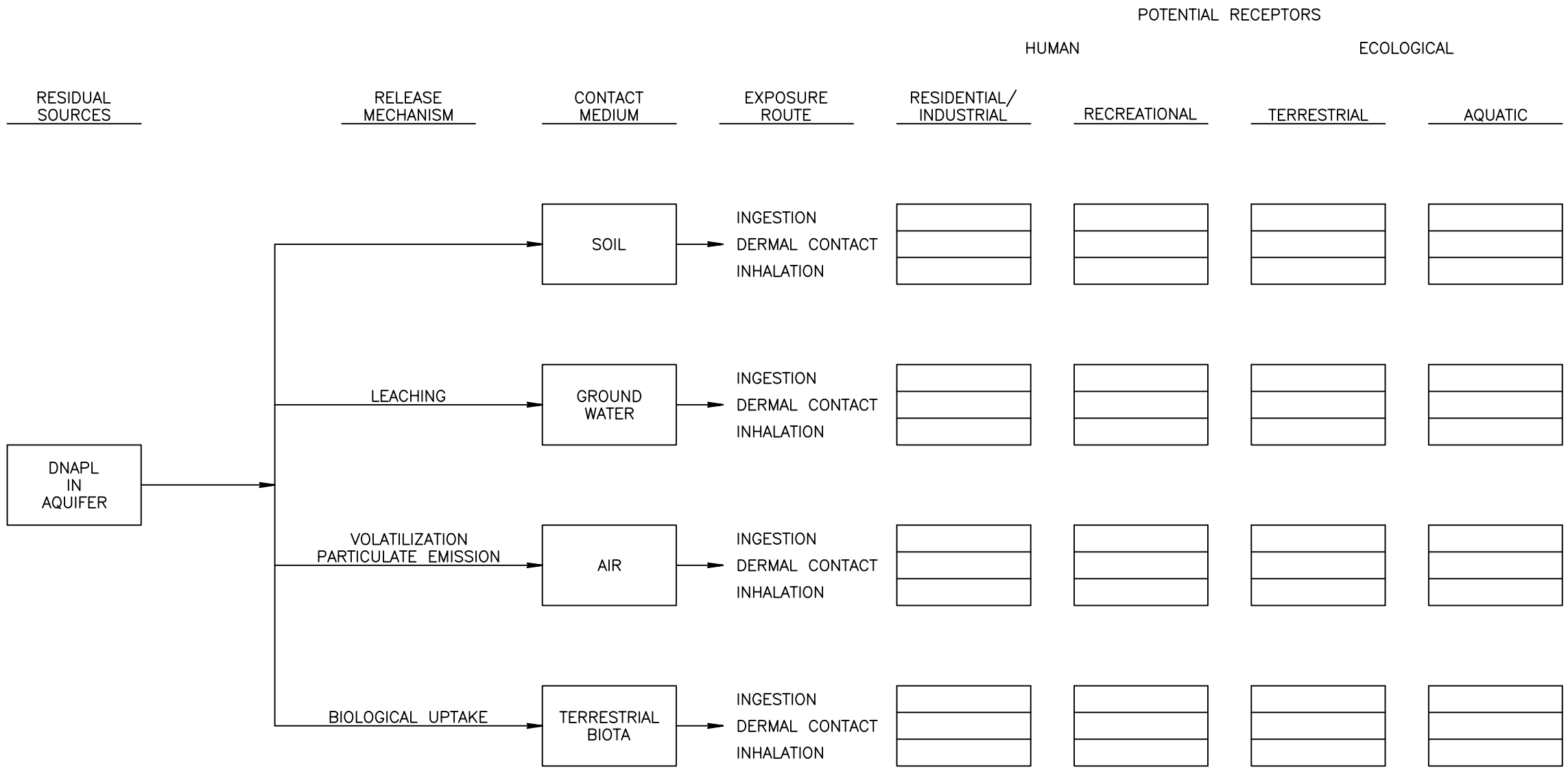
DRAWN BY: M. Haworth	DATE: April 21, 2009
CHECKED BY: JT	EDITED BY: ENC041509
FILE NAME:	

FIGURE 7

Site Conceptual Model

Former Occidental Chemical Site
Montague, MI

PROJECT NUMBER 98355	SCALE: As shown



AECOM

FIGURE 8
SITE CONCEPTUAL EXPOSURE MODEL
FOR CURRENT CONDITIONS 2009

OCCIDENTAL CHEMICAL CORPORATION SITE
MONTAGUE, MICHIGAN

FILE NAME:	DRN	PROJECT NO.	DATE	QC BY:
98355 Fg7.dwg	NLW	98355.03	04/23/09	ENC

Plotted By: david.tonis
Layout-Sheet Name: MODEL
Plot File Date Created: May/04/2009 11:34 AM

Filename: L:\WORK\98355\CAD\98355 FG7.DWG



Aerial Photo Source: Abrams Aerial Survey Corporation

Industrial Properties

Residental Properties

Property Line

DNAPL

0 300 600 1,200 1,800 2,400 Feet

N W E S

AECOM

Figure 9

Potential Receptors Map

Former Occidental Chemical Site
Montague, Michigan

98355	April 2009	Creator: ENC040709
		Q.C: JT

White Lake

L:\work\GIS\MSRMI\2009Maps\Habitat_Restoration_Areas.mxd

Aerial Photo Source: Abrams Aerial Survey Corporation

Perennial Native Grasses
Strip of Perennial Native Grasses
Annual Grain Wildlife Plots
Dune Grass
Strip of Dune Grass
Property Line

0 300 600 1,200 1,800 2,400
Feet

N
W E
S

AECOM

Figure 10

Habitat Restoration Areas

Former Occidental Chemical Site
Montague, Michigan

98355	April 2009	Creator: ENC040709
		Q.C: JT



Aerial Photo Source: Abrams Aerial Survey Corporation

MW-97-05 Monitoring Well (Select Wells Shown)

598.0 Groundwater Contour Line (in feet)

Extent of DNAPL Contamination

Extent of Dissolved Volatile Organics Plume

Groundwater Flow Direction

0 300 600 1,200 1,800 2,400 Feet

N W E S

AECOM

Figure 11

Groundwater Countour Map
March 2005

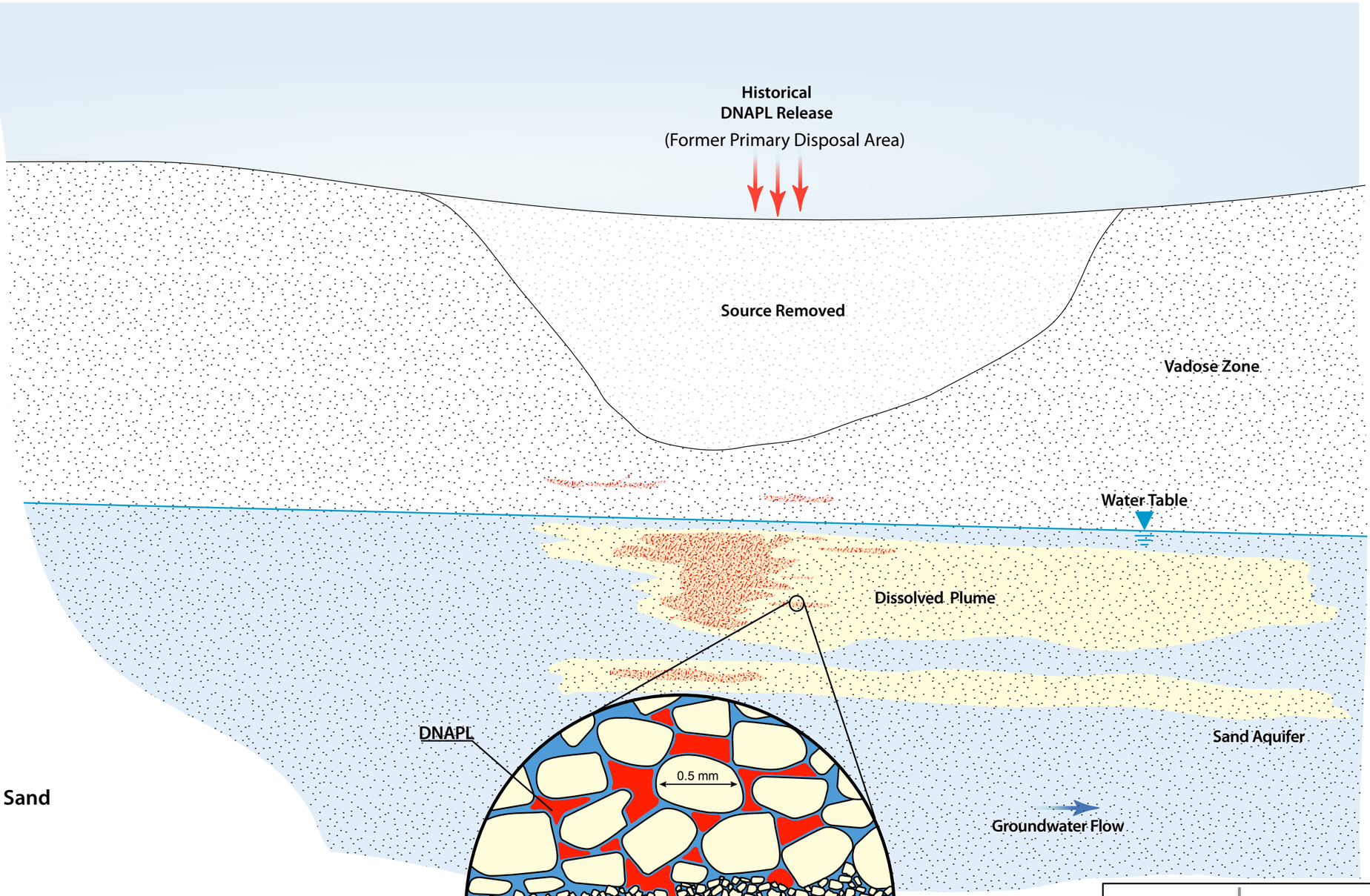
Former Occidental Chemical Site
Montague, Michigan

98355	April 2009	Creator: ENC040709
		Q.C: JT

Soil Core From Residual Source Area



*Area circled in red presented conceptually in inset at right



AECOM
5555 Glenwood Hills Parkway, SE Suite 200 Grand Rapids, MI 49512 (616) 942-9600

DRAWN BY: M. Haworth	DATE: April 16, 2009
CHECKED BY: JT	EDITED BY: ENC041609
FILE NAME:	

FIGURE NO. 12

Conceptual DNAPL Architecture Model

Former Occidental Chemical
Montague, MI

PROJECT NUMBER	98355	SCALE:	N/A



Aerial Photo Source: Abrams Aerial Survey Corporation

MW-05-02 — Monitoring Well (Not All Shown)

Ph — Purge Well

Property Line

Fence

Extent of C-56 Concentration > Criteria

Extent of C-66 and C-58 Concentrations > Criteria

Extent of DNAPL Contamination

Extent of Dissolved Volatile Organics Plume

0 300 600 1,200 1,800 2,400 Feet

N W E S

AECOM

Figure 13

Total CVOC
and
C-Series Compounds

Former Occidental Chemical Site
Montague, Michigan

98355	August 2009	Creator: CPP081409
		Q.C: JT



Aerial Photo Source: Abrams Aerial Survey Corporation

MW-05-02 Monitoring Well (Select Wells Shown)

Ph Purge Well

Extent of DNAPL Contamination

Property Line

TI Zone

0 300 600 1,200 1,800 2,400 Feet

N W E S

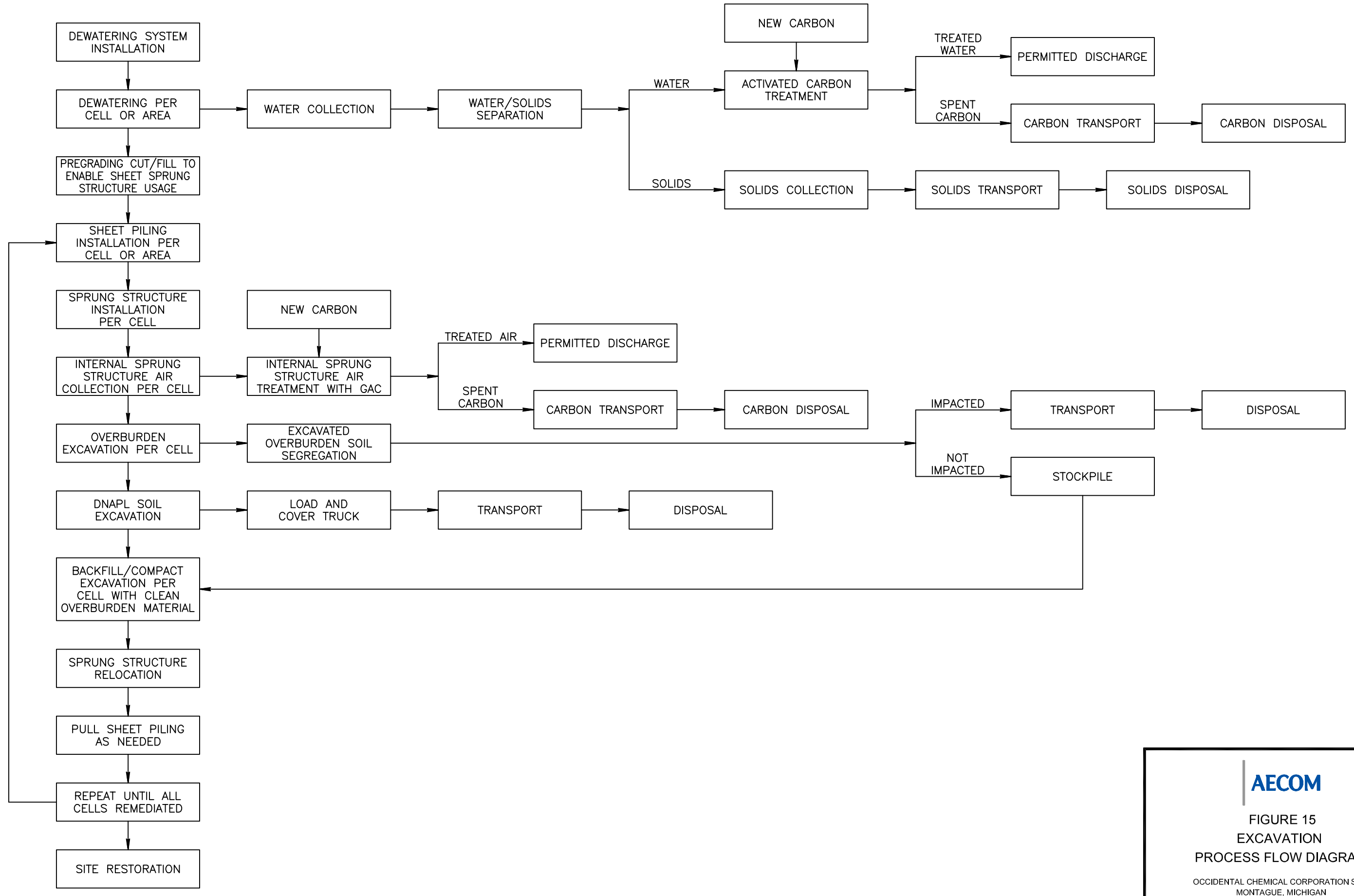
AECOM

Figure 14

TI Zone

Former Occidental Chemical Site
Montague, Michigan

98355	April 2009	Creator: CPP090209
		Q.C: JT



AECOM

FIGURE 15
EXCAVATION
PROCESS FLOW DIAGRAM

OCCIDENTAL CHEMICAL CORPORATION SITE
MONTAGUE, MICHIGAN

FILE NAME:	DRN	PROJECT NO.	DATE	QC BY:
98355 Fg13.dwg	NLW	98355.03	04/27/09	ENC

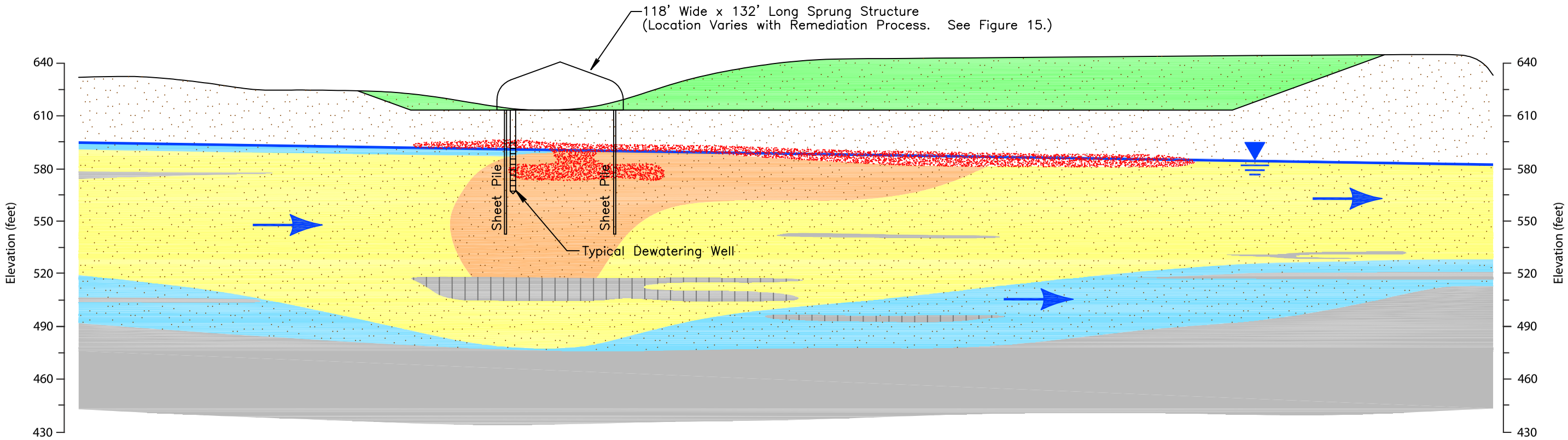
Plotted By: david.tanis
Layout-Sheet Name: MODEL
Plot File Date Created: May/04/2009 11:37 AM

Filename: L:\WORK\98355\CAD\98355 FG13.DWG

Conceptual Profile of Former Fine Chemical Production Area

North

South



Legend

- Cut Area
- DNAPL
- Dissolved VOC Plume
- Dissolved C–56 Plume
- Sand Aquifer
- Silt
- Clay
- Water Table
- Groundwater Flow Direction

0 100 200

Approximate Horizontal Scale (Feet)

AECOM

FIGURE 16

CONCEPTUAL GRADING PLAN TO ENABLE PLACEMENT OF TEMPORARY SPRUNG STRUCTURE

OCCIDENTAL CHEMICAL CORPORATION SITE
MONTAGUE, MICHIGAN

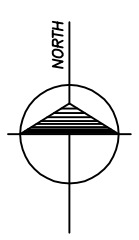
FILE NAME:	DRN	PROJECT NO.	DATE	QC BY:
98355 Fg14.dwg	NLW	98355.03	04/27/09	ENC

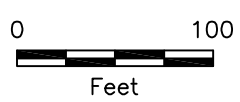
Plotted By: david.tanis
Layout-Sheet Name: LAYOUT1
Plot File Date Created: May/04/2009 11:43 AM

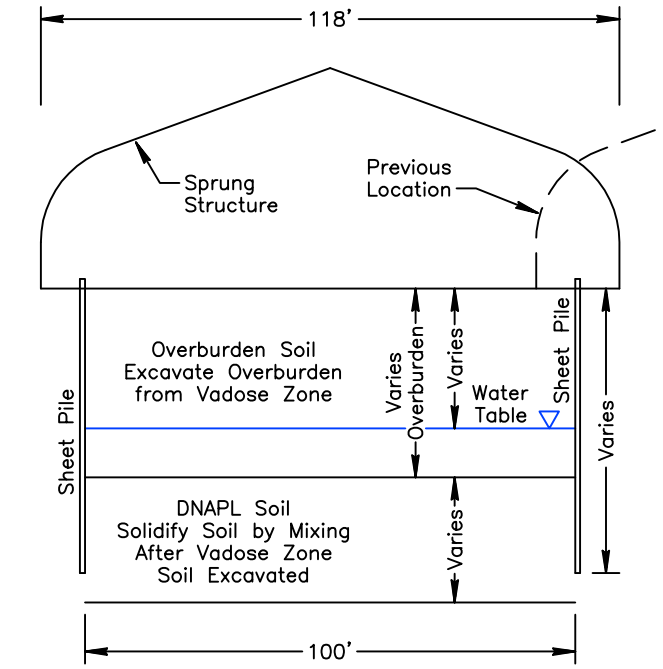
Filename: L:\WORK\98355\CAD\98355 FG14.DWG



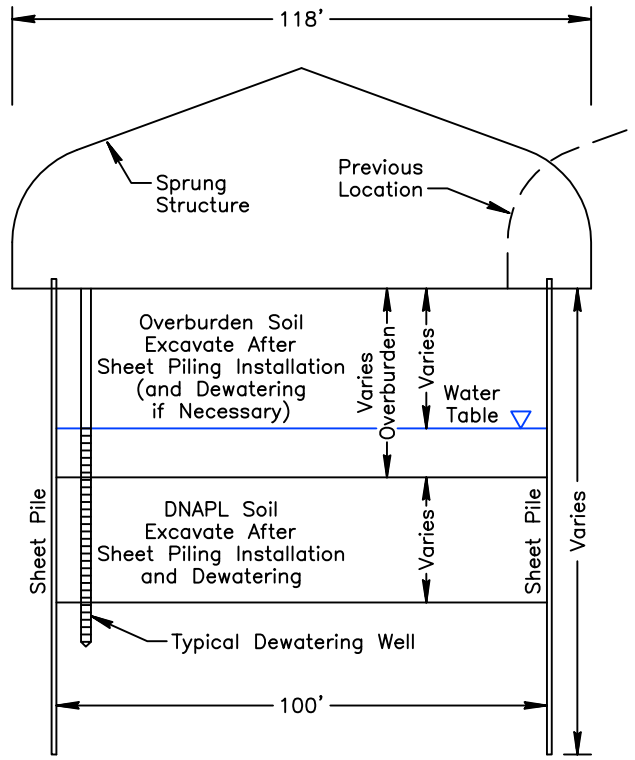
DNAPL EXTENT AREA 3C
SCALE: 1"=100'



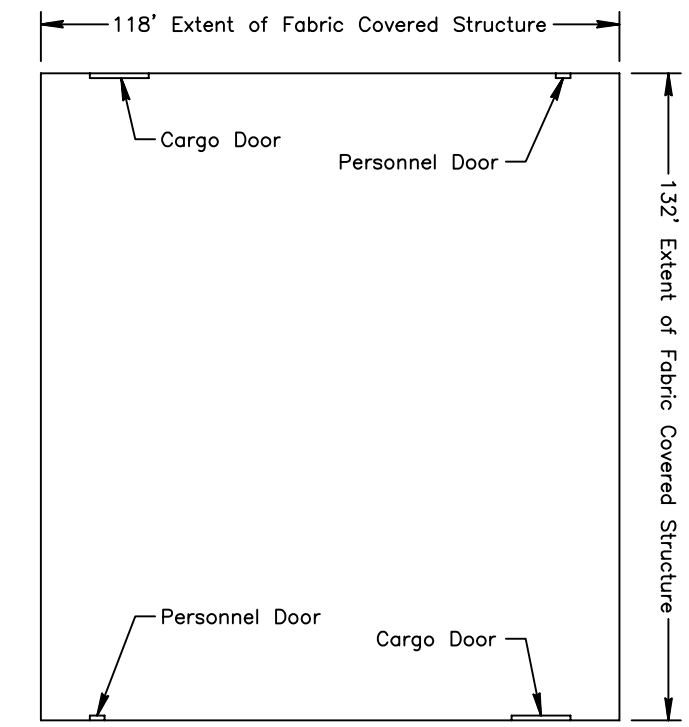




3/5 TEMPORARY SPRUNG STRUCTURE IN SITU SOLIDIFICATION PROFILE
SCALE: 1"=40'



2/5 TEMPORARY SPRUNG STRUCTURE EXCAVATION PROFILE
SCALE: 1"=40'



1/5 TEMPORARY SPRUNG STRUCTURE PLAN VIEW
SCALE: 1"=40'

AECOM

FIGURE 17
CONCEPTUAL TEMPORARY
SPRUNG STRUCTURE PLAN

OCCIDENTAL CHEMICAL CORPORATION SITE
MONTAGUE, MICHIGAN

FILE NAME:	DRN	PROJECT NO.	DATE	QC BY:
98355 Fg15.dwg	NLW	98355.03	04/23/09	ENC

Plotted By: david.tanis
Layout-Sheet Name: LAYOUT1
Plot File Date Created: May/04/2009 11:49 AM
Filename: L:\WORK\98355\CAD\98355 FG15.DWG

SOURCE	REMEDIAL OPTION	WORK PROCESS	EXPOSURE ROUTE	WORKER	NON–WORKER	ECOLOGICAL	COMMENTS
DNAPL	EXCAVATION UNDER SPRUNG STRUCTURE	SHEET PILING INSTALLATION/ REMOVAL	INGESTION DERMAL CONTACT INHALATION				Prior to overburden and DNAPL soil excavation under a sprung structure, sheet piling will be installed to temporarily structurally stabilize 100 ft. x 100 ft. sections. The sheet piling installation can't be done under the sprung structure due to the sheeting lengths needed. The sheet piling will be removed after each 100 ft. x 100 ft. section is completed.
		SOIL OVERBURDEN REMOVAL	INGESTION DERMAL CONTACT INHALATION				Some of the soil in the vadose zone is believed to be impacted. Therefore, exposure pathways are deemed potentially complete during this work process.
		DEWATERING	INGESTION DERMAL CONTACT INHALATION				In order to excavate the DNAPL soils, the saturated zone will have to be dewatered with a flow rate up to 1,200 gpm maintained during excavation. The recovered groundwater will be treated with granular activated carbon and discharged. The treatment equipment will be outside the sprung structure.
		RESIDUAL DNAPL EXCAVATION	INGESTION DERMAL CONTACT INHALATION				Although workers will be expected to use personal protective equipment, the potential exists for failures that would result in potential exposures.
		WASTE LOADING	INGESTION DERMAL CONTACT INHALATION				Although workers will be expected to use personal protective equipment, the potential exists for failures that would result in potential exposures. Non–worker exposure may occur from breach of control barrier during truck entrance and exit. Non–worker exposure limited to particulate and volatile fugitive emissions due to existing access restrictions. Terrestrial ecological receptors may be exposed to fugitive emissions of particulate and volatile emissions during waste loading and truck movement across the control barrier.
		WASTE TRANSPORTATION	INGESTION DERMAL CONTACT INHALATION				Worker, non–worker, and terrestrial ecological receptors potentially exposed to volatile emissions during waste transport.
		SPRUNG STRUCTURE RELOCATION	INGESTION DERMAL CONTACT INHALATION				Work process required movement of 118 ft. x 132 ft. sprung structure which will potentially result in worker and non–worker exposure to particulate and volatile emissions. Terrestrial ecological receptors will be potentially exposed to fugitive particulate and volatile emissions.
		TRANSPORTATION ACCIDENT	INGESTION DERMAL CONTACT INHALATION				Though unlikely, the potential exists for vehicular transportation accident that may result in direct contact exposure to truck driver and emergency response personnel. Non–workers and ecological receptors may be exposed to particulate and volatile emissions.

POTENTIALLY COMPLETE EXPOSURE PATHWAY AND ROUTE

MINOR OR INCOMPLETE EXPOSURE PATHWAY AND ROUTE

REDUCED LIKELIHOOD OF OCCURRENCE

AECOM

FIGURE 18

SITE CONCEPTUAL EXPOSURE MODEL
EXCAVATION WITH CONTROL

OCCIDENTAL CHEMICAL CORPORATION SITE
MONTAGUE, MICHIGAN

FILE NAME:	DRN	PROJECT NO.	DATE	QC BY:
98355 Fg16.dwg	NLW	98355.03	04/27/09	ENC

Plotted By: david.tanis
Layout–Sheet Name: MODEL
Plot File Date Created: May/04/2009 11:52 AM

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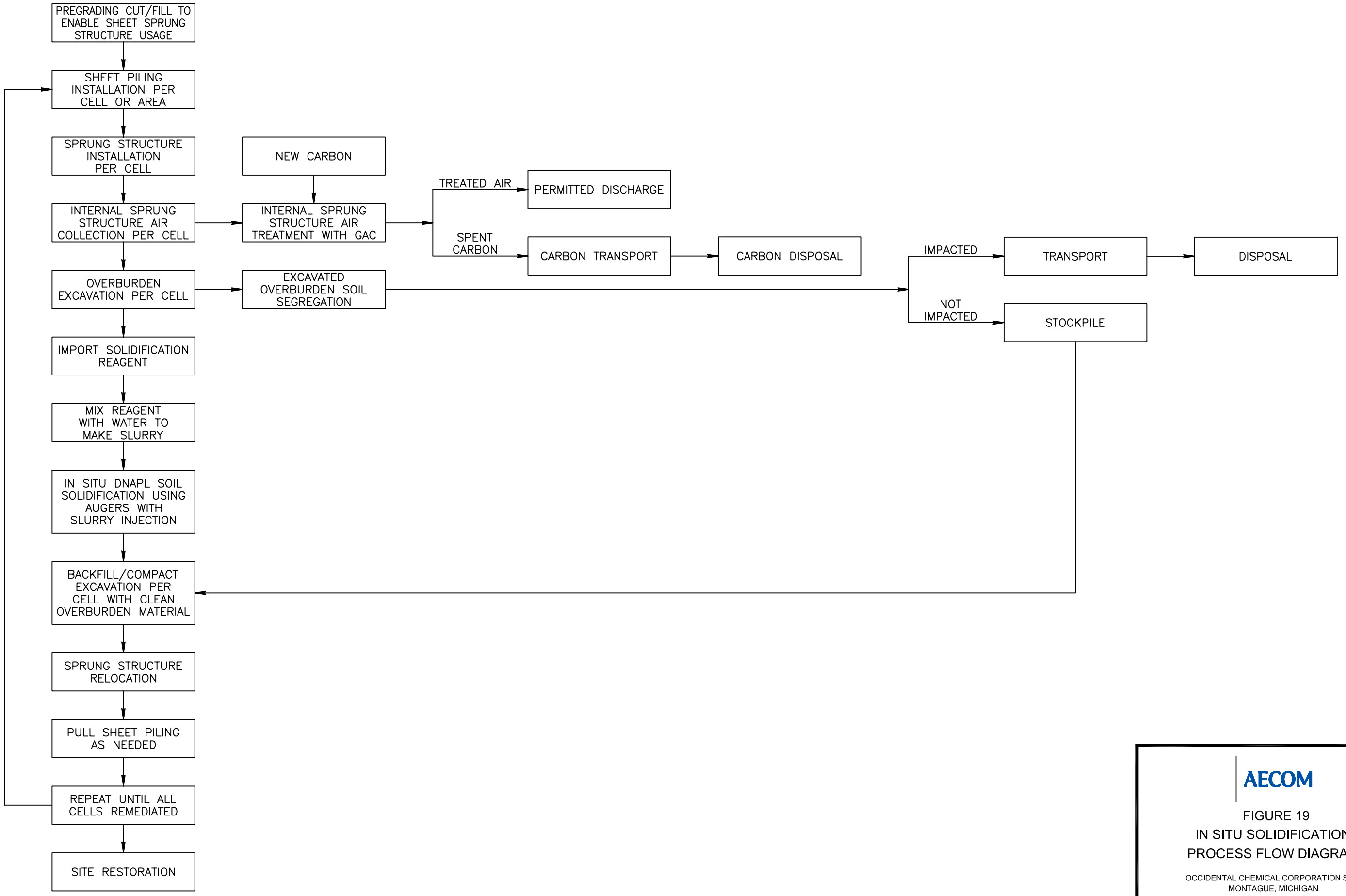


AECOM

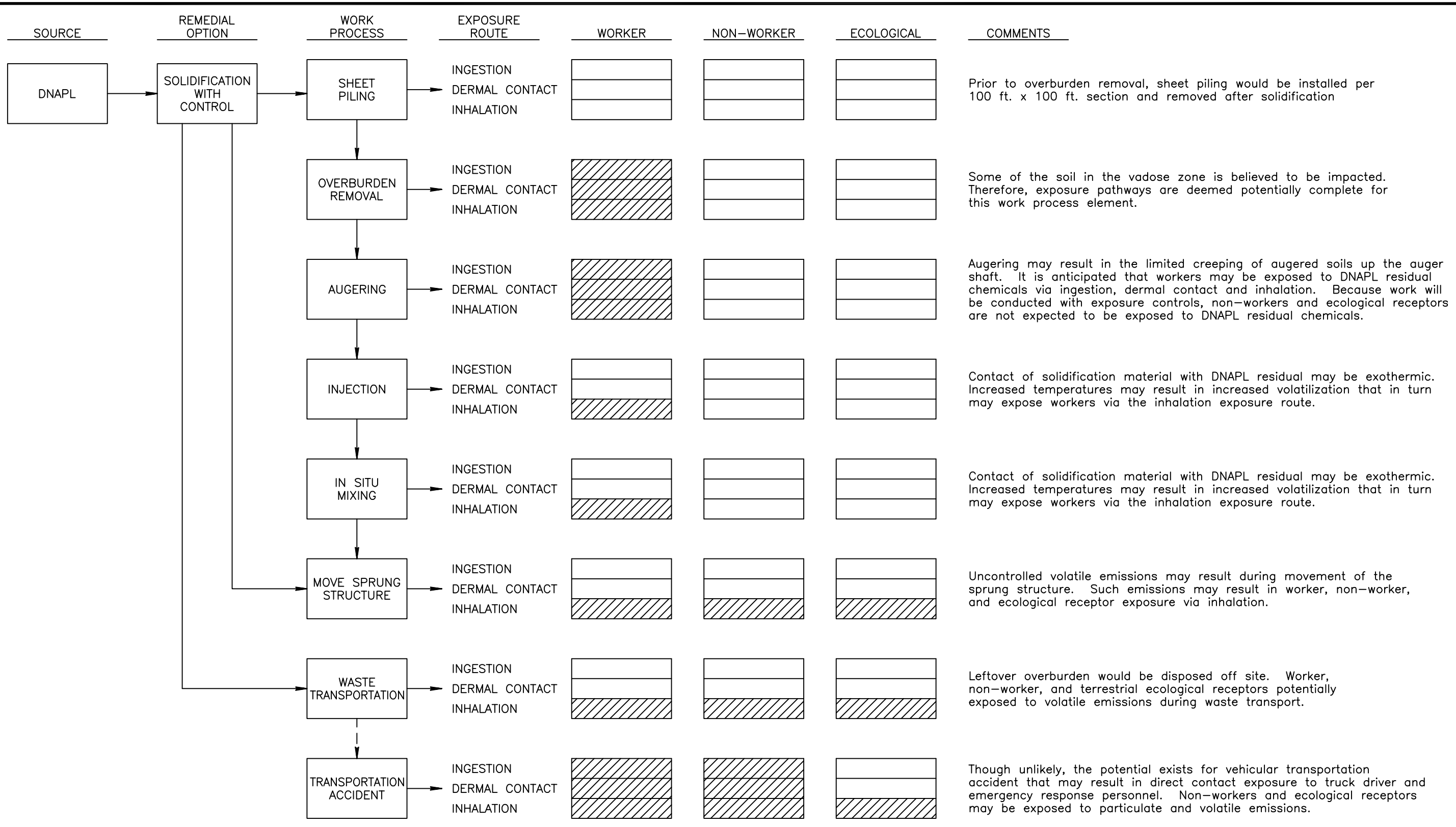
FIGURE 19
IN SITU SOLIDIFICATION
PROCESS FLOW DIAGRAM

OCCIDENTAL CHEMICAL CORPORATION SITE
MONTAGUE, MICHIGAN

FILE NAME:	DRN	PROJECT NO.	DATE	QC BY:
98355 Fg17.dwg	NLW	98355.03	04/27/09	ENC

Plotted By: david.tanis
Layout-Sheet Name: MODEL
Plot File Date Created: May/04/2009 11:54 AM

Filename: L:\WORK\98355\CAD\98355 FG17.DWG



AECOM

FIGURE 20

SITE CONCEPTUAL EXPOSURE MODEL
SOLIDIFICATION WITH CONTROL

OCCIDENTAL CHEMICAL CORPORATION SITE
MONTAGUE, MICHIGAN

FILE NAME:	DRN	PROJECT NO.	DATE	QC BY:
98355 Fg18.dwg	NLW	98355.03	04/27/09	ENC

Plotted By: david.tanis
Layout–Sheet Name: MODEL
Plot File Date Created: May/04/2009 11:58 AM

Filename: L:\WORK\98355\CAD\98355 FG18.DWG



Aerial Photo Source: Abrams Aerial Survey Corporation

- Approximate Locations for Conceptual Purge Wells
- MW-97-05 — Monitoring Well (Select Wells Shown)
- Purge Well
- Extent of Dissolved Volatile Organics Plume
- New Water Line for Conceptual Purge Wells
- Extent of DNAPL Contamination
- Capture Zone

0 300 600 1,200 1,800 2,400 Feet

N W E S

AECOM

Figure 21

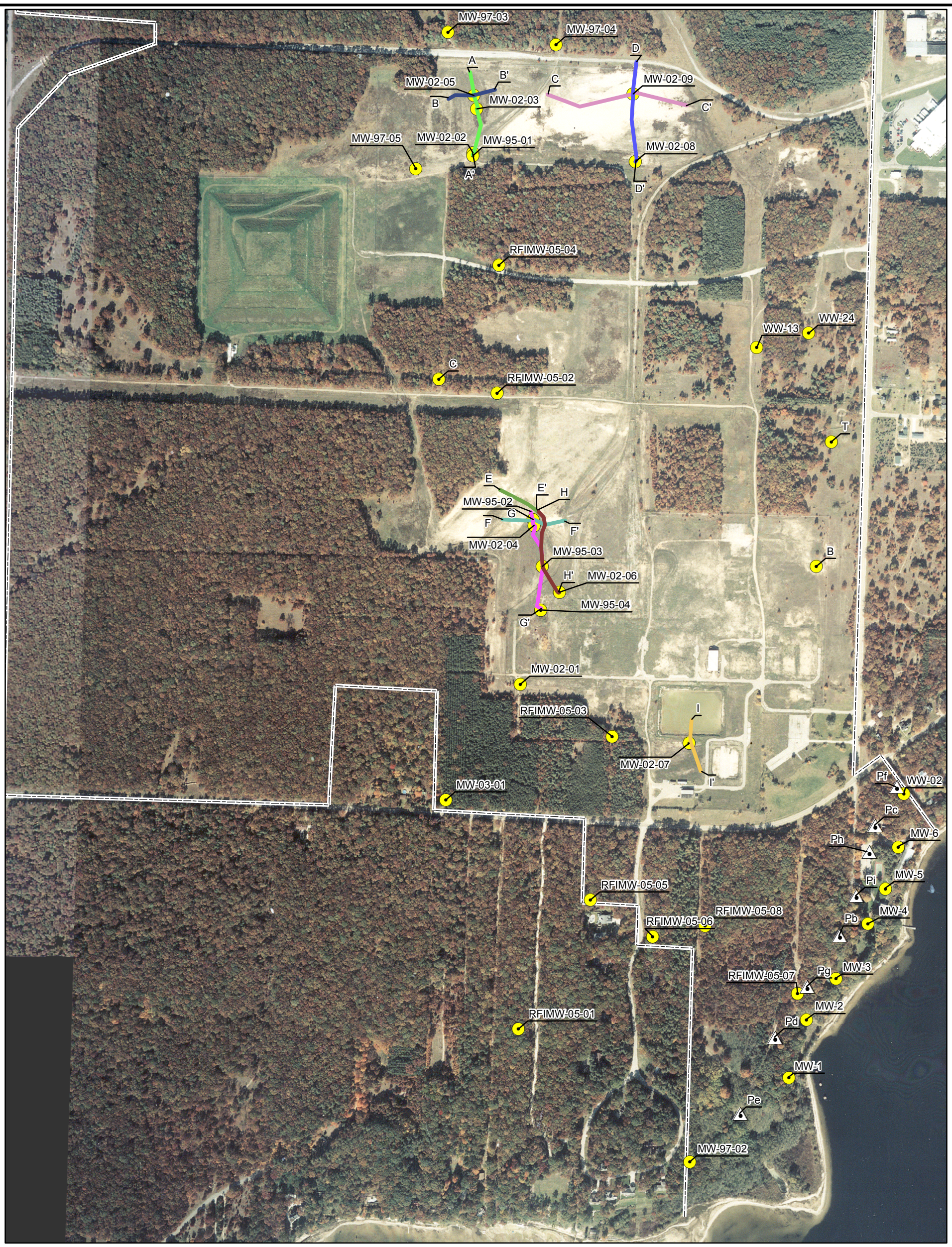
Zone of Capture Map
Showing Ground Water
Extraction Wells

Former Occidental Chemical Site
Montague, Michigan

98355	August 2009	Creator: CPP082009
		Q.C: JT

APPENDIX A

Cross Sections Showing DNAPL Distribution



L:\work\GIS\MSRM\2009 Maps\Cross_Section_Location_Overview.mxd

Aerial Photo Source: Abrams Aerial Survey Corporation

MW-05-02 Monitoring Well
Ph Purge Well
Property Line
A - A' Cross Section
B - B' Cross Section
C - C' Cross Section
D - D' Cross Section
E - E' Cross Section
F - F' Cross Section
G - G' Cross Section
H - H' Cross Section
I - I' Cross Section

0 300 600 1,200 1,800 2,400 Feet

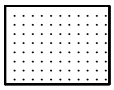
N W E S

AECOM

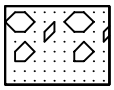
Appendix
Cross Sections:
Plan View

Former Occidental Chemical Site
Montague, Michigan

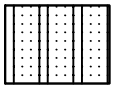
98355	August 2009	Creator: ENC081709
		Q.C: JT



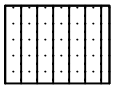
SAND



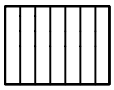
GRAVELLY SAND



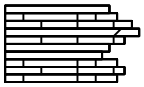
SILTY SAND



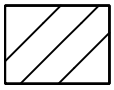
SANDY SILT



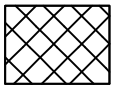
SILT



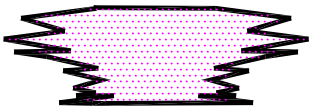
SILT, CLAYEY SILT, CLAY SEQUENCE



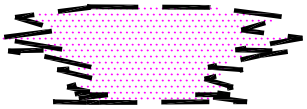
CLAY



SENSITIVE FINES



DNAPL



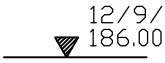
DNAPL PRESENCE INFERRED



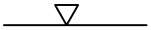
PERMANENT WELL SCREEN



VERTICAL AQUIFIER SAMPLE INTERVAL



WATER TABLE MEASURED FROM WELL



WATER TABLE INTERPURTED FROM CPT DATA

INFERRED WATER TABLE

NOTE: HATCH SIZE SHOWN FOR CLARITY ONLY.

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FIGURE 19

CROSS SECTION LEGEND

MILLER SPRINGS REMEDIATION MANAGEMENT, INC
MONTAGUE, MICHIGAN

PROJECT NUMBER	24791.23

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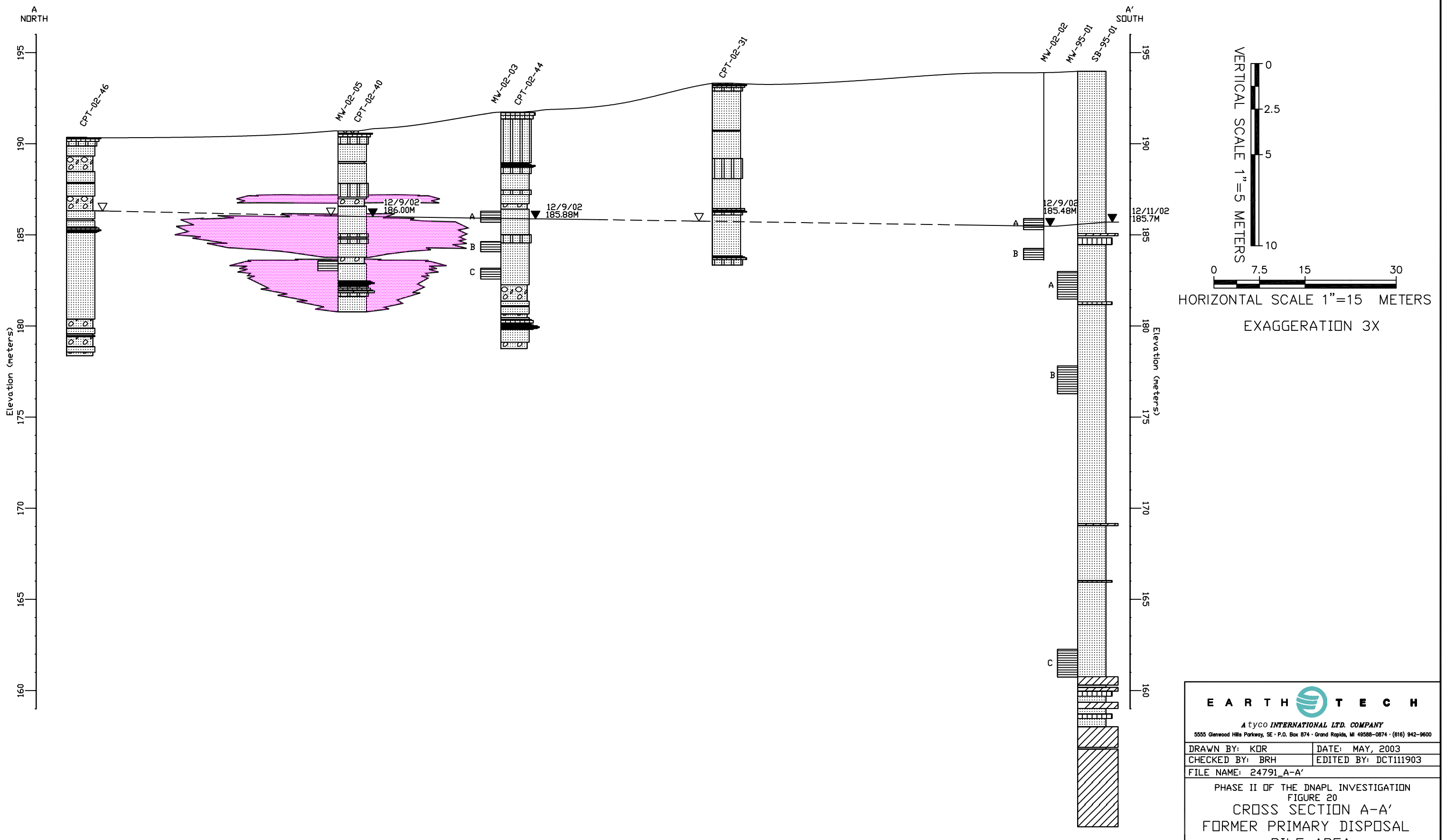

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FILE NAME: 24791_A-A'	

PHASE II OF THE DNAPL INVESTIGATION
FIGURE 20

CROSS SECTION A-A'
FORMER PRIMARY DISPOSAL PILE AREA
AREA 1

MILLER SPRINGS REMEDIATION MANAGEMENT, INC.
MONTAGUE, MICHIGAN

PROJECT NUMBER 24791.23

24791\PROJADMIN\24791.23_DNAPL PHASE II\PHASE II REPORT\CROSS SECTIONS\A-A'

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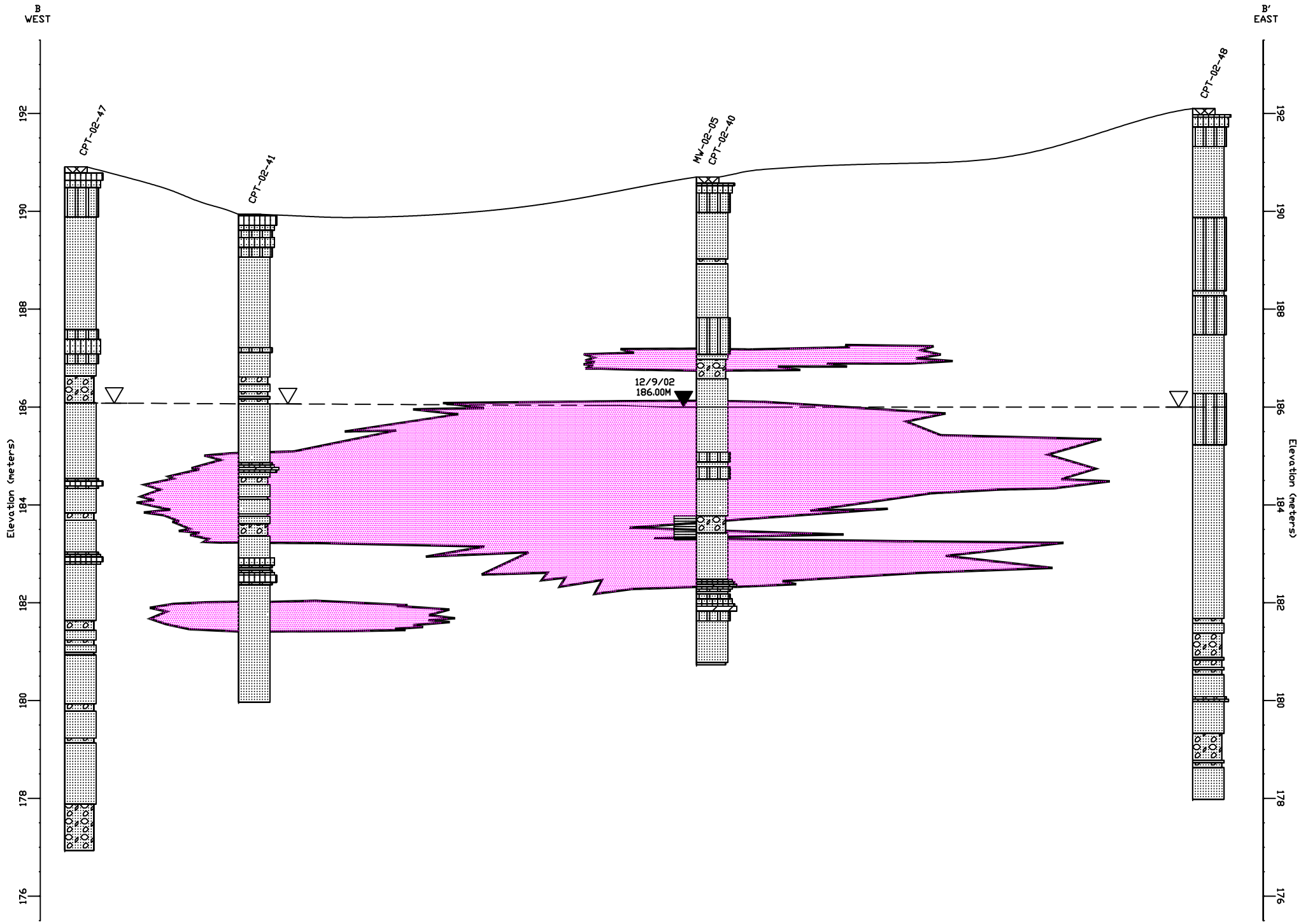

VERTICAL SCALE 1"=2.5 METERS

0
1.25
2.5
5

0 5 10 20

HORIZONTAL SCALE 1"=10 METERS

EXAGGERATION 4X

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FILE NAME: 24791_B-B'	

PHASE II OF THE DNAPL INVESTIGATION
FIGURE 21

CROSS SECTION B-B'
FORMER PRIMARY DISPOSAL PILE AREA
AREA 1

MILLER SPRINGS REMEDIATION MANAGEMENT, INC.
MONTAGUE, MICHIGAN

PROJECT NUMBER	24791.23

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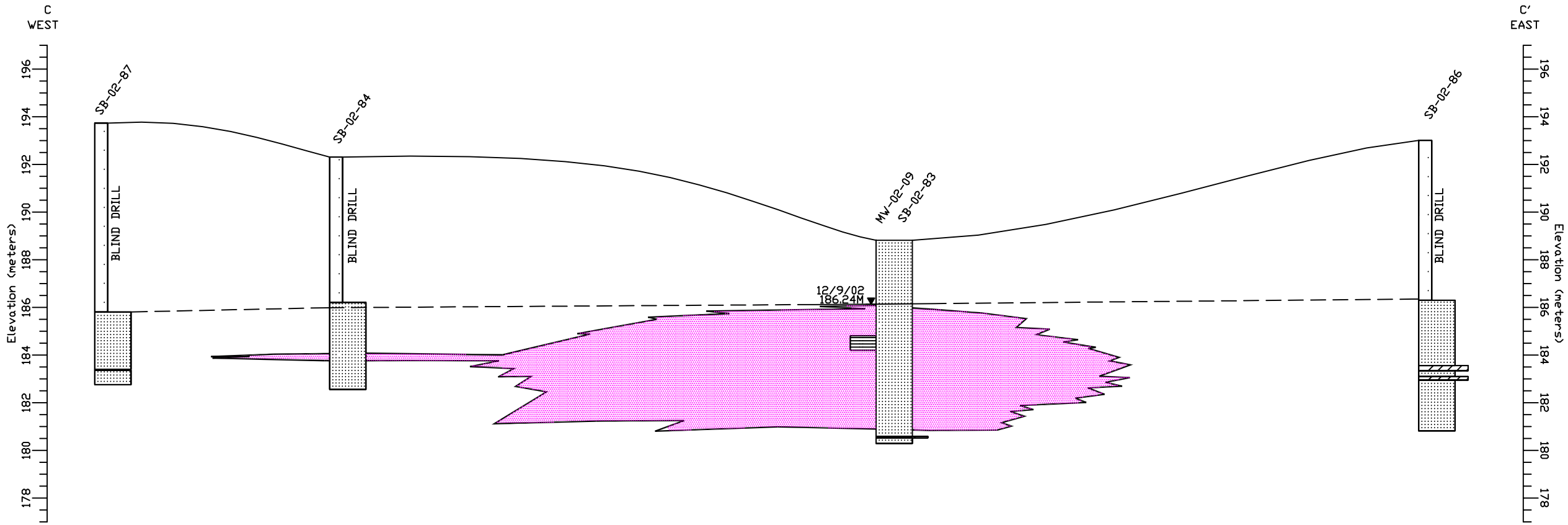

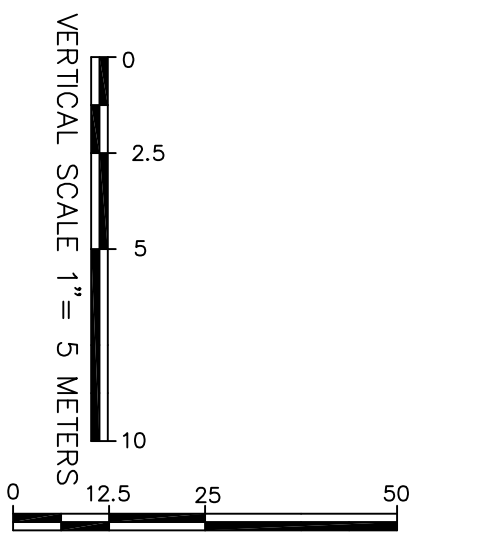

24791\PROJADMIN\24791.23_DNAPL PHASE II\PHASE II REPORT\CROSS SECTIONS\C-C'

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FILE NAME: 24791_C-C'	

PHASE II OF THE DNAPL INVESTIGATION
FIGURE 22

CROSS SECTION C-C'
FORMER PRIMARY FLY ASH DISPOSAL PILE AREA
AREA 2

MILLER SPRINGS REMEDIATION MANAGEMENT, INC
MONTAGUE, MICHIGAN

PROJECT NUMBER	24791.23

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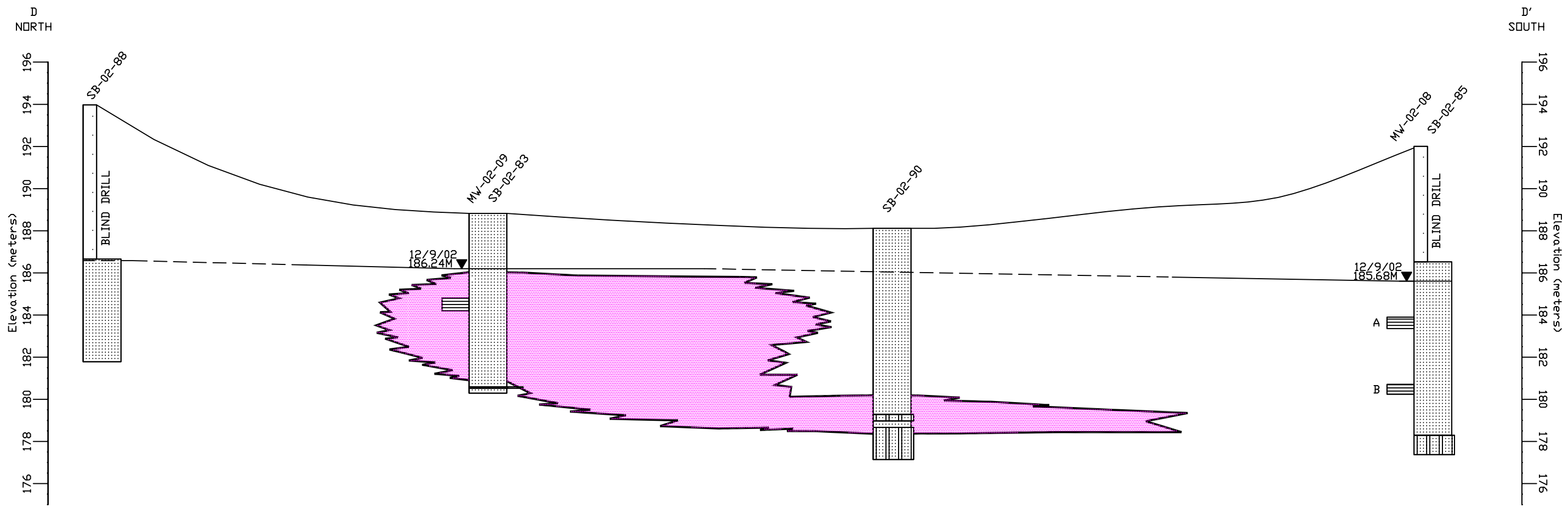

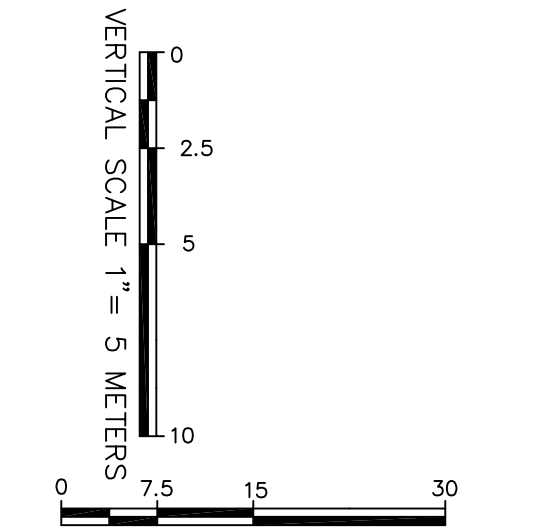

EXAGGERATION 3X

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FILE NAME: 24791_D-D'	

PHASE II OF THE DNAPL INVESTIGATION
FIGURE 23

CROSS SECTION D-D'
FORMER PRIMARY FLY ASH DISPOSAL PILE AREA
AREA 2

MILLER SPRINGS REMEDIATION MANAGEMENT, INC
MONTAGUE, MICHIGAN

PROJECT NUMBER	24791.23

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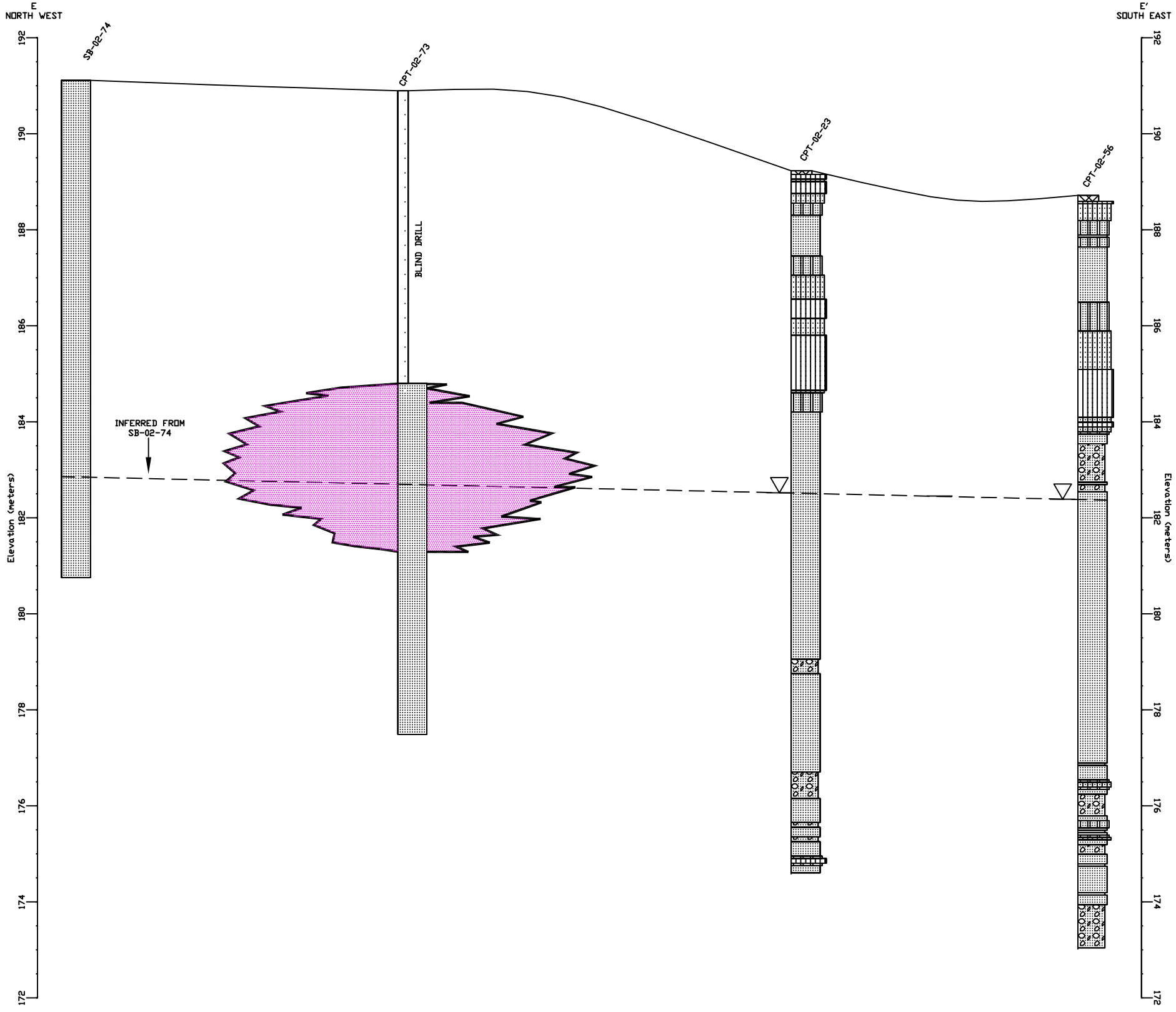

VERTICAL SCALE 1" = 2.5 METERS

0
1.25
2.5
5

0 5 10 20

HORIZONTAL SCALE 1"=10 METERS

EXAGGERATION 4X

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PHASE II OF THE DNAPL INVESTIGATION
FIGURE 24

CROSS SECTION E-E'
FORMER FINE CHEMICAL PRODUCTION AREA
AREA 3

MILLER SPRINGS REMEDIATION MANAGEMENT, INC
MONTAGUE, MICHIGAN

PROJECT NUMBER	24791.23

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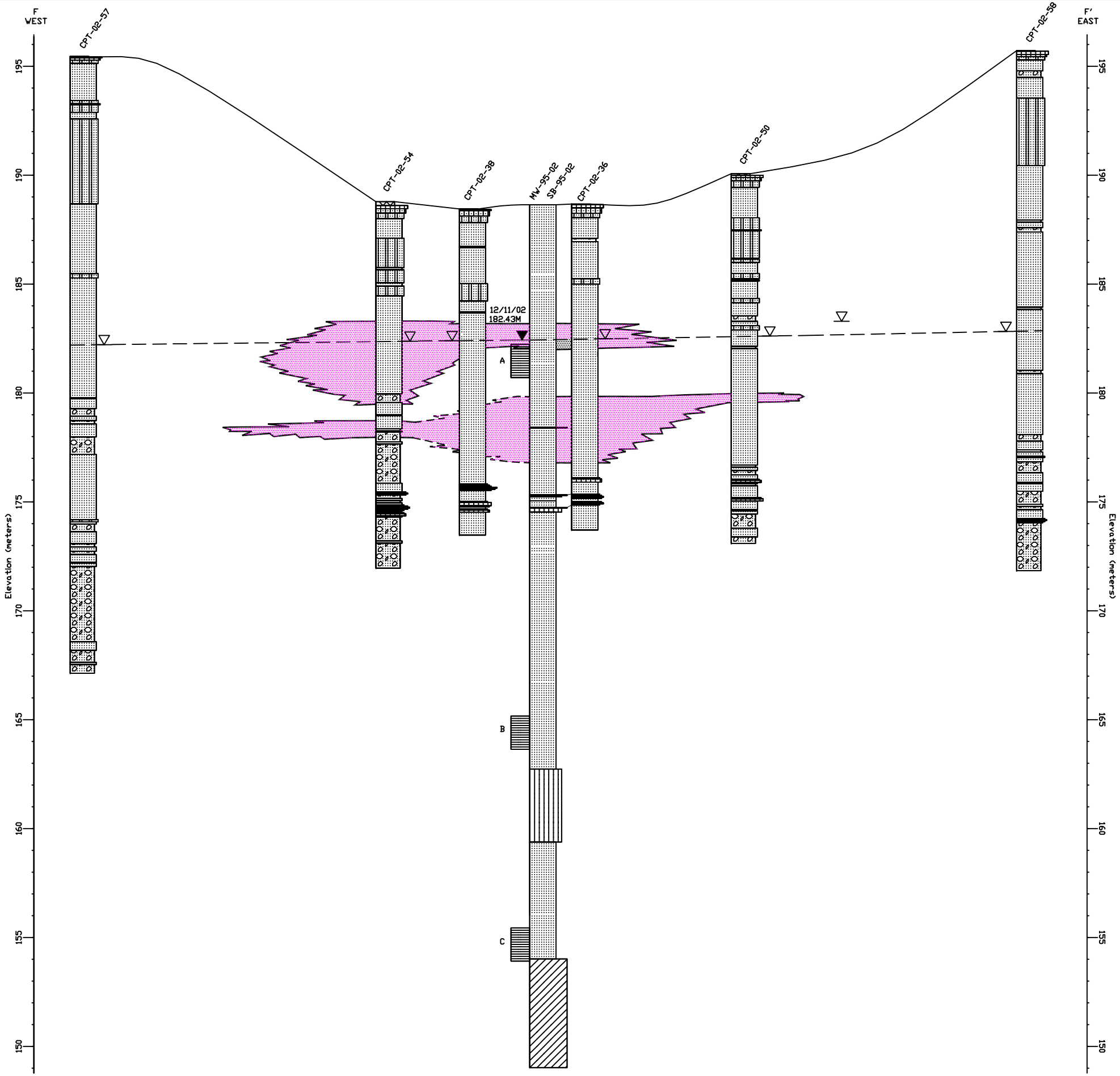

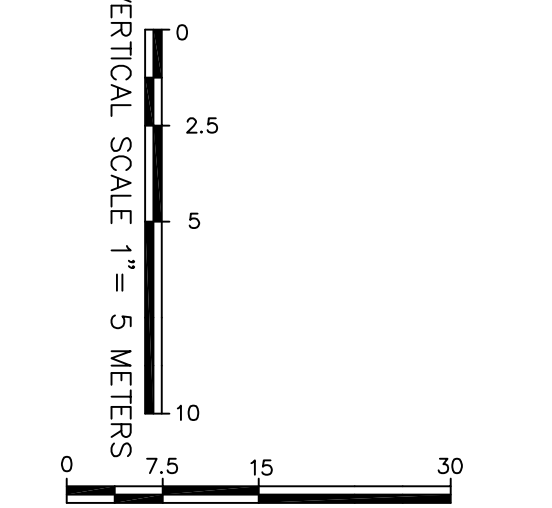

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FILE NAME: 24791-F_F'	

PHASE II OF THE DNAPL INVESTIGATION
FIGURE 25

CROSS SECTION F-F'
FORMER FINE CHEMICAL PRODUCTION AREA
AREA 3

MILLER SPRINGS REMEDIATION MANAGEMENT, INC
MONTAGUE, MICHIGAN

PROJECT NUMBER 24791.23

24791\PROJADMIN\24791.23_DNAPL PHASE II\PHASE II REPORT\CROSS SECTIONS\F_F'

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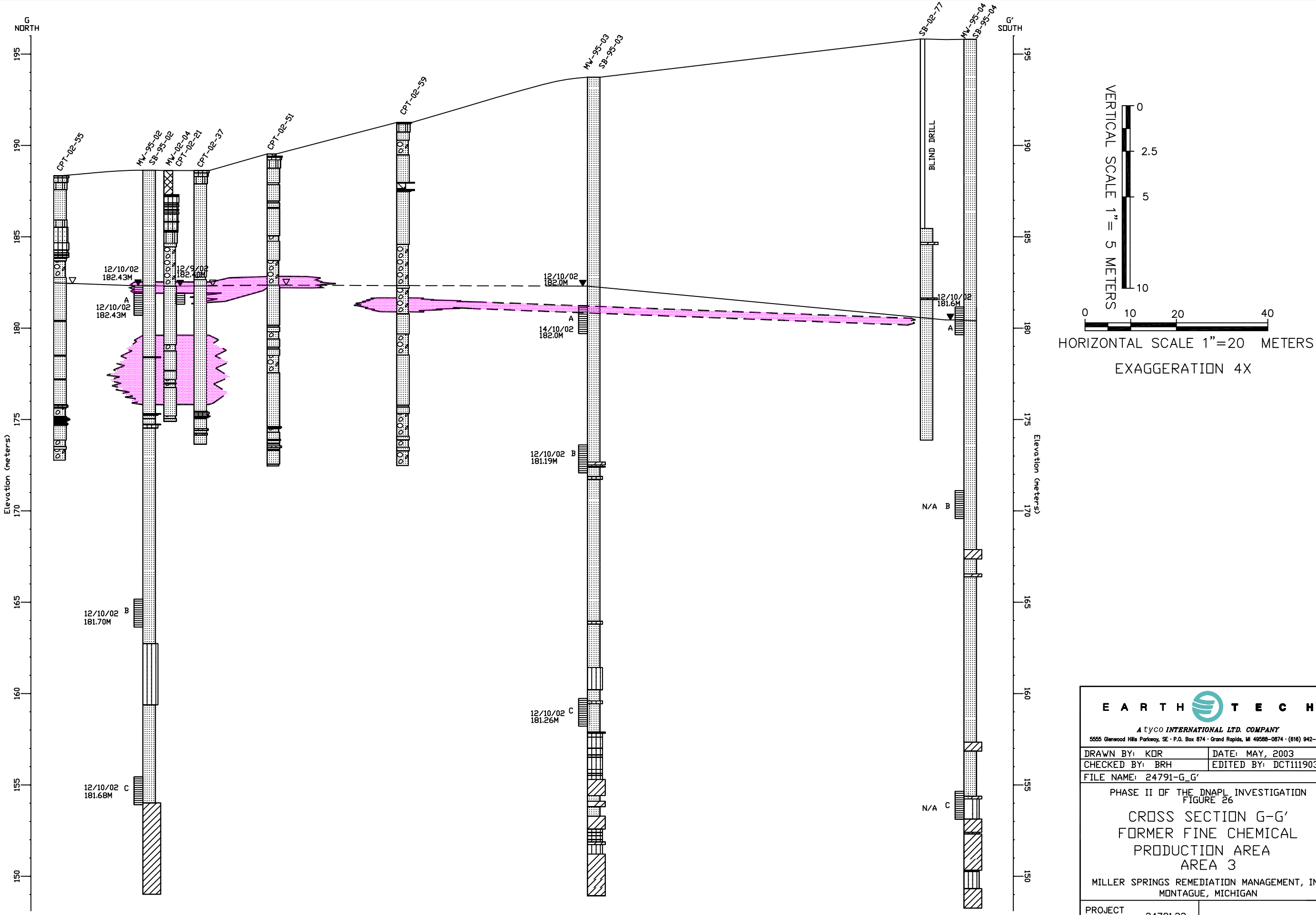

24791\PROJADMIN\24791.23_DNAPL PHASE II\PHASE II REPORT\CROSS SECTIONS\G_G'

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PHASE II OF THE DNAPL INVESTIGATION
FIGURE 26

CROSS SECTION G-G'
FORMER FINE CHEMICAL PRODUCTION AREA
AREA 3

MILLER SPRINGS REMEDIATION MANAGEMENT, INC
MONTAGUE, MICHIGAN

PROJECT NUMBER 24791.23

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H
NORTH

H'
SOUTH

CPT-02-56
CPT-02-53
CPT-02-50
CPT-02-52
CPT-02-59
MW-95-03
SB-95-03
MW-02-06
SB-95-70
FLUID DRILL

12/10/02
182.0M
A
16/10/02
182.0M
12/9/02
181.63M
A
B
12/10/02
181.19M
B
12/10/03
181.26M
C

Elevation (meters)
195
190
185
180
175
170
165
160
155
150

VERTICAL SCALE 1" = 5 METERS
0
2.5
5
10

0
7.5
15
30
HORIZONTAL SCALE 1"=15 METERS

EXAGGERATION 3X

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FILE NAME: 24791-H_H'	

PHASE II OF THE DNAPL INVESTIGATION
FIGURE 27

CROSS SECTION H-H'
FORMER FINE CHEMICAL PRODUCTION AREA
AREA 3

MILLER SPRINGS REMEDIATION MANAGEMENT, INC
MONTAGUE, MICHIGAN

PROJECT NUMBER 24791.23

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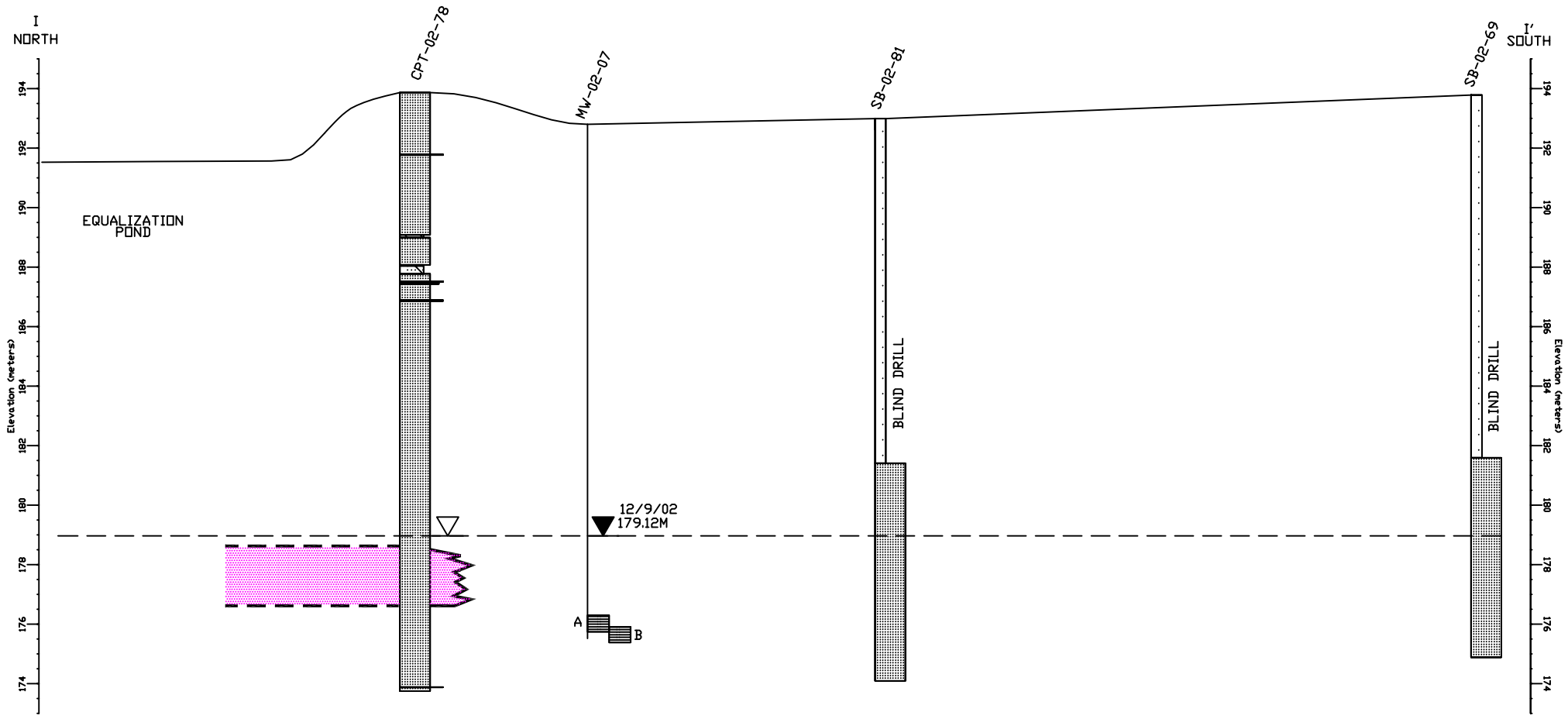

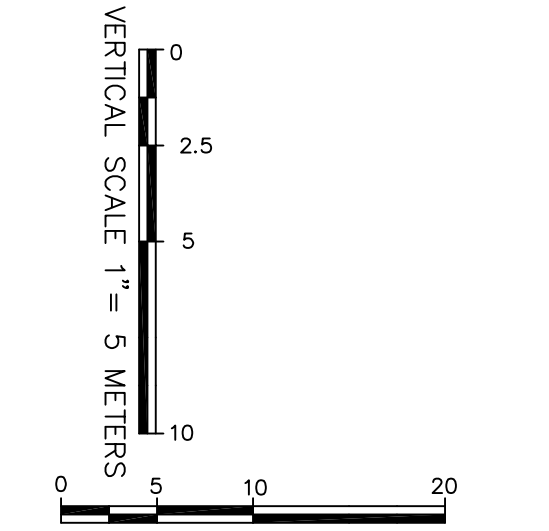

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CHECKED BY: BRH	EDITED BY: DCT111903
FILE NAME: 24791-I_I'	

PHASE II OF THE DNAPL INVESTIGATION
FIGURE 28

CROSS SECTION I-I'
EQUALIZATION POND AREA
AREA 5

MILLER SPRINGS REMEDIATION MANAGEMENT, INC
MONTAGUE, MICHIGAN

PROJECT NUMBER	24791.23

APPENDIX B

Purge Well Performance Data 2009

Glenn Springs Holdings, Inc.
A subsidiary of Occidental Petroleum

Clint Babcock
Project Manager
Direct Dial (972) 687-7506

5005 LBJ Freeway, Suite 1350
Dallas, TX 75244-6119
Facsimile (972) 687-7524

February 25, 2009

Mr. David Slayton
Waste and Hazardous Materials Division
Michigan Department of Environmental Quality
P.O. Box 30241
Lansing, MI 48909-7741

Re: Occidental Chemical Corporation
Montague, Michigan MID 006014906
2008 Annual Groundwater Monitoring Report

Dear Mr. Slayton:

Enclosed is the "2008 Annual Groundwater Monitoring Report " for Occidental's Montague, Michigan, facility. This report presents groundwater monitoring data collected in accordance with the requirements of the Groundwater Monitoring Plan (GMP) for the Site for the period January to December 2008.

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering the information, the information submitted is, to be the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine or imprisonment for knowing violations.

If you have any questions regarding this report, please do not hesitate to contact the undersigned at (972) 687-7506.

Very truly yours,

Glenn Springs Holdings, Inc.

Clint Babcock
Project Manager

CB/dl
Enc.
cc: Ken Bardo
Joseph Branch
Mike Mateyk
James Tolbert

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1.2 REPORT ORGANIZATION 2

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2.3 RESULTS 4
2.4 EVALUATION 5

3.0 PLUME BOUNDARY DEMONSTRATION 6
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3.4 DATA EVALUATION 7

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4.2 WORK PERFORMED 9
4.3 RESULTS 10
4.4 DATA EVALUATION 10

1.0 INTRODUCTION

Glenn Springs Holdings, Inc. (GSHI) is performing corrective actions at the former Occidental Chemical Corporation manufacturing facility in Montague, Michigan (the Facility). These corrective actions are being performed, in part, to comply with the requirements of an Administrative Order (AO) issued by the United States Environmental Protection Agency (USEPA) dated March 24, 1993. At the completion of the Resource Conservation and Recovery Act (RCRA) Facility Investigation and the Corrective Measures Study, the USEPA issued the Final Decision on July 18, 2001 stating the corrective action requirements for the Facility.

The Final Decision requires groundwater monitoring at the Facility. Section 4 of the Program Management Plan presents the management approach for the groundwater monitoring. The groundwater monitoring program is defined in the document entitled "Groundwater Monitoring Plan (GMP) for the Occidental Chemical Corporation Site in Montague, Michigan (USEPA ID No. MID 006014906)". The GMP was approved by the USEPA in January 2002.

The 2002 GMP replaces the previous groundwater monitoring plan for the Facility. In accordance with Paragraph XV of the Consent Judgment (October 31, 1979), GSHI requested approval of the 2002 GMP from the Michigan Department of Environmental Quality (MDEQ). The MDEQ Waste Management Division reviewed GSHI's request for compliance with Consent Judgment and Part 111, Hazardous Waste Management, of Michigan's Natural Resources and Environmental Protection Act 1994, PA 451, as amended, and granted approval in a letter from the MDEQ (Jim Sygo) to GSHI (Ken Price) dated July 18, 2002. The GMP was implemented following approval by the MDEQ. Prior to this date, groundwater monitoring activities were conducted in accordance with 1979 Consent Judgement.

The Facility is located in Montague Township north of White Lake in Muskegon County, Michigan (Figure 1.1).

1.1 OBJECTIVES

The following are the objectives for the groundwater monitoring program. These objectives were defined in Section 1.1 of the GMP.

- Demonstrate that the groundwater collection system halts any unacceptable discharge of chlorinated organic compounds to White Lake.

2.0 GROUNDWATER COLLECTION DEMONSTRATION

2.1 PROGRAM REQUIREMENTS

GSHI operates eight purge wells that completely halt the flow of impacted groundwater to White Lake. The locations of the purge wells are shown on Figure 2.1. GSHI is required to demonstrate that the groundwater collection system completely halts discharge of chlorinated organic compounds to White Lake.

This component of the monitoring program has been established to demonstrate that impacted groundwater is not discharging to White Lake. To accomplish this, a monitoring program has been implemented that will show that the 48-hour average water level in White Lake is at least 0.10 feet higher than the water level in the aquifer. If the water level in the aquifer is below the water level in White Lake, the groundwater flow from the lake is towards the purge wells. When this condition exists, it can be concluded that the impacted groundwater is completely captured

Six performance monitoring wells were installed in areas of the plume that are least likely to be influenced by the purge wells. The locations of the performance monitoring wells are shown on Figure 2.1. White Lake water levels are measured at a stilling well placed on a dock east of the performance monitoring network and shown on Figure 2.1.

A comparison of the level of White Lake to the level of water in the monitoring wells is performed on data collected at a minimum of two times per week, or over 100 times per year. Approximately 19,000 White Lake Level measurements are utilized in calculating average water levels (192 per event) every 12 months.

Monitoring methods and calculations are outlined in the GMP. The GMP requires that manual water level measurements be collected in each of the six performance monitoring wells and at White Lake (stilling well) at least two times per week. In addition, White Lake water levels are collected every 15 minutes to calculate the corresponding average lake levels for each semi-weekly water level collection event.

Reporting requirements and actions are outlined in the GMP. Monthly reports to the USEPA and MDEQ are required. Monthly reports summarize the calculated average monthly difference between the water level in the wells and in White Lake and report any necessary actions implemented to assure that the purge system maintains at least a 0.10-foot lower water level in all of the performance monitoring wells.

summarizes purge well pumping data, provides an assessment of the average monthly performance of the six monitoring wells with White Lake level elevations, and demonstrates purge well efficiency.

Over 100 water levels were collected from the performance monitoring wells for comparison to corresponding average White Lake water levels. A tabulation of water levels depths and calculated elevations are presented in Appendix A.

A summary of the calculated water level performance results for 2008 is presented in Table 2.1.

2.4 EVALUATION

Examination of Table 2.1 shows that an inward hydraulic gradient was maintained at all times during 2008. The measured water level differential far exceeded the required differential of 0.1 feet in all six performance monitoring wells. An assessment of the results confirms that the required objective of the groundwater collection system to completely halt the discharge of groundwater contaminated with chlorinated organic compounds to White Lake was achieved.

stabilization parameters were measured at 10-minute intervals using a YSI 556 and a flow-through cell. The following stabilization parameters were monitored: pH, temperature, conductivity, oxidation reduction potential (ORP), and dissolved oxygen (DO). Stabilization parameters were measured and recorded in the field. A summary of the final field stabilization parameters is presented in Appendix B. Groundwater samples were collected once stabilization was achieved.

Samples were collected, handled, and documented in accordance with the GMP. Appropriate sample volumes, container types, preservation procedures, and maximum holding times for the Site-specific analytical parameters were followed. Chain of Custody protocol was strictly adhered to during all phases of sample collection, transport, and delivery to the analytical laboratory for analysis.

3.3 RESULTS

Analytical results for the 2008 semi-annual plume boundary demonstration monitoring events are summarized in Table 3.2. The applicable groundwater protection standards are also listed for comparison purposes.

3.4 DATA EVALUATION

Analytical results show that the concentrations of all constituents of concern are below applicable groundwater protection standards in all plume boundary demonstration monitoring wells. The analytical results confirm plume stability within the boundary of impacted groundwater delineated during the RCRA Facility Investigation.

Tetrachloroethene (PCE) was detected in monitoring wells MW-03-01 (1 micrograms per liter [µg/L] [May]), MW-05-01 (3 µg/L [May]), MW-97-02 (1 µg/L [May]), and C (4 µg/L [May] and 4 µg/L [November]) at concentrations below the groundwater protection standard (5.0 µg/L). Trichloroethene (TCE) was detected in monitoring wells WW-2 (1.0 µg/L [November]), and T (3.0 µg/L [May] and 3.0 µg/L [November]) at concentrations below the groundwater protection standard (5.0 µg/L). These results are consistent with previous monitoring events.

No semi-volatile constituents of concern were detected during 2008.

4.0 CONCENTRATION REMOVED FROM THE AQUIFER

4.1 PROGRAM REQUIREMENTS

Eight purge wells are being pumped continuously as part of the groundwater collection system to remove impacted groundwater from the aquifer. Samples of the groundwater from each purge well are collected quarterly and analyzed for the parameters in Table 3.1. These analyses are intended to provide a baseline of information on the concentrations of the compounds in the water being removed from the aquifer. These purge wells are located in a line extending across the plume of impacted groundwater, and samples from each purge well represents a view of the section of the aquifer upgradient from that purge well. The analysis of the groundwater collected at each purge well provides a basis for evaluating trends in the concentrations of contaminants in the groundwater and the rate of removal of contaminants.

The locations of the eight purge wells used to determine the concentration removed from the aquifer are shown on Figure 2.1.

4.2 WORK PERFORMED

Quarterly purge well groundwater sampling was performed in accordance with the procedures and analytical methods described in the approved GMP. Samples were collected and analyzed from all purge wells (eight total) for the constituents of concern listed in Table 3.1. Samples were submitted to H2M located in Melville, NY. All samples were analyzed using Method SW-8260 for VOCs and SW-8121 for SVOCs. Chloride was analyzed using USEPA Method 325.2.

Groundwater samples were collected from the purge wells on the following dates:

i) January 29, 2008;

ii) April 24, 2008;

iii) July 23, 2008; and

iv) October 30, 2008.

Groundwater samples are collected from a sample tap located at each purge well pump house. Samples are collected, handled, and documented in accordance with the GMP. Appropriate sample volumes, container types, preservation procedures, and maximum holding times for the Site-specific analytical parameters were followed. Chain of

primary constituent of concern in all the purge wells. The highest concentrations following Pg occur in wells Pi (1,900 µg/L to 3,300 µg/L), Pb (1,700 µg/L to 3,100 µg/L), and Pd (1,500 µg/L to 2,400 µg/L). Carbon tetrachloride is typically found at the next highest concentration. The highest concentrations following Pg occur in wells Pd (range 290 µg/L to 530 µg/L), Pb (range 180 µg/L to 350 µg/L), and Pi (range 190 µg/L to 280 µg/L).

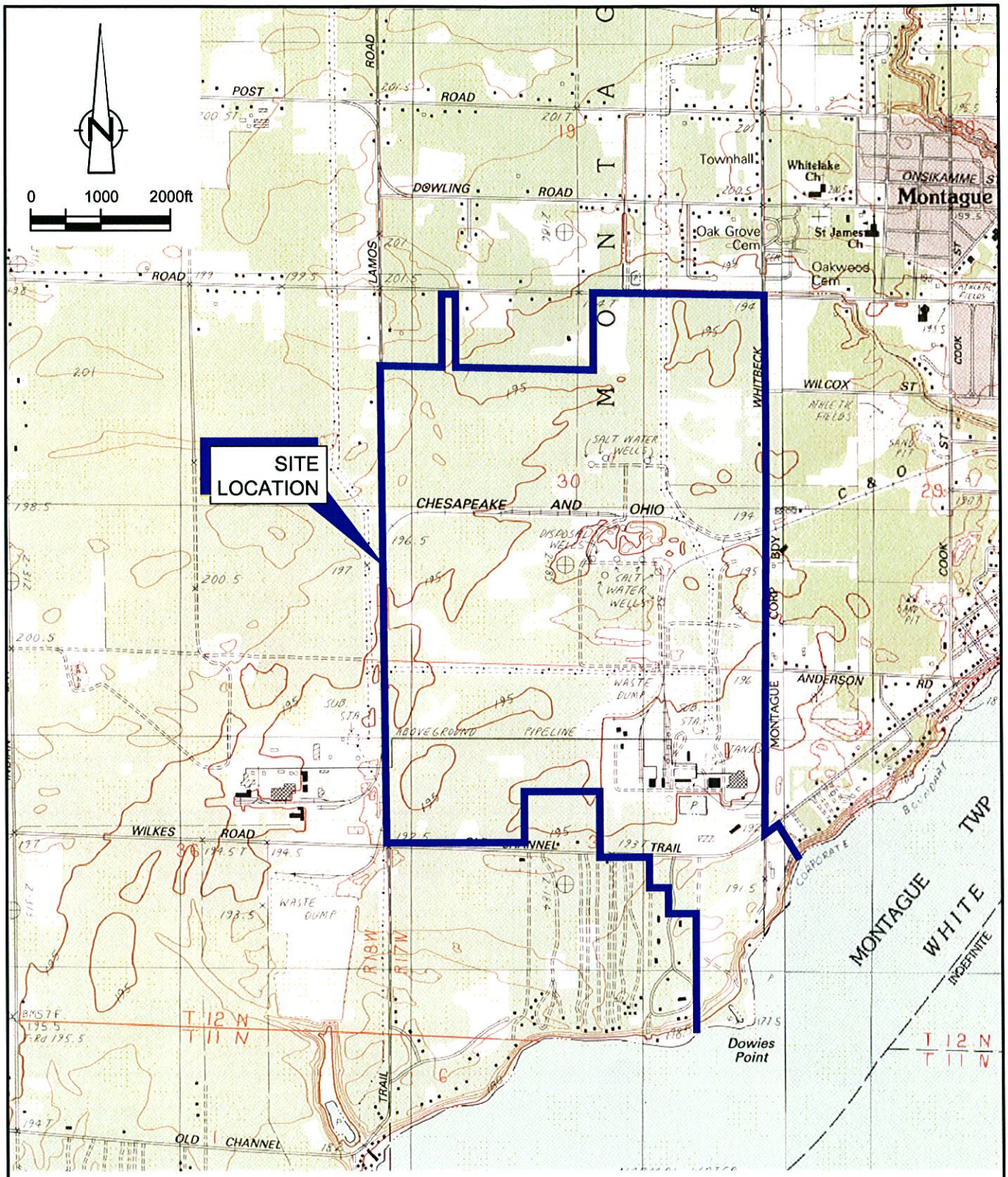
The 2008 analytical results are consistent with historical data. The purge well exhibiting the highest concentrations of these constituents is Pg. In general, the concentration-time graphs show a stable or decreasing trend in the constituents of concern concentrations over time. Only Purge Well Pi shows an increasing trend in PCE concentration. Purge Wells Pb, Pc, and Pi had historically increasing PCE concentrations; however, concentrations have stabilized or decreased since 2005. Pi, Pb, and Pc Purge Wells are located in the central area of the plume.

A summary of the total mass of VOCs and SVOCs removed in 2008 is shown in Table 4.3. Examination of this table shows that over 6,800 pounds of VOCs and SVOCs were removed by the purge wells during 2008. Purge Well Pf removed very little mass (less than 1 pound). The majority of the mass was removed by Purge Wells Pg (3,487 pounds), Pi (1,120 pounds), Pb (946 pounds), and Pd (883 pounds).

In general, as shown on Figure 4.1, the rate of mass removal has declined steadily from approximately 27 pounds/day in 1990 to an annual average rate of approximately 19 pounds/day in 2008. The 2008 removal rate is within the normal range of fluctuation experienced over previous 3 years as shown in the table below.

Year	*Annual Total Mass Removed (lbs)*	*Mass Removal Rate (lb/day)*
2005	7,883	22
2006	6,868	19
2007	5,862	16
2008	6,800	19

The above information shows that the rate of mass removal over the past 4 years has been relatively constant and may have reached asymptotic conditions.



REFERENCE:

UNITED STATES GEOLOGIC SURVEY
MONTAGUE, FLOWER CREEK, MICHIGAN QUADRANGLES
TOPOGRAPHIC, 7.5 MINUTES SERIES 1983
SCALE: 1:25,000

figure 1.1

SITE LOCATION
GLENN SPRINGS HOLDINGS, INC.
Montague, Michigan

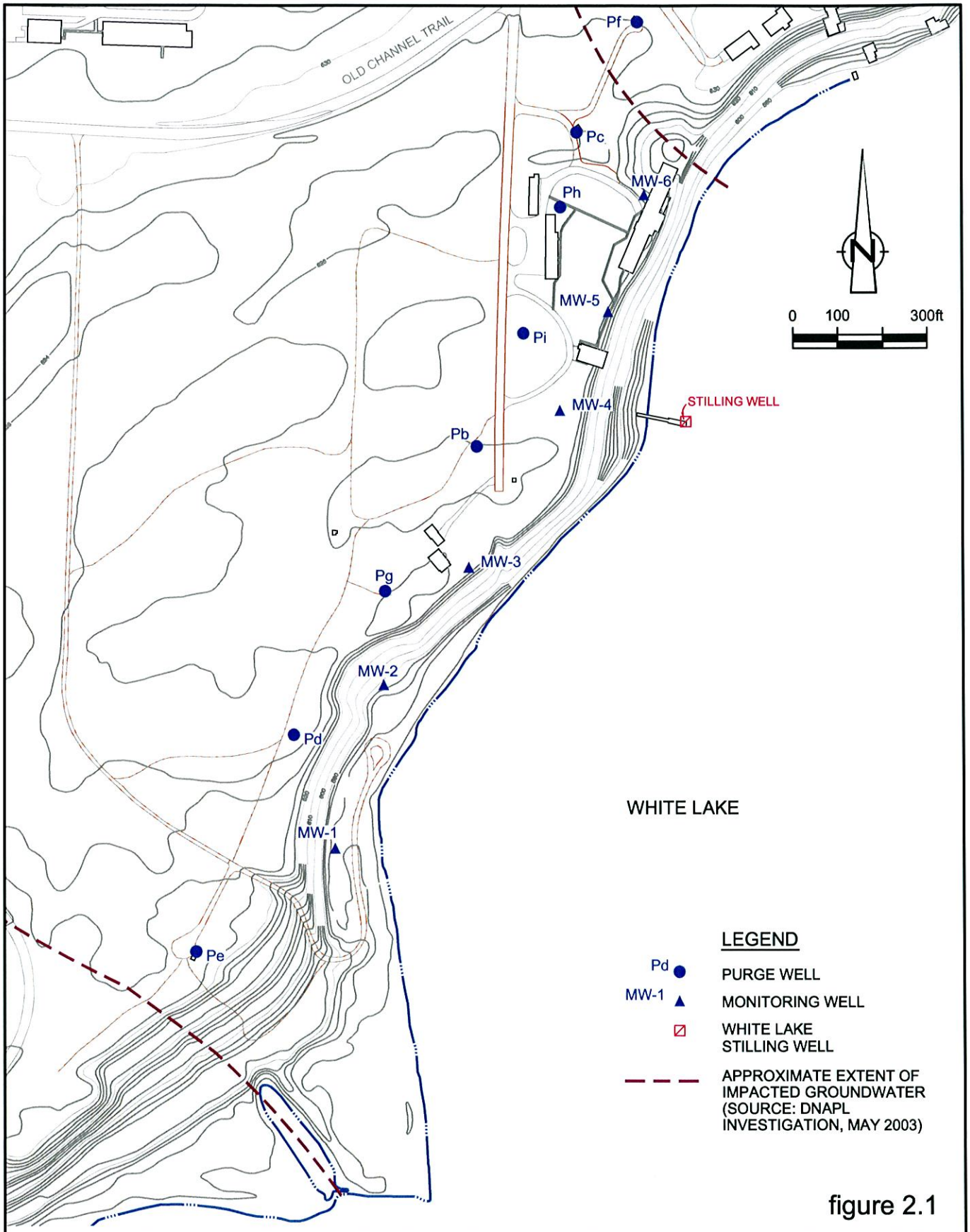


figure 2.1

GROUNDWATER COLLECTION DEMONSTRATION WELL LOCATIONS
GLENN SPRINGS HOLDINGS, INC.
Montague, Michigan

CRA

09970-B0331(025)GN-WA002 FEB 02/2009

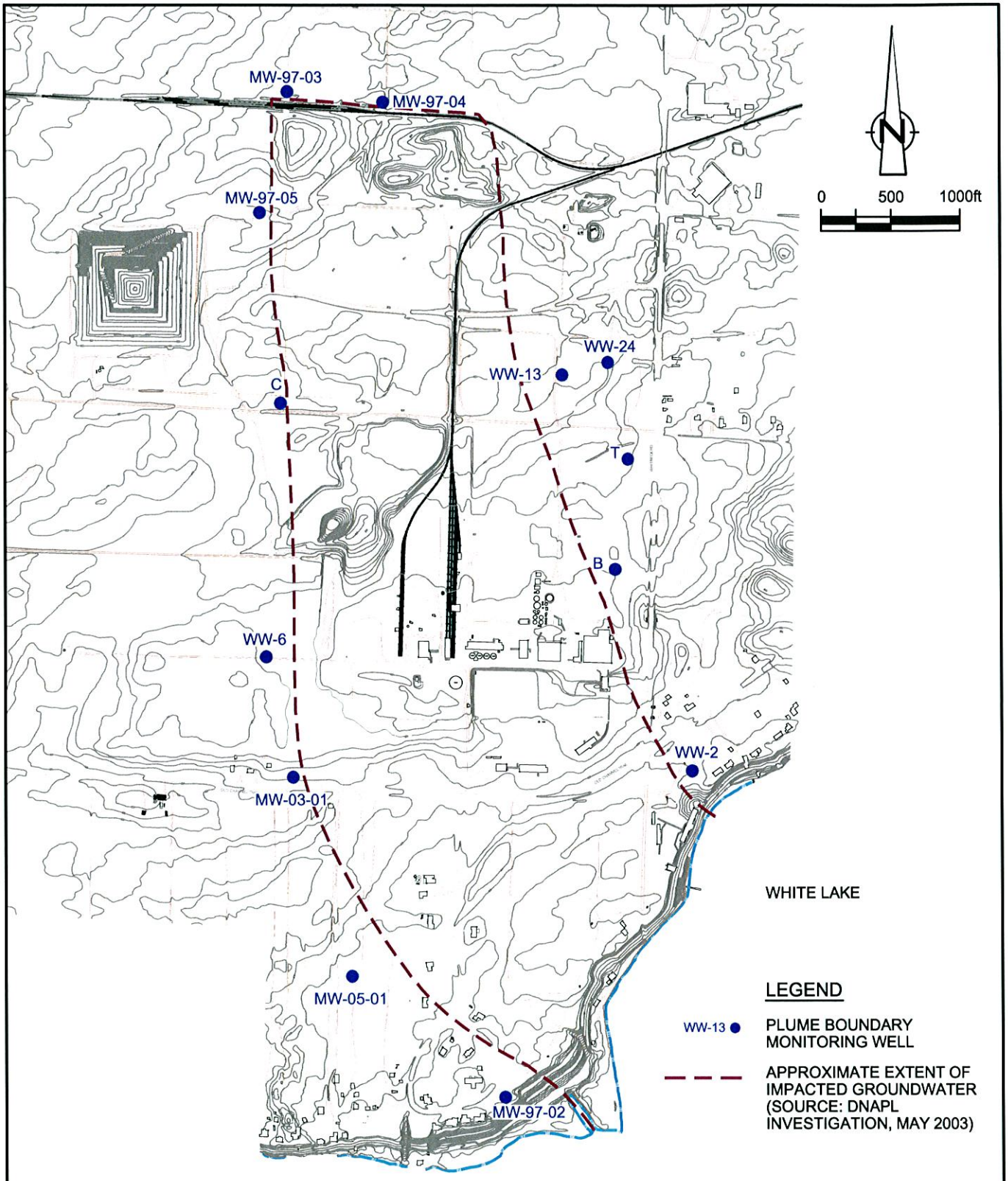


figure 3.1

PLUME BOUNDARY WELL LOCATIONS
GLENN SPRINGS HOLDINGS, INC.
Montague, Michigan

09970-B0331(025)GN-WA003 JAN 13/2009

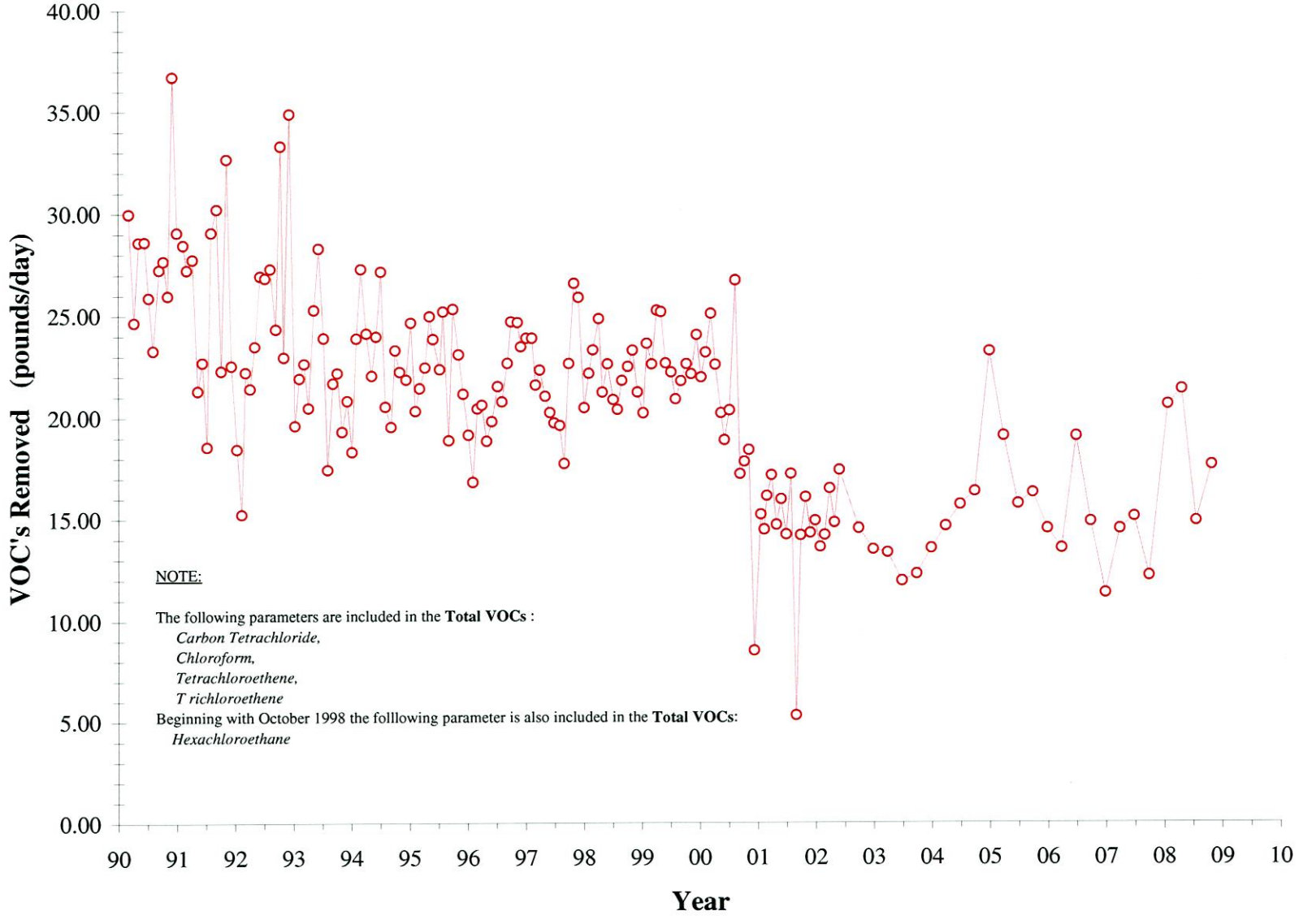


figure 4.1

PURGE WELL MASS REMOVAL RATES
GLENN SPRINGS HOLDINGS, INC.
Montague, Michigan

TABLE 2.1

SUMMARY OF PERFORMANCE RESULTS - 2008
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Month	White Lake Elevation (ft.AMSL)	MW-1		MW-2		MW-3	
		Avg.Difference (feet)	Avg. Elevation (ft.AMSL)	Avg.Difference (feet)	Avg. Elevation (ft.AMSL)	Avg.Difference (feet)	Avg. Elevation (ft.AMSL)
January	577.31	-0.40	576.91	-0.39	576.92	-0.44	576.87
February	577.56	-0.46	577.10	-0.44	577.12	-0.46	577.10
March	577.59	-0.30	577.29	-0.33	577.26	-0.35	577.24
April	578.17	-0.38	577.79	-0.46	577.71	-0.51	577.66
May	578.46	-0.19	578.27	-0.26	578.20	-0.35	578.11
June	578.86	-0.15	578.71	-0.18	578.68	-0.31	578.55
July	579.11	-0.21	578.90	-0.17	578.94	-0.26	578.85
August	579.09	-0.19	578.90	-0.15	578.94	-0.18	578.91
September	578.99	-0.24	578.75	-0.25	578.74	-0.27	578.72
October	578.64	-0.16	578.48	-0.16	578.48	-0.22	578.42
November	578.31	-0.12	578.19	-0.12	578.19	-0.21	578.10
December	578.22	-0.25	577.97	-0.20	578.02	-0.31	577.91
YEAR 2008 AVERAGE:	578.36	-0.25	578.11	-0.26	578.10	-0.32	578.04

Note:
ft. AMSL - Feet Above Mean Sea Level.

TABLE 2.1

SUMMARY OF PERFORMANCE RESULTS - 2008
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Month	*White Lake Elevation (ft.AMSL)*	*MW-4*		*MW-5*		*MW-6*	
		Avg.Difference (feet)	*Avg. Elevation (ft.AMSL)*	*Avg.Difference (feet)*	*Avg. Elevation (ft.AMSL)*	*Avg.Difference (feet)*	*Avg. Elevation (ft.AMSL)*
January	577.31	-0.87	576.44	-0.54	576.77	-0.42	576.89
February	577.56	-0.73	576.83	-0.48	577.08	-0.39	577.17
March	577.59	-0.56	577.03	-0.36	577.23	-0.30	577.29
April	578.17	-0.65	577.52	-0.48	577.69	-0.38	577.79
May	578.46	-0.45	578.01	-0.19	578.27	-0.13	578.33
June	578.86	-0.52	578.34	-0.24	578.62	-0.16	578.70
July	579.11	-0.43	578.68	-0.22	578.89	-0.17	578.94
August	579.09	-0.33	578.76	-0.12	578.97	-0.24	578.85
September	578.99	-0.53	578.46	-0.19	578.80	-0.25	578.74
October	578.64	-0.57	578.07	-0.23	578.41	-0.19	578.45
November	578.31	-0.53	577.78	-0.27	578.04	-0.23	578.08
December	578.22	-0.46	577.76	-0.28	577.94	-0.30	577.92
YEAR 2008 AVERAGE:	578.36	-0.55	577.81	-0.30	578.06	-0.26	578.10

Note:
ft. AMSL - Feet Above Mean Sea Leve

TABLE 3.1

ANALYTICAL PARAMETERS
GROUNDWATER MONITORING PLAN
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Compound	*Short Name*	*Analytical Method Number*	*Target Detection Limit (µg/L)*	*Residential and Commercial Drinking Water Criteria (µg/L)*	*Groundwater Surface Water Interface Criteria (µg/L)*
Hexachlorobenzene	C-66	8121	0.01	**1.0**	ID
Hexachlorocyclopentadiene	C-56	8121	0.01	**50**	ID
Octachlorocyclopentene	C-58	8121	1.0	**50**	ID
Hexachlorobutadiene	C-46	8121	0.01	15	**0.053**
Hexachloroethane		8121	2.0	7.3	**6.7**
Tetrachlorethene	PCE	8260	1.0	**5.0**	45
Trichloroethene	TCE	8260	1.0	**5.0**	200
Carbon tetrachloride		8260	1.0	**5.0**	45
Chloroform		8260	1.0	**100**	170
Chloride		325.3	1000	250000	**125000**
cis-1,2-Dichloroethylene		8260	0.5	**70**	ID
trans-1,2-Dichloroethylene		8260	0.5	**100**	ID

Notes:

Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup criteria.

µg/L Microgram per Liter.
ID Inadequate Data.
NA Not Applicable.

TABLE 3.2

2008 ANALYTICAL RESULTS SUMMARY
PLUME BOUNDARY DEMONSTRATION
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*MW-03-01*	*MW-03-01*	*MW-05-01*	*MW-05-01*	*MW-05-01*
Sample ID:		*Residential and Commercial Drinking Water Criteria* a	*Groundwater Surface Water Interface Criteria* b	*GW-9970-052708-BW-031*	*GW-9970-111008-BW-031*	*GW-9970-052708-BW-051*	*GW-9970-111208-BW-051*	*GW-9970-111208-BW-DUP2*
Sample Date:				*5/27/2008*	*11/10/2008*	*5/27/2008*	*11/12/2008*	*11/12/2008 (Duplicate)*
Parameters	*Units*							
Volatile Organic Compounds								
Carbon tetrachloride	µg/L	5.0	45	1 U	1 U	1 U	1 U	1 U
Chloroform (Trichloromethane)	µg/L	100	170	1 U	1 U	1 U	1 U	1 U
cis-1,2-Dichloroethene	µg/L	70	-	1 U	1 U	1 U	1 U	1 U
Tetrachloroethene	µg/L	5.0	45	1	1 U	3	1 U	1 U
trans-1,2-Dichloroethene	µg/L	100	-	1 U	1 U	1 U	1 U	1 U
Trichloroethene	µg/L	5.0	200	1 U	1 U	1 U	1 U	1 U
Semi-volatile Organic Compounds								
Hexachlorobenzene	µg/L	**1.0**	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	0.053	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	6.7	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
General Chemistry								
Chloride	mg/L	250	125	1.8	1.50	3.8	3.52	3.38

Notes:
- - Not applicable.
U - Non-detect at associated value.
Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup criteria.

TABLE 3.2

2008 ANALYTICAL RESULTS SUMMARY
PLUME BOUNDARY DEMONSTRATION
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*MW-97-02*	*MW-97-02*	*MW-97-03*	*MW-97-03*	*MW-97-04*
Sample ID:		*Residential and Commercial Drinking Water Criteria*	*Groundwater Surface Water Interface Criteria*	*GW-9970-052708-BW-972*	*GW-9970-111208-BW-972*	*GW-9970-052908-BW-973*	*GW-9970-111208-BW-973*	*GW-9970-052908-BW-974*
Sample Date:				*5/27/2008*	*11/12/2008*	*5/29/2008*	*11/12/2008*	*5/29/2008*
Parameters	*Units*	a	b					
Volatile Organic Compounds								
Carbon tetrachloride	µg/L	5.0	45	1 U	1 U	1 U	1 U	1 U
Chloroform (Trichloromethane)	µg/L	100	170	1 U	1 U	1 U	1 U	1 U
cis-1,2-Dichloroethene	µg/L	70	-	1 U	1 U	1 U	1 U	1 U
Tetrachloroethene	µg/L	5.0	45	1	1 U	1 U	1 U	1 U
trans-1,2-Dichloroethene	µg/L	100	-	1 U	1 U	1 U	1 U	1 U
Trichloroethene	µg/L	5.0	200	1 U	1 U	1 U	1 U	1 U
Semi-volatile Organic Compounds								
Hexachlorobenzene	µg/L	**1.0**	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	**0.053**	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	6.7	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
General Chemistry								
Chloride	mg/L	250	125	48.4	59.9	19.2	20.6	1.7

Notes:
- - Not applicable.
U - Non-detect at associated value.
Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup criteria.

TABLE 3.2

2008 ANALYTICAL RESULTS SUMMARY
PLUME BOUNDARY DEMONSTRATION
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*MW-97-04*	*MW-97-04*	*MW-97-05*	*MW-97-05*	*WELL B*
Sample ID:		*Residential and Commercial Drinking Water Criteria*	*Groundwater Surface Water Interface Criteria*	*GW-9970-052908-BW-DUP2*	*GW-9970-111108-BW-974*	*GW-9970-052908-BW-975*	*GW-9970-111208-BW-975*	*GW-9970-052808-BW-B*
Sample Date:				*5/29/2008 (Duplicate)*	*11/11/2008*	*5/29/2008*	*11/12/2008*	*5/28/2008*
Parameters	*Units*	*Criteria* a	*Criteria* b					
Volatile Organic Compounds								
Carbon tetrachloride	µg/L	**5.0**	45	1 U	1 U	1 U	1 U	1 U
Chloroform (Trichloromethane)	µg/L	100	170	1 U	1 U	1 U	1 U	1 U
cis-1,2-Dichloroethene	µg/L	70	-	1 U	1 U	1 U	1 U	1 U
Tetrachloroethene	µg/L	**5.0**	45	1 U	1 U	1 U	1 U	1 U
trans-1,2-Dichloroethene	µg/L	100	-	1 U	1 U	1 U	1 U	1 U
Trichloroethene	µg/L	**5.0**	200	1 U	1 U	1 U	1 U	1 U
Semi-volatile Organic Compounds								
Hexachlorobenzene	µg/L	**1.0**	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	**0.053**	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	6.7	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
General Chemistry								
Chloride	mg/L	250	125	1.9	1.94	11.8	11.6	19.9

Notes:
- - Not applicable.
U - Non-detect at associated value.
Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup criteria.

TABLE 3.2

2008 ANALYTICAL RESULTS SUMMARY
PLUME BOUNDARY DEMONSTRATION
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*WELL B*	*WELL B*	*WELL C*	*WELL C*	*WELL T*
Sample ID:		*Residential and Commercial Drinking Water Criteria* a	*Groundwater Surface Water Interface Criteria* b	*GW-9970-111108-BW-B*	*GW-9970-111108-BW-DUP1*	*GW-9970-052908-BW-C*	*GW-9970-111208-BW-C*	*GW-9970-052808-BW-T*
Sample Date:				*11/11/2008*	*11/11/2008 (Duplicate)*	*5/29/2008*	*11/12/2008*	*5/28/2008*
Parameters	*Units*							
Volatile Organic Compounds								
Carbon tetrachloride	µg/L	5.0	45	1 U	1 U	1 U	1 U	1 U
Chloroform (Trichloromethane)	µg/L	100	170	1 U	1 U	1 U	1 U	1 U
cis-1,2-Dichloroethene	µg/L	70	-	1 U	1 U	1 U	1 U	1 U
Tetrachloroethene	µg/L	5.0	45	1 U	1 U	4	4	1 U
trans-1,2-Dichloroethene	µg/L	100	-	1 U	1 U	1 U	1 U	1 U
Trichloroethene	µg/L	5.0	200	1 U	1 U	1 U	1 U	3
Semi-volatile Organic Compounds								
Hexachlorobenzene	µg/L	**1.0**	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	**0.053**	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	6.7	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
General Chemistry								
Chloride	mg/L	250	125	18.9	18.3	5.0	5.82	7.8

Notes:
- - Not applicable.
U - Non-detect at associated value.
Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup criteria.

TABLE 3.2

2008 ANALYTICAL RESULTS SUMMARY
PLUME BOUNDARY DEMONSTRATION
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*WELL T*	*WW-02*	*WW-02*	*WW-02*	*WW-06*
Sample ID:		*Residential and Commercial Drinking Water Criteria*	*Groundwater Surface Water Interface Criteria*	*GW-9970-111108-BW-T*	*GW-9970-052808-BW-DUP1*	*GW-9970-052808-BW-WW2*	*GW-9970-111008-BW-WW2*	*GW-9970-052808-BW-WW6*
Sample Date:				*11/11/2008*	*5/28/2008 (Duplicate)*	*5/28/2008*	*11/10/2008*	*5/28/2008*
Parameters	*Units*	a	b					
Volatile Organic Compounds								
Carbon tetrachloride	µg/L	5.0	45	1 U	1 U	1 U	1 U	1 U
Chloroform (Trichloromethane)	µg/L	100	170	1 U	1 U	1 U	1 U	1 U
cis-1,2-Dichloroethene	µg/L	70	-	1 U	1 U	1 U	1 U	1 U
Tetrachloroethene	µg/L	5.0	45	1 U	1 U	1 U	1 U	1 U
trans-1,2-Dichloroethene	µg/L	100	-	1 U	1 U	1 U	1 U	1 U
Trichloroethene	µg/L	5.0	200	3	1 U	1 U	1	1 U
Semi-volatile Organic Compounds								
Hexachlorobenzene	µg/L	1.0	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	0.053	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	6.7	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
General Chemistry								
Chloride	mg/L	250	125	7.74	29.1	29.1	22.5	1.8

Notes:
- - Not applicable.
U - Non-detect at associated value.
Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup criteria.

TABLE 3.2

2008 ANALYTICAL RESULTS SUMMARY
PLUME BOUNDARY DEMONSTRATION
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*WW-06*	*WW-13*	*WW-13*	*WW-24*
Sample ID:		*Residential and Commercial Drinking Water Criteria*	*Groundwater Surface Water Interface Criteria*	*GW-9970-111208-BW-WW6*	*GW-9970-052808-BW-WW13*	*GW-9970-111108-BW-WW13*	*GW-9970-052808-BW-WW24*
Sample Date:				*11/12/2008*	*5/28/2008*	*11/11/2008*	*5/28/2008*
Parameters	*Units*	a	b				
Volatile Organic Compounds							
Carbon tetrachloride	µg/L	5.0	45	1 U	1 U	1 U	1 U
Chloroform (Trichloromethane)	µg/L	100	170	1 U	1 U	1 U	1 U
cis-1,2-Dichloroethene	µg/L	70	-	1 U	1 U	1 U	1 U
Tetrachloroethene	µg/L	5.0	45	1 U	1 U	1 U	1 U
trans-1,2-Dichloroethene	µg/L	100	-	1 U	1 U	1 U	1 U
Trichloroethene	µg/L	5.0	200	1 U	1 U	1 U	1 U
Semi-volatile Organic Compounds							
Hexachlorobenzene	µg/L	**1.0**	-	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	**0.053**	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	**6.7**	0.010 U	0.010 U	0.010 U	0.010 U
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U
General Chemistry							
Chloride	mg/L	250	**125**	2.34	1 U	1.25	8.6

Notes:
- - Not applicable.
U - Non-detect at associated value.
Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup criteria.

TABLE 3.2

2008 ANALYTICAL RESULTS SUMMARY
PLUME BOUNDARY DEMONSTRATION
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*WW-24*
Sample ID:		*Residential and Commercial Drinking Water Criteria*	*Groundwater Surface Water Interface Criteria*	*GW-9970-111108-BW-WW24*
Sample Date:				*11/11/2008*
Parameters	*Units*	a	b	
Volatile Organic Compounds				
Carbon tetrachloride	µg/L	5.0	45	1 U
Chloroform (Trichloromethane)	µg/L	100	170	1 U
cis-1,2-Dichloroethene	µg/L	70	-	1 U
Tetrachloroethene	µg/L	5.0	45	1 U
trans-1,2-Dichloroethene	µg/L	100	-	1 U
Trichloroethene	µg/L	5.0	200	1 U
Semi-volatile Organic Compounds				
Hexachlorobenzene	µg/L	1.0	-	0.010 U
Hexachlorobutadiene	µg/L	15	0.053	0.010 U
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U
Hexachloroethane	µg/L	7.3	6.7	0.010 U
Octachlorocyclopentene	µg/L	50	-	0.010 U
General Chemistry				
Chloride	mg/L	250	125	7.64

Notes:
- - Not applicable.
U - Non-detect at associated value.
Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup criteria.

TABLE 4.1

PUMPING RATES AND TREATMENT SYSTEM EFFICIENCY
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN
JANUARY TO DECEMBER 2008

Month:	January			February			March			April		
Purge Well	%Run	Pumping Rate (gpm) Actual	Effective	%Run	Pumping Rate (gpm) Actual	Effective	%Run	Pumping Rate (gpm) Actual	Effective	%Run	Pumping Rate (gpm) Actual	Effective
Pb	99.44%	84	84	100.00%	70	70	99.80%	62	62	99.92%	62	62
Pc	99.43%	98	97	100.00%	88	88	99.84%	110	110	100.00%	110	110
Pd	99.84%	87	87	99.55%	67	67	99.81%	78	78	99.93%	78	78
Pe	99.37%	120	119	99.99%	102	102	99.80%	109	109	99.61%	109	109
Pf	99.44%	36	36	99.96%	25	25	99.84%	25	25	100.00%	25	25
Pg	99.44%	72	72	100.00%	60	60	99.80%	74	74	99.92%	74	74
Ph	99.43%	135	134	100.00%	121	121	99.84%	120	120	99.68%	120	120
Pi	99.45%	87	87	99.99%	60	60	99.85%	61	61	93.04%	61	57
Total:		**719**	**715**		**593**	**593**		**639**	**638**		**639**	**634**

Notes:
gpn Gallons Per Minute.

TABLE 4.1

PUMPING RATES AND TREATMENT SYSTEM EFFICIENCY
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN
JANUARY TO DECEMBER 2008

Purge Well	Month:	May			June			July			August		
			Pumping Rate (gpm)			Pumping Rate (gpm)			Pumping Rate (gpm)			Pumping Rate (gpm)	
		%Run	Actual	Effective	%Run	Actual	Effective	%Run	Actual	Effective	%Run	Actual	Effective
Pb		100.01%	63	63	99.93%	83	83	99.95%	74	74	99.46%	74	74
Pc		99.87%	92	92	99.97%	105	105	99.95%	103	103	91.28%	103	94
Pd		100.01%	65	65	99.96%	74	74	100.07%	58	58	96.73%	58	56
Pe		100.01%	97	97	99.97%	100	100	99.95%	99	99	91.25%	99	90
Pf		99.87%	23	23	99.97%	23	23	99.96%	20	20	91.08%	20	18
Pg		100.01%	67	67	99.96%	67	67	100.08%	63	63	99.33%	63	63
Ph		99.87%	112	112	99.96%	112	112	99.97%	110	110	99.21%	110	109
Pi		99.88%	76	76	99.97%	75	75	99.96%	66	66	99.52%	66	66
	Total:		595	595		639	639		593	593		593	570

Notes:
gpn Gallons Per Minute.

TABLE 4.1

PUMPING RATES AND TREATMENT SYSTEM EFFICIENCY
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN
JANUARY TO DECEMBER 2008

Month:	September			October			November			December			Monthly Average	
Purge Well		Pumping Rate (gpm)			Pumping Rate (gpm)			Pumping Rate (gpm)			Pumping Rate (gpm)		Pumping Rate (gpm)	
	%Run	Actual	Effective	%Run	Actual	Effective	%Run	Actual	Effective	%Run	Actual	Effective	Actual	Effective
Pb	99.46%	74	74	98.71%	72	71	99.94%	60	60	99.97%	61	61	70	70
Pc	91.28%	103	94	98.43%	126	124	99.88%	110	110	99.79%	112	112	105	103
Pd	96.73%	58	56	99.48%	70	70	96.12%	86	83	98.98%	94	93	73	72
Pe	91.25%	99	90	99.48%	115	114	93.53%	114	107	99.74%	112	112	106	104
Pf	91.08%	20	18	99.48%	25	25	100.08%	17	17	100.00%	18	18	23	23
Pg	99.33%	63	63	99.48%	73	73	99.94%	67	67	99.97%	66	66	67	67
Ph	99.21%	110	109	99.33%	130	129	99.90%	115	115	99.93%	116	116	118	117
Pi	99.52%	66	66	92.54%	83	77	99.92%	73	73	99.25%	77	76	71	70
Total:		**593**	**570**		**694**	**683**		**642**	**631**		**656**	**654**	**633**	**626**

Notes:
gpm Gallons Per Minute.

TABLE 4.2

2008 ANALYTICAL RESULTS SUMMARY - PURGE WELLS
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*Pb*	*Pb*	*Pb*	*Pb*	*Pc*
Sample ID:		*Residential and Commercial Drinking Water Criteria* a	*Groundwater Surface Water Interface Criteria* b	*WG-9970-BFB-012908-PB*	*WG-9970-JAB-042408-PB*	*WG-9970-JAB-072308-PB*	*WG-9970-BFB-103008-PB*	*WG-9970-BFB-012908-PC*
Sample Date:				*1/29/2008*	*4/24/2008*	*7/23/2008*	*10/30/2008*	*1/29/2008*
Parameters	*Units*							
Volatile Organic Compounds								
Carbon tetrachloride	µg/L	5.0	45	290[ab]	280[ab]	350[ab]	180[ab]	6.2[a]
Chloroform (Trichlorometha	µg/L	**100**	170	67	66	67	35	1 U
cis-1,2-Dichloroethene	µg/L	70	-	12	12	8.3	11	1 U
Tetrachloroethene	µg/L	5.0	45	2900[ab]	3100[ab]	1700[ab]	2400[ab]	65[ab]
trans-1,2-Dichloroethene	µg/L	**100**	-	1 U	1 U	1 U	1 U	1 U
Trichloroethene	µg/L	5.0	200	18[a]	20[a]	14[a]	17[a]	2.1
Semi-volatile Organic Compounds								
Hexachlorobenzene	µg/L	**1.0**	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	**0.053**	0.010 U	0.010 U	1.2[b]	1.0[b]	0.82[b]
Hexachlorocyclopentadiene	µg/L	**50**	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	6.7	110[ab]	6.6	98[ab]	65[ab]	4.8
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
General Chemistry								
Chloride	mg/L	250	**125**	25.0	22.5	21.5	16.1	17.3

Notes:

J	Estimated value.
U	Non-detect at associated value.
	Detection above criteria.
	Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup

TABLE 4.2

2008 ANALYTICAL RESULTS SUMMARY - PURGE WELLS
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*Pc*	*Pc*	*Pc*	*Pd*	*Pd*
Sample ID:		*Residential and*	*Groundwater*	*WG-9970-JAB-042408-PC*	*WG-9970-JAB-072308-PC*	*WG-9970-BFB-103008-PC*	*WG-9970-BFB-012908-PD*	*WG-9970-JAB-042408-PD*
Sample Date:		*Commercial*	*Surface Water*	*4/24/2008*	*7/23/2008*	*10/30/2008*	*1/29/2008*	*4/24/2008*
		Drinking Water	*Interface*					
Parameters	*Units*	*Criteria*	*Criteria*					
		a	b					
Volatile Organic Compounds								
Carbon tetrachloride	µg/L	5.0	45	8[a]	12[a]	8[a]	390[a,b]	410[a,b]
Chloroform (Trichlorometha	µg/L	100	170	1 U	1 U	1 U	85	67
cis-1,2-Dichloroethene	µg/L	70	-	1 U	1 U	1 U	10	9
Tetrachloroethene	µg/L	5.0	45	75[a,b]	40[a]	77[a,b]	2400[a,b]	2400[a,b]
trans-1,2-Dichloroethene	µg/L	100	-	1 U	1 U	1 U	1 U	1 U
Trichloroethene	µg/L	5.0	200	1 U	1.3	2	22[a]	19[a]
Semi-volatile Organic Compounds								
Hexachlorobenzene	µg/L	1.0	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	0.053	0.010 U	1.4[b]	1.3[b]	0.010 U	0.010 U
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	6.7	3.1	6.5	5.5	65[a,b]	32[a,b]
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
General Chemistry								
Chloride	mg/L	250	125	13.9	20.0	21.2	148[b]	133[b]

Notes:

J	Estimated value.
U	Non-detect at associated value.
	Detection above criteria.
	Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup

TABLE 4.2

2008 ANALYTICAL RESULTS SUMMARY - PURGE WELLS
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*Pd*	*Pd*	*Pe*	*Pe*	*Pe*
Sample ID:		*Residential and*	*Groundwater*	*WG-9970-JAB-072308-PD*	*WG-9970-BFB-103008-PD*	*WG-9970-BFB-012908-PE*	*WG-9970-JAB-042408-PE*	*WG-9970-JAB-072308-PE*
Sample Date:		*Commercial*	*Surface Water*	*7/23/2008*	*10/30/2008*	*1/29/2008*	*4/24/2008*	*7/23/2008*
		Drinking Water	*Interface*					
Parameters	*Units*	*Criteria*	*Criteria*					
		a	b					
Volatile Organic Compounds								
Carbon tetrachloride	µg/L	5.0	45	530[ab]	290[ab]	28[a]	19[a]	28[a]
Chloroform (Trichlorometha	µg/L	100	170	79	59	5.0	3	2.6
cis-1,2-Dichloroethene	µg/L	70	-	5.9	7	6.7	7	4.4
Tetrachloroethene	µg/L	5.0	45	1500[ab]	2300[ab]	300[ab]	200[ab]	130[ab]
trans-1,2-Dichloroethene	µg/L	100	-	1 U	1 U	1 U	1 U	1 U
Trichloroethene	µg/L	5.0	200	17[a]	20[a]	7.2[a]	7[a]	4.9
Semi-volatile Organic Compounds								
Hexachlorobenzene	µg/L	1.0	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	0.053	0.048	0.048	0.028	0.010 U	0.010 U
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	6.7	54[ab]	50[ab]	4.7	0.15	0.31
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
General Chemistry								
Chloride	mg/L	250	125	145[b]	130[b]	177[b]	163[b]	164[b]

Notes:

J	Estimated value.
U	Non-detect at associated value.
	Detection above criteria.
	Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup

TABLE 4.2

2008 ANALYTICAL RESULTS SUMMARY - PURGE WELLS
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*Pe*	*Pf*	*Pf*	*Pf*	*Pf*
Sample ID:		*Residential and*	*Groundwater*	*WG-9970-BFB-103008-PE*	*WG-9970-BFB-012908-PF*	*WG-9970-JAB-042408-PF*	*WG-9970-JAB-072308-PF*	*WG-9970-BFB-103008-PF*
Sample Date:		*Commercial*	*Surface Water*	*10/30/2008*	*1/29/2008*	*4/24/2008*	*7/23/2008*	*10/30/2008*
		Drinking Water	*Interface*					
Parameters	*Units*	*Criteria*	*Criteria*					
		a	b					
Volatile Organic Compounds								
Carbon tetrachloride	µg/L	5.0	45	**18**[4]	1 U	1 U	1 U	1 U
Chloroform (Trichlorometha	µg/L	100	170	2	1 U	1 U	1 U	1 U
cis-1,2-Dichloroethene	µg/L	70	-	5	1 U	1 U	1 U	1 U
Tetrachloroethene	µg/L	5.0	45	**180**[4b]	1.9	3	1.9	5
trans-1,2-Dichloroethene	µg/L	100	-	1 U	1 U	1 U	1 U	1 U
Trichloroethene	µg/L	5.0	200	**6**[4]	1 U	1 U	1 U	1 U
Semi-volatile Organic Compounds								
Hexachlorobenzene	µg/L	1.0	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	0.053	0.010 U	0.010 U	0.010 U	0.010 U	0.017
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	6.7	0.29	1.8	0.98	0.48	0.59
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
General Chemistry								
Chloride	mg/L	250	125	**163**[5]	14.4	11.0	9.6	7.90

Notes:

J	Estimated value.
U	Non-detect at associated value.
	Detection above criteria.
	Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup

TABLE 4.2

2008 ANALYTICAL RESULTS SUMMARY - PURGE WELLS
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*Pg*	*Pg*	*Pg*	*Pg*	*Ph*
Sample ID:		*Residential and*	*Groundwater*	*WG-9970-BFB-012908-PG*	*WG-9970-JAB-042408-PG*	*WG-9970-JAB-072308-PG*	*WG-9970-BFB-103008-PG*	*WG-9970-BFB-012908-PH*
Sample Date:		*Commercial*	*Surface Water*	*1/29/2008*	*4/24/2008*	*7/23/2008*	*10/30/2008*	*1/29/2008*
		Drinking Water	*Interface*					
Parameters	*Units*	*Criteria*	*Criteria*					
		a	b					
Volatile Organic Compounds								
Carbon tetrachloride	µg/L	5.0	45	**1900**[JD]	**2400**[JD]	**3400**[JD]	**1700**[JD]	**32**[J]
Chloroform (Trichlorometha	µg/L	100	170	**230**[JD]	200 U	**250**[JD]	**180**[JD]	9.9
cis-1,2-Dichloroethene	µg/L	70	-	3.1	2	1.8	3	5.4
Tetrachloroethene	µg/L	5.0	45	**7400**[JD]	**11000**[JD]	**5300**[JD]	**7600**[JD]	**490**[JD]
trans-1,2-Dichloroethene	µg/L	100	-	1 U	1 U	1 U	1 U	5.7
Trichloroethene	µg/L	5.0	200	**33**[J]	**34**[J]	**26**[J]	**34**[J]	**17**[J]
Semi-volatile Organic Compounds								
Hexachlorobenzene	µg/L	**1.0**	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	0.053	0.010 U	0.010 U	**3.4**[D]	**2.7**[D]	**0.90**[D]
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	6.7	**370**[JD]	**380**[JD]	**2400**[JD]	**380**[JD]	**18**[JD]
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
General Chemistry								
Chloride	mg/L	250	125	31.7	42.6	41.7	38.0	**202**[D]

Notes:

J	Estimated value.
U	Non-detect at associated value.
	Detection above criteria.
	Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup

TABLE 4.2

2008 ANALYTICAL RESULTS SUMMARY - PURGE WELLS
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*Ph*	*Ph*	*Ph*	*Pi*	*Pi*
Sample ID:		*Residential and*	*Groundwater*	*WG-9970-JAB-042408-PH*	*WG-9970-JAB-072308-PH*	*WG-9970-BFB-103008-PH*	*WG-9970-BFB-012908-PI*	*WG-9970-JAB-042408-PI*
Sample Date:		*Commercial*	*Surface Water*	*4/24/2008*	*7/23/2008*	*10/30/2008*	*1/29/2008*	*4/24/2008*
		Drinking Water	*Interface*					
Parameters	*Units*	*Criteria*	*Criteria*					
		a	b					
Volatile Organic Compounds								
Carbon tetrachloride	µg/L	5.0	45	40[a]	56[a,b]	26[a]	190[a,b]	210[a,b]
Chloroform (Trichlorometha	µg/L	100	170	10	8.8	8	220[a,b]	180[a,b]
cis-1,2-Dichloroethene	µg/L	70	-	6	3.4	4	78[a]	65
Tetrachloroethene	µg/L	5.0	45	530[a,b]	310[a,b]	450[a,b]	3300[a,b]	3100[a,b]
trans-1,2-Dichloroethene	µg/L	100	-	5	3.3	4	4.2	3
Trichloroethene	µg/L	5.0	200	16[a]	11[a]	14[a]	60[a]	57[a]
Semi-volatile Organic Compounds								
Hexachlorobenzene	µg/L	1.0	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	0.053	2.5 U	1.5[b]	1.3 J[b]	2.2[b]	0.92[b]
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	6.7	17[a,b]	19[a,b]	16[a,b]	58[a,b]	22[a,b]
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U	0.010 U	0.010 U	0.010 U
General Chemistry								
Chloride	mg/L	250	125	199[b]	198[b]	168[b]	534[a,b]	543[a,b]

Notes:

J	Estimated value.
U	Non-detect at associated value.
	Detection above criteria.
	Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup

TABLE 4.2

2008 ANALYTICAL RESULTS SUMMARY - PURGE WELLS
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

Sample Location:				*Pi*	*Pi*
Sample ID:		*Residential and Commercial Drinking Water Criteria* a	*Groundwater Surface Water Interface Criteria* b	*WG-9970-JAB-072308-PI*	*WG-9970-BFB-103008-PI*
Sample Date:				*7/23/2008*	*10/30/2008*
Parameters	*Units*				
Volatile Organic Compounds					
Carbon tetrachloride	µg/L	5.0	45	280[ab]	190[ab]
Chloroform (Trichlorometha	µg/L	100	170	200[ab]	160[a]
cis-1,2-Dichloroethene	µg/L	70	-	58	67
Tetrachloroethene	µg/L	5.0	45	1900[ab]	3000[ab]
trans-1,2-Dichloroethene	µg/L	100	-	3.2	4
Trichloroethene	µg/L	5.0	200	52[a]	59[a]
Semi-volatile Organic Compounds					
Hexachlorobenzene	µg/L	**1.0**	-	0.010 U	0.010 U
Hexachlorobutadiene	µg/L	15	**0.053**	2.7[b]	2.7[b]
Hexachlorocyclopentadiene	µg/L	50	-	0.010 U	0.010 U
Hexachloroethane	µg/L	7.3	6.7	29[ab]	28[ab]
Octachlorocyclopentene	µg/L	50	-	0.010 U	0.010 U
General Chemistry					
Chloride	mg/L	250	125	713[ab]	671[ab]

Notes:

J	Estimated value.
U	Non-detect at associated value.
	Detection above criteria.
	Bold numbers indicate the more stringent criteria derived from State of Michigan Part 201 generic cleanup

TABLE 4.3

TOTAL VOC's AND SVOCs REMOVED IN 2008
GLENN SPRINGS HOLDINGS, INC.
MONTAGUE, MICHIGAN

			Mass Removed by Purge Well (pounds)							
Quarter	*Days*	*Total Removed (pounds)*	*Pb*	*Pc*	*Pd*	*Pe*	*Pf*	*Pg*	*Ph*	*Pi*
First	91	1887	312	8	282	46	0.1	781	85	372
Second	91	1965	236	10	250	28	0.1	1116	82	242
Third	92	1374	183	7	140	19	0.1	792	50	184
Fourth	92	1661	215	13	211	27	0.2	798	75	322
	Total:	**6887**	**946**	**39**	**883**	**120**	**0.5**	**3487**	**292**	**1120**

Notes:
SVOC Semi-Volatile Organic Compounds.
VOC Volatile Organic Compounds.

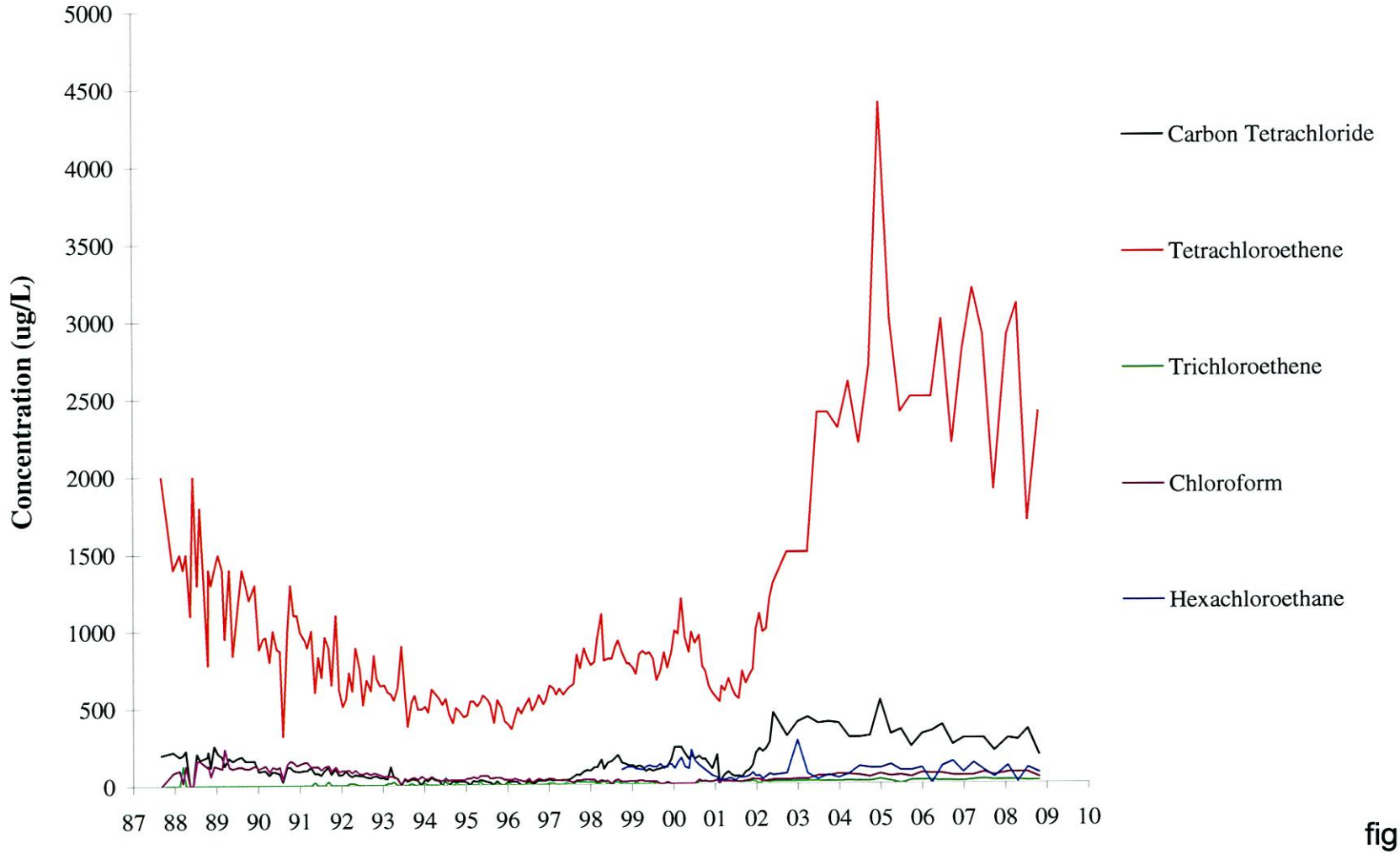


figure C.1

CONCENTRATION vs TIME
PURGE WELL Pb
GLENN SPRINGS HOLDINGS, INC.
Montague, Michigan

09970-B0331(025)GN-WA005 JAN 29/2009

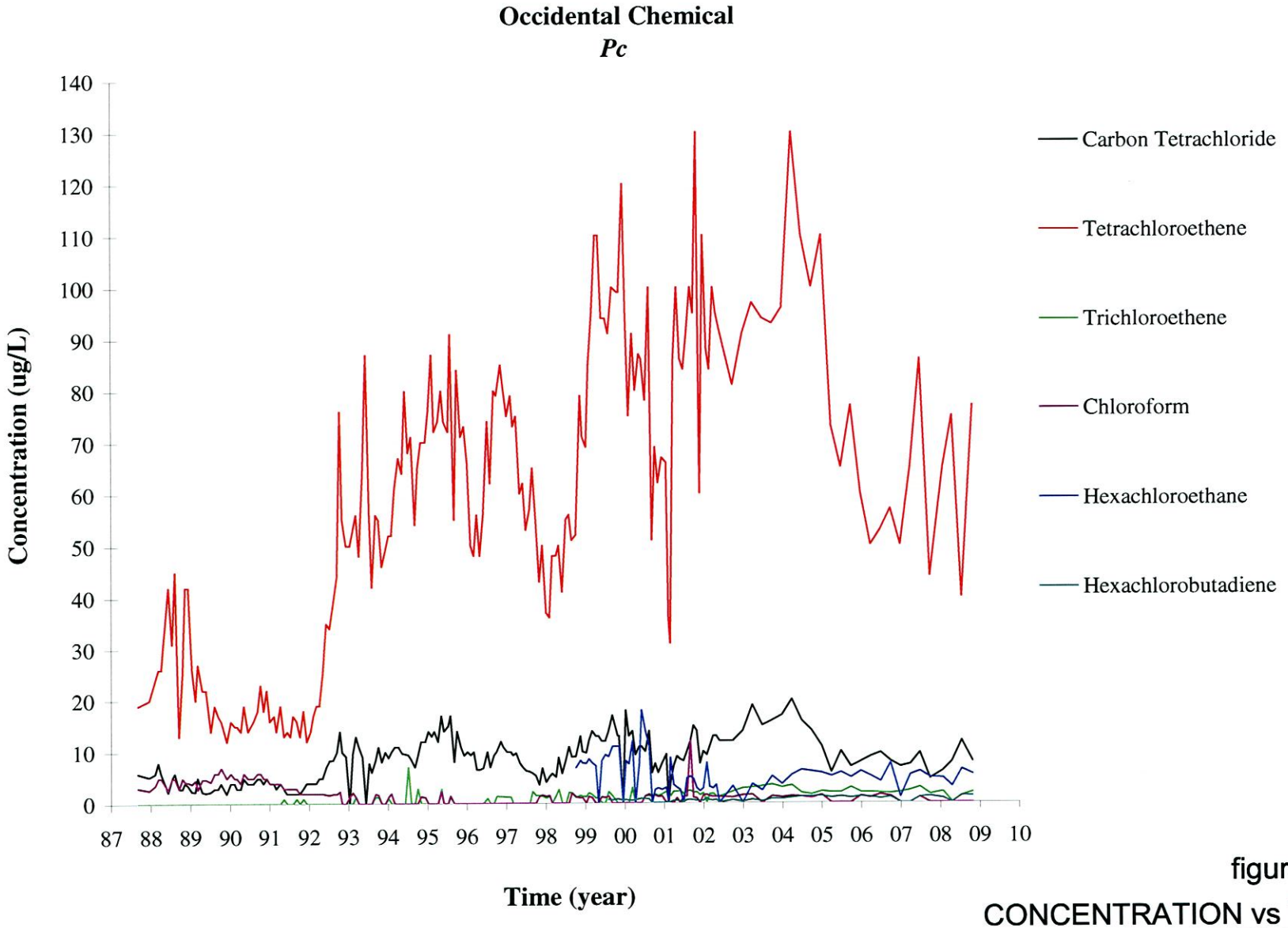


figure C.2

CONCENTRATION vs TIME
PURGE WELL Pc
GLENN SPRINGS HOLDINGS, INC.
Montague, Michigan

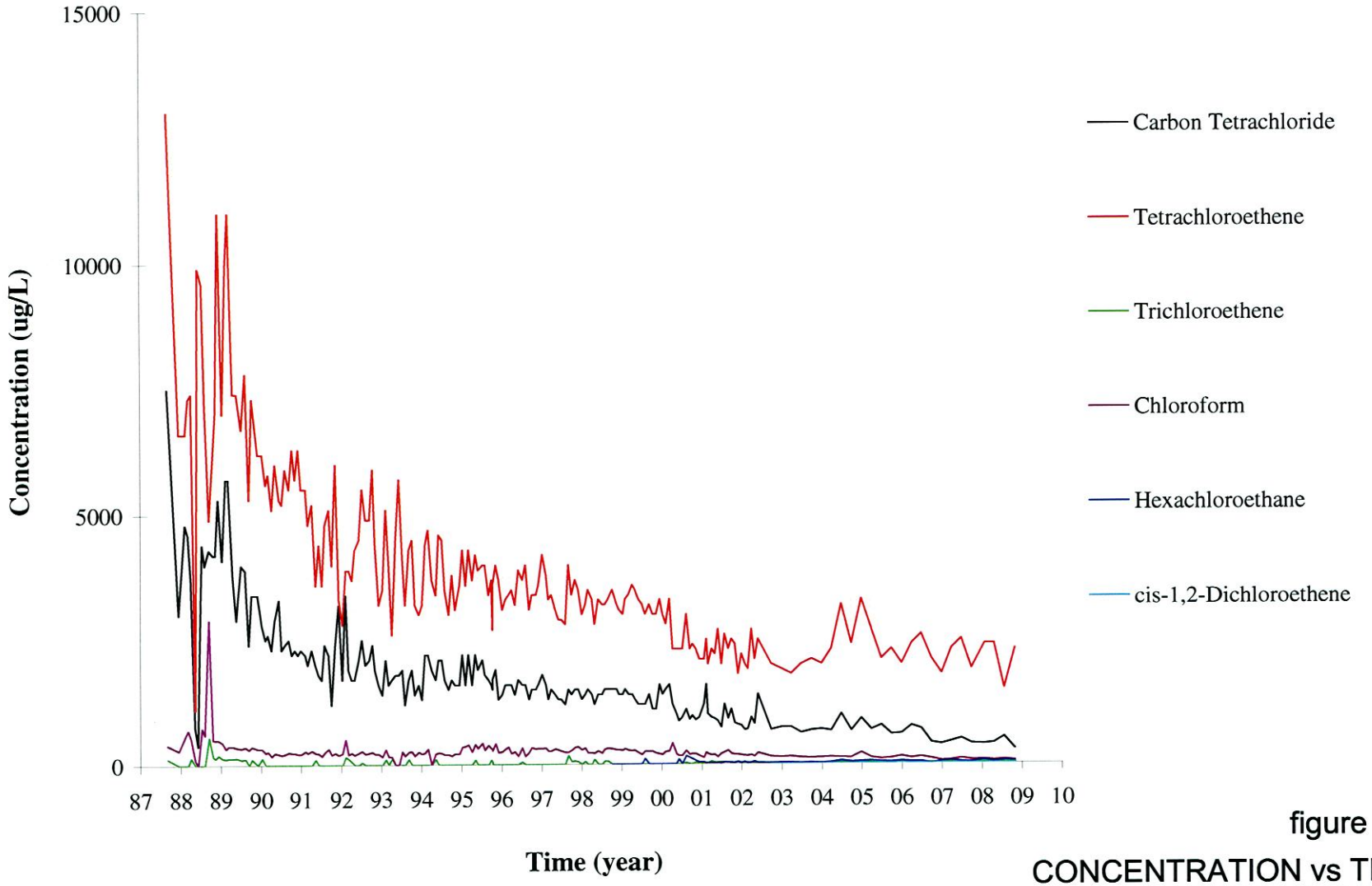


figure C.3

CONCENTRATION vs TIME
PURGE WELL Pd
GLENN SPRINGS HOLDINGS, INC.
Montague, Michigan

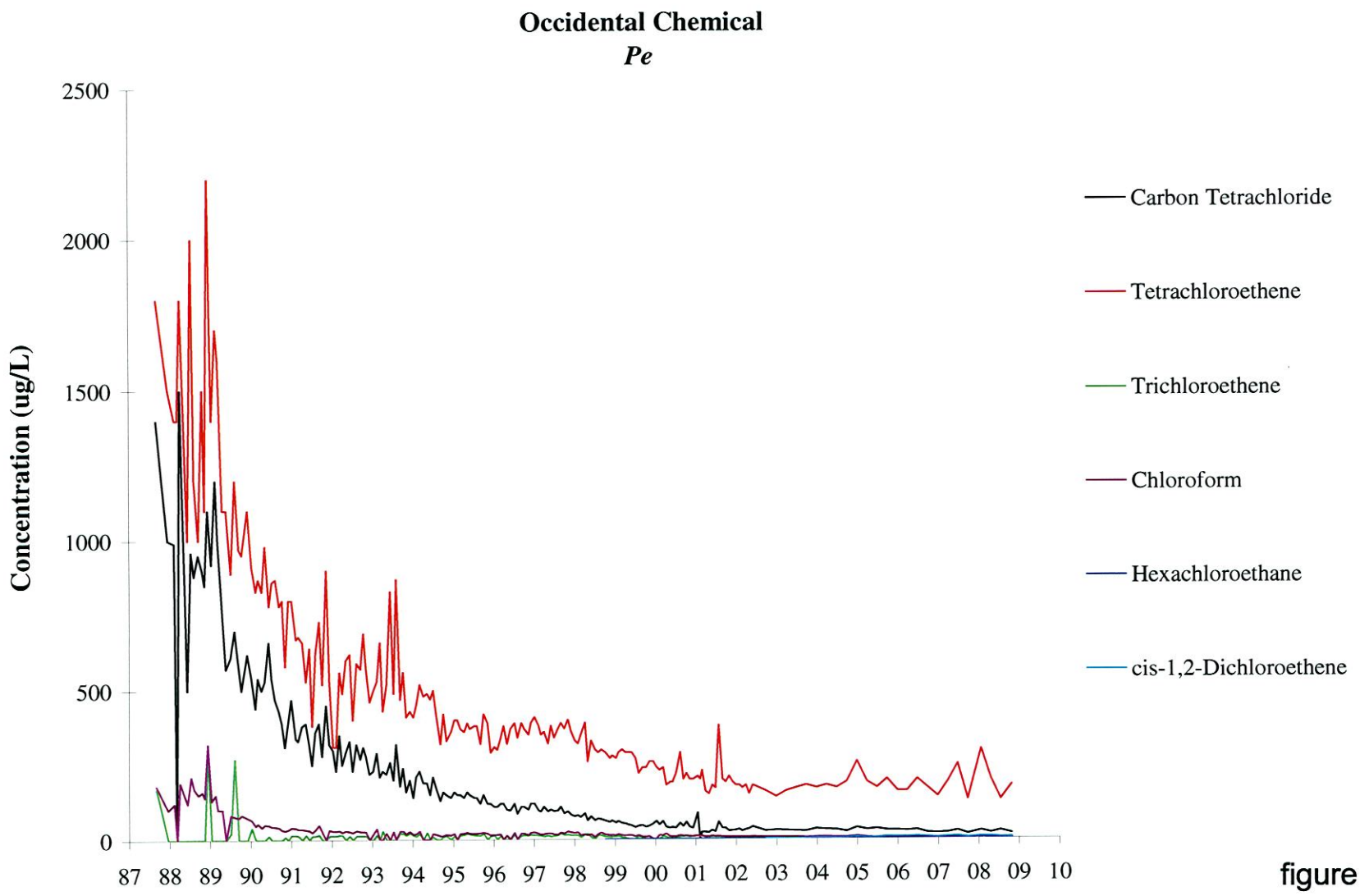


figure C.4

CONCENTRATION vs TIME
PURGE WELL Pe
GLENN SPRINGS HOLDINGS, INC.
Montague, Michigan

09970-B0331(025)GN-WA005 JAN 29/2009

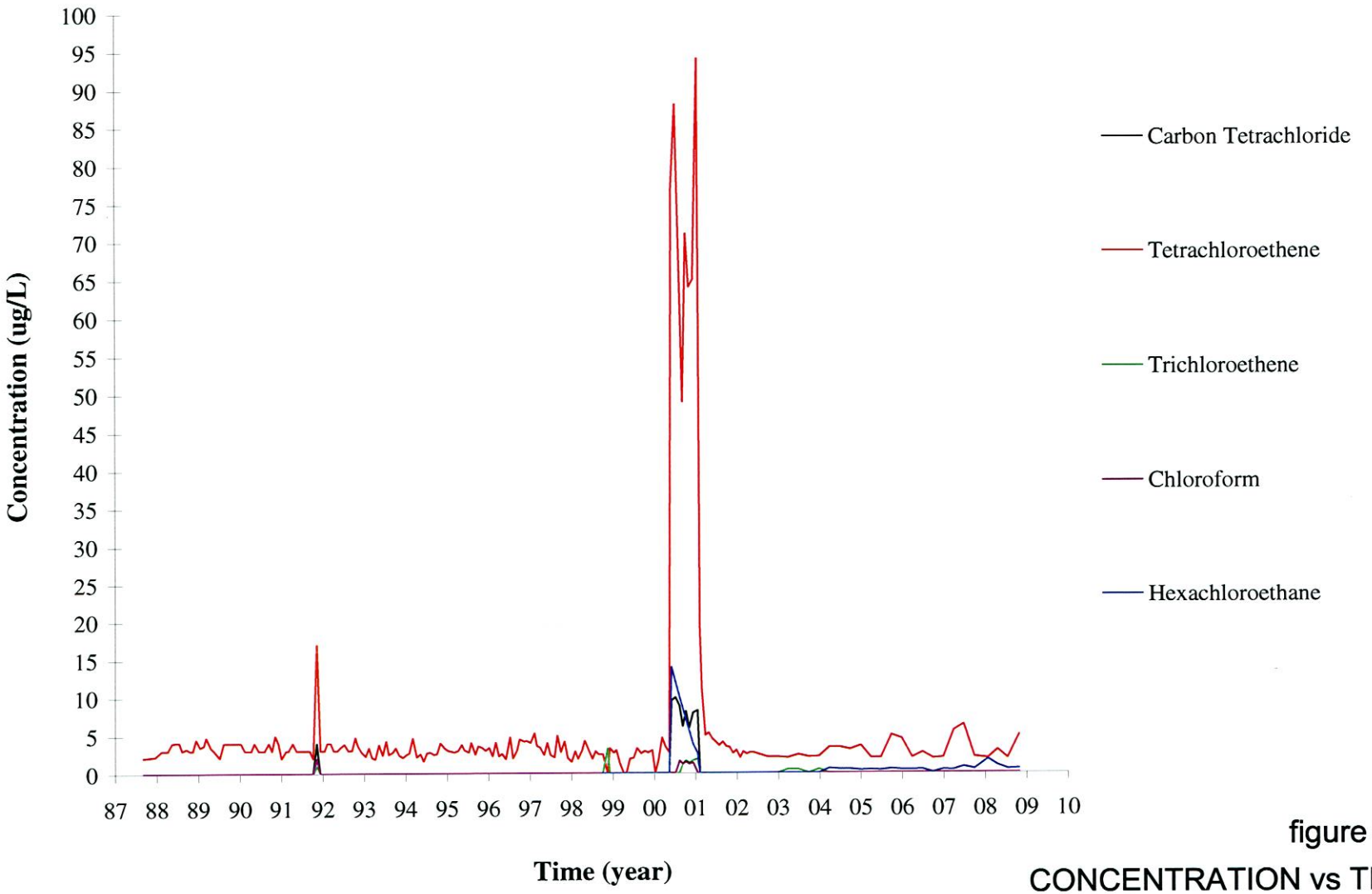


figure C.5

CONCENTRATION vs TIME
PURGE WELL Pf
GLENN SPRINGS HOLDINGS, INC.
Montague, Michigan

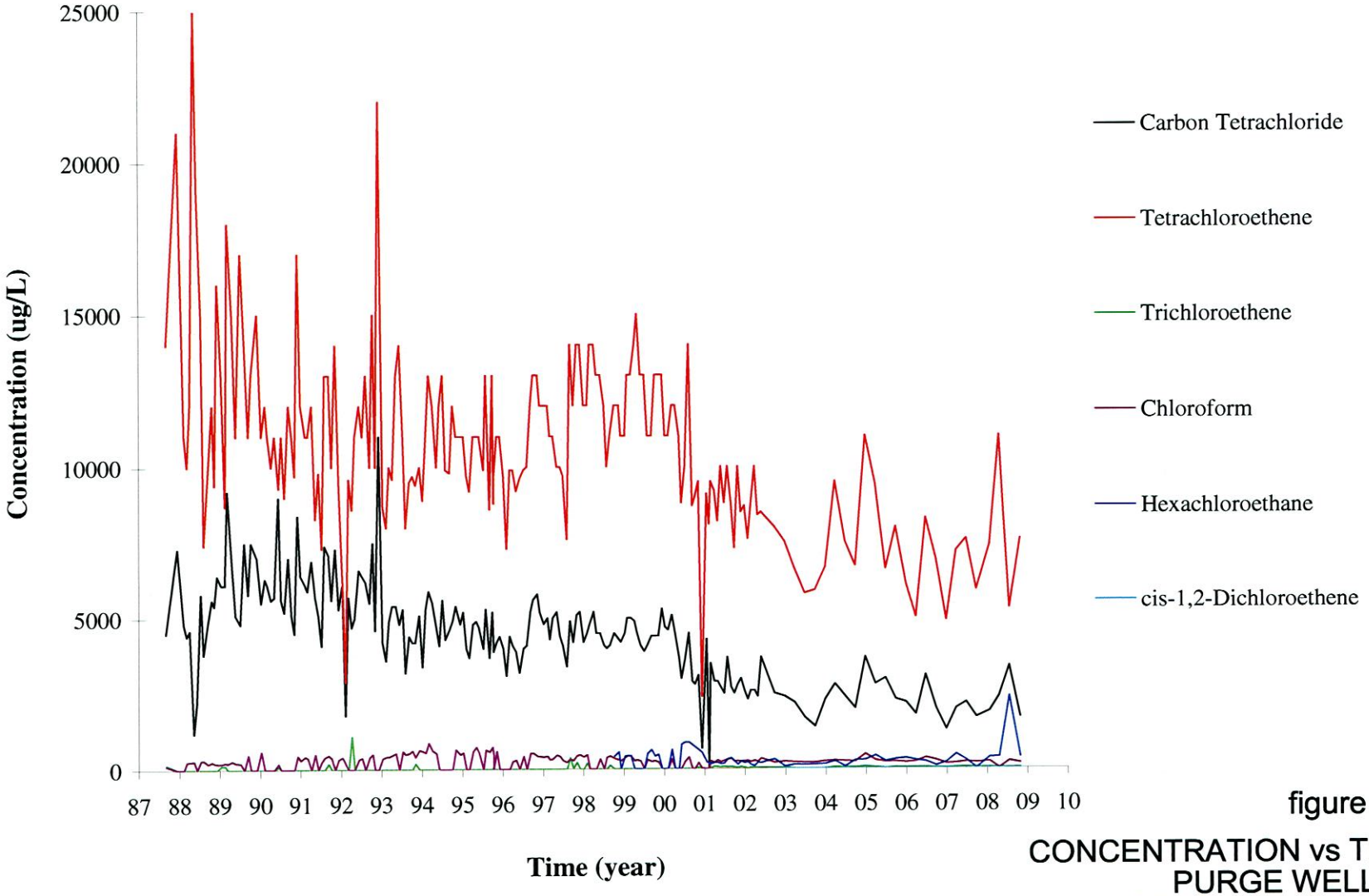


figure C.6

CONCENTRATION vs TIME
PURGE WELL Pg
GLENN SPRINGS HOLDINGS, INC.
Montague, Michigan

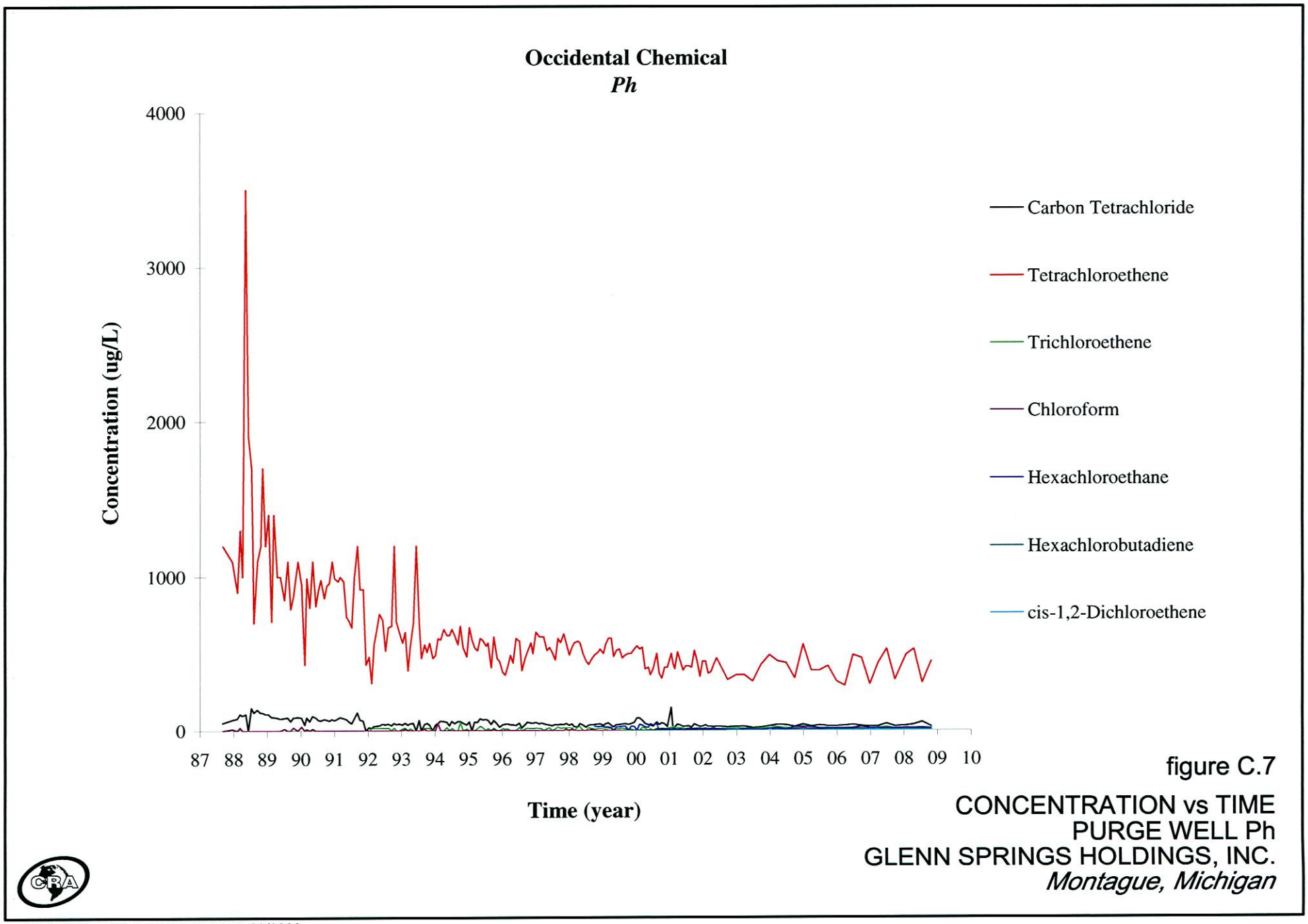


figure C.7

CONCENTRATION vs TIME
PURGE WELL Ph
GLENN SPRINGS HOLDINGS, INC.
Montague, Michigan

09970-B0331(025)GN-WA005 JAN 29/2009

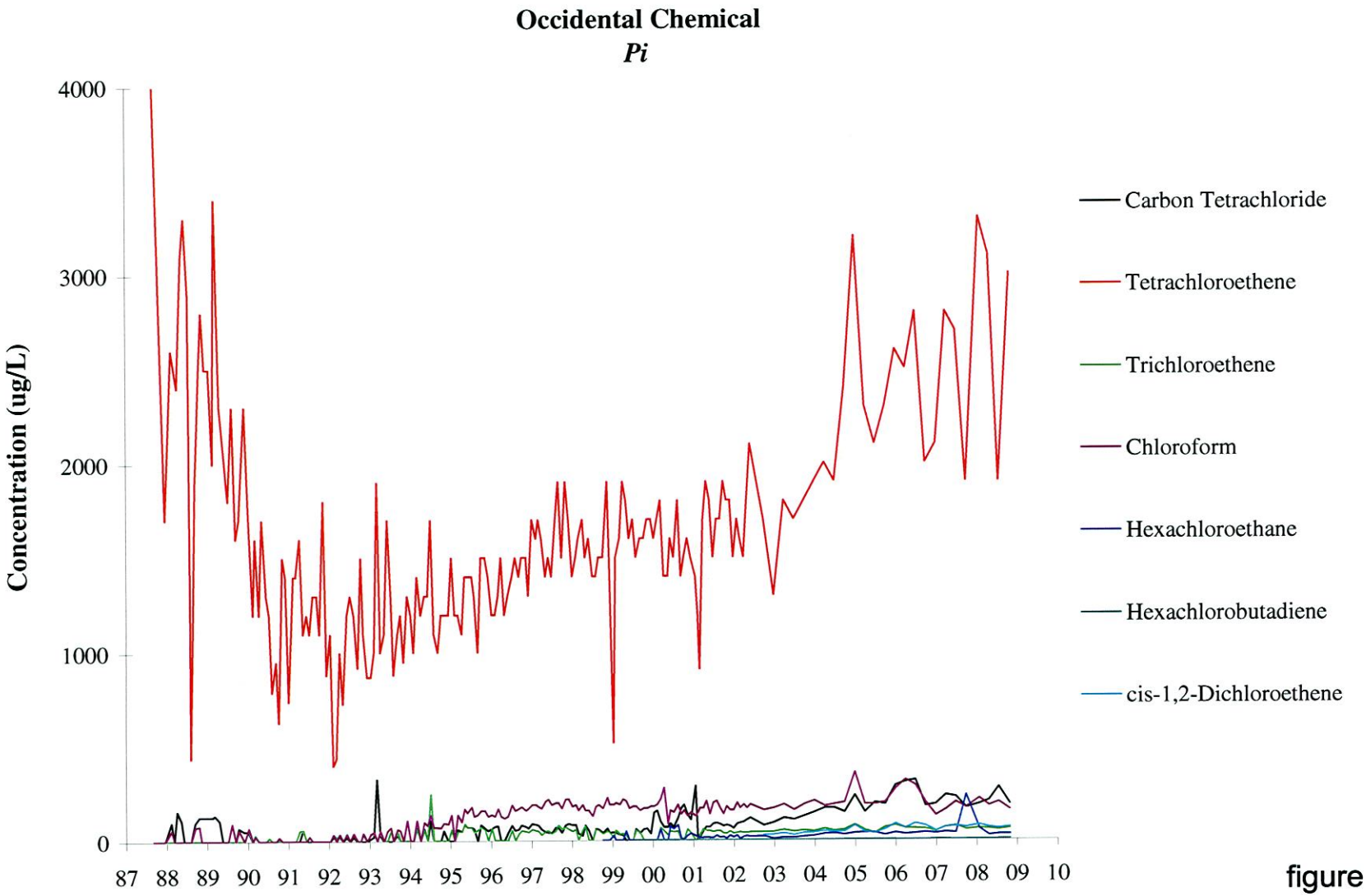


figure C.8

CONCENTRATION vs TIME
PURGE WELL Pi
GLENN SPRINGS HOLDINGS, INC.
Montague, Michigan

APPENDIX C

REMChlor Model Calculations and Results

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APPENDIX C

TABLES

Table M1
Source Area Parameters

	Former Primary Ash Disposal Area (FPADA)	Former Primary Disposal Area (FPDA)	Former Fine Chemical Production Area (FCPA)	Former Equalization Pond Area (FEPA)
Approximate Distance to White Lake (receptor)	1950m	1950m	1000m	600m
Tetrachloroethene				
Concentration (g/L)	1.10E-06	1.10E-03	4.55E-02	6.40E-05
Mass (kg)	0	4999.635157	22108.36835	49.5585377
Width (m)	196	55	69.6	17
Depth (m)	7.4	7.4	9.5	6.7
Year of source data	2002	2002	2002	2002
Gamma	1	1	1	1
C-56				
Concentration (g/L)	2.40E-04	1.10E-03	1.29E-03	9.80E-04
Mass (kg)	12109.3255	128968.5712	71626.71926	1876.453353
Width (m)	196	55	69.6	17
Depth (m)	7.4	7.4	9.5	6.7
Year of source data	2002	2002	2002	2002
Gamma	1	1	1	1
C-58				
Concentration (g/L)	1.00E-04	2.10E-04	7.95E-05	1.10E-05
Mass (kg)	12457.03474	244212.982	9658.630044	162.0737062
Width (m)	196	55	69.6	17
Depth (m)	7.4	7.4	9.5	6.7
Year of source data	2002	2002	2002	2002
Gamma	1	1	1	1
Carbon tetrachloride				
Concentration (g/L)	1.00E-06	4.50E-03	2.25E-02	2.50E-06
Mass (kg)	0	3107.983618	0.867060979	0.198090085
Width (m)	196	55	69.6	17
Depth (m)	7.4	7.4	9.5	6.7
Year of source data	2002	2002	2002	2002
Gamma	1	1	1	1
Hexachloroethane				
Concentration (g/L)	4.60E-06	2.90E-04	9.13E-04	9.80E-05
Mass (kg)	0	398.3267512	3830.942735	0
Width (m)	196	55	69.6	17
Depth (m)	7.4	7.4	9.5	6.7
Year of source data	2002	2002	2002	2002
Gamma	1	1	1	1

Notes:
Each contaminant is modeled separately with its daughter products
Concentration = initial source zone concentration for contaminant of interest, which is the averaged concentration of DNAPL chemical near/within the source area.
Mass = initial source zone contaminant mass (kg)
Source width = width perpendicular to groundwater flow direction
Source depth = vertical thickness of source zone
Year of source data: this will be considered to and will be used as the basis for scenarios.
Gamma = exponent between 0.5 and 2; closer to 0.5 if DNAPL in sand and for younger sites; closer to 2 if DNAPL in clay and for older sites

Table M2
Aquifer Properties

	Former Primary Ash Disposal Area (FPADA)	Former Primary Disposal Area (FPDA)	Former Fine Chemical Production Area (FCPA)	Former Equalization Pond Area (FEPA)
Darcy velocity (m/yr)	40	40	40	40
Effective porosity	0.2	0.2	0.2	0.2
Sigmav	0.14	0.14	0.14	0.14
vMin	0.5	0.5	0.5	0.5
vMax	1.5	1.5	1.5	1.5
Number of Stream Tubes	100	100	100	100
alphay	0.01	0.01	0.01	0.01
alphaz	0.001	0.001	0.001	0.001

Notes:

Darcy flux (velocity) = pore velocity times porosity = hydraulic conductivity times gradient; based on slug test/pump test data 60 ft/d*0.006 = 0.36 ft/d = 131 ft/y = 40 m/y

Sigmav = ratio of pore velocity standard deviation divided by mean pore velocity. Relates to "shape" of plume and dispersivity. For low dispersivity, such as in sand (plume width is small compared to length), a value of 0.14 is used. This corresponds to a longitudinal dispersivity of x/100

vMin = minimum normalized streamtube velocity; typically set to 0 unless a very small sigmav is used. However, 0.5 in most examples. Symetrical around 1 with vMax

vMax = maximum normalized streamtube velocity; 1+4xSigmav

Number of Stream Tubes: used to simulate longitudinal dispersion; can range from 10 to 500; more tubes smoothes curve but increases calculation time. Less critical for smaller dispersions.

alphay = transverse dispersivity; generally 1/10 of longitudinal value; due to large velocity, assume transverse dispersivity is small

alphaz = vertical dispersivity; generally 1/100 or less of longitudinal value; due to large velocity, assume vertical dispersivity is small

Table M3
Chemical Properties

	Tetrachloroethene	C-56	C-58	Carbon tetrachloride	Hexachloroethane
Partitioning coefficient (K_{oc})	100	9770	38,000[3]	150	1490
Retardation Factor	1.16	16.632	609.0048	1.24	3.384
Daughters and yield	TCE: 0.79	0	0	Choroform: 0.78	aerobic:none expected
	DCE: 0.74			Methylene Cl: 0.71	anaerobic: PCE possible
	VC: 0.64			Methyl Cl: 0.59	
Hydrolysis (half life)	na[4]	15 days	50 days[1]	40 years[5]	none expected
Rate constant	na	16.9/yr	5.06/yr	na	na
Solubility in water (mg/L)	200	1.8	?	793	50
Cleanup level (mg/L)	0.005	0.05	0.05	0.005	0.0067
Density of NAPL fluid (g/cc)	1.6	1.7	1.7[2]	1.6	2.1

Notes:
Retardation factor is the same for the parent and daughter products and is calculated assuming a soil density of 1.6, porosity of 20%, fraction organic carbon (foc) of 0.02 % and Koc value

Partitioning coefficients from literature. Fraction of organic carbon is assumed to be 0.02% (foc = 0.0002).

Yield = mass of component created by decay of previous compound; typically molecular weight of daughter divided by molecular weight of parent. Value is zero if decay without producing any important daughter products

[1] This value has less confidence than the value for C-56 per Appendix B of Earth Tech 2006.

[2] Could not find data; however, it is assumed the same as C-56 .

[3] Octachlorocyclopentene: log Kow = 4.66; not readily biodegradable
from: http://ecb.jrc.ec.europa.eu/DOCUMENTS/PBT_EVALUATION/PBT_sum108_CAS_77-47-4.pdf
If Koc is not available, it can be estimated from log10Koc=0.00028 + 0.983 log10(Kow)
from: Talmage and others 1999 p. 8

[4] Tetrachloroethylene: Hydrolysis only at high temperatures and basic solutions (http://www.atsdr.cdc.gov/toxprofiles/tp18-c5.pdf)
Other hydrolysis estimates range from 9 months to 1,000,000,000 yrs
Overall half-life for tetrachloroethylene of 30 - 300 days (http://www.intox.org/databank/documents/chemical/tetrachl/ukpid28.htm)

[5] Carbon Tetrachloride: from abstract (http://cat.inist.fr/?aModele=afficheN&cpsidt=3186063)

References:

Hexachloroethane:	http://www.atsdr.cdc.gov/toxprofiles/tp97-c5. Koc average of 3 values
	http://www.atsdr.cdc.gov/toxprofiles/tp97-c3.pdf
C-58	http://ecb.jrc.ec.europa.eu/DOCUMENTS/PBT_EVALUATION/PBT_sum108_CAS_77-47-4.pdf

Partitioning coefficients for PCE and carbon tetrachloride based on estimate weighting more heavily to predominant species and data below.

http://rais.ornl.gov/cgi-bin/tox/TOX_select
RAIS results for CHEM_PARAMS 3/23/2009

Chemical	CAS	Diffusivity-in-Water (cm^2/s)	Unitless-Henry's-Law-Constant	Molecular-Weight (g/mol)	Organic-Carbon-Partition-Coefficient (L/kg)	Water-Solubility (mg/L)	Vapor Pressure (mm Hg)
Dichloroethylene,-1,2-cis-	156-59-2	1.13E-05	1.67E-01	96.9	4.38E+01	3.50E+03	2.01E+02
Tetrachloroethylene	127-18-4	9.46E-06	7.24E-01	166.0	1.07E+02	2.06E+02	1.85E+01
Trichloroethylene	79-01-6	1.02E-05	4.03E-01	131.0	6.77E+01	1.28E+03	6.90E+01
Vinyl-Chloride	75-01-4	1.20E-05	1.14E+00	62.5	2.37E+01	8.80E+03	2.98E+03
Carbon-Tetrachloride	56-23-5	9.78E-06	1.13E+00	154.0	4.86E+01	7.93E+02	
Chloroform	67-66-3	1.09E-05	1.50E-01	119.0	3.50E+01	7.95E+03	
Methylene-Chloride	75-09-2	1.25E-05	1.33E-01	84.9	2.37E+01	1.30E+04	

Table M4
Decay Rates (/yr)

Constituent	Decay Rate	Daughter	Decay Rate	Daughter	Decay Rate	Basis (Note 2)
PCE to TCE	0.004	TCE to cis-1,2-DCE	0.08	cis-1,2-DCE to VC	0	Based on ratio of concentrations for 4 sampling events in 2008 at well Pg
C-56	16.9	na	na	na	na	Hydrolysis
C-58	5.06	na	na	na	na	Hydrolysis
Carbon tetrachloride to chloroform	0.008	Chloroform to Methylene Chloride	0	Methylene Chloride to Methyl Chloride	0	Based on 2005 well concentrations
Hexachloroethane	0	na	na	na	na	No decay mechanisms under aerobic conditions except volatilization

Time Period Input (years)	
T1	Note 1
T2	Note 1
Distance Input (meters)	
X1	Note 1
X2	Note 1

Notes:

Note 1: These values can be anything as long as they are within the time modeled and the length of the area modeled because the decay rates are constant for all nine cases.

Note 2: Available data did not include vinyl chloride (VC), methylene chloride, or methyl chloride. Therefore, decay to these daughter products is assumed to be zero.
Enter a decay rate for each time/distance matric for each parent and daughter compound.
Decay rate units: 1/yr

Table M5
Summary of Modeling Results

				Years to Reach Groundwater Cleanup Standard			
Compound	Scenario	Gamma	sigmav	Former Primary Ash Disposal Area (FPADA)	Former Primary Disposal Area (FPDA)	Former Fine Chemical Production Area (FCPA)	Former Equalization Pond Area (FEPA)
PCE	1	0.5	0.14	na	567	45.5	320
	1	0.8	0.14	na	1040	88	410
	1	1	0.14	na	1540	174	440
	1	1	0.31623	na	ne	176	ne
	1	2	0.14	na	3800	1700	440
	2	1	0.14	na	890	138	40
C-56	1	0.5	0.14	1380	>10000	4050	800
	1	1	0.14	1365	>10000	6900	1220
	1	2	0.14	1035	>10000	8500	1440
	2	1	0.14	12	4900	1980	280
C-58	1	0.5	0.14	2150	>10000	3400	standard not exceeded; 11 ug/L max predicted conc
	1	1	0.14	1480	>10000	2090	standard not exceeded; 11 ug/L max predicted conc
	1	2	0.14	890	>10000	1200	standard not exceeded; 11 ug/L max predicted conc
	2	1	0.14	45	79	36	standard not exceeded; 11 ug/L max predicted conc
Carbon Tetrachloride (CT)	1	0.5	0.14	na	100	na	na
	1	0.8	0.14	na	186	na	na
	1	1	0.14	na	308	na	na
	1	2	0.14	na	1230	na	na
	2	1	0.14	na	210	na	na

Table M5
Summary of Modeling Results

				Years to Reach Groundwater Cleanup Standard			
Compound	Scenario	Gamma	sigmav	Former Primary Ash Disposal Area (FPADA)	Former Primary Disposal Area (FPDA)	Former Fine Chemical Production Area (FCPA)	Former Equalization Pond Area (FEPA)
Hexachloroethane (C-26)	1	0.5	0.14	na	200	335	na
	1	0.8	0.14	na	295	581	na
	1	1	0.14	na	355	810	na
	1	2	0.14	na	510	1720	na
	2	1	0.14	na	160	445	na

Note: Fly Ash Pile is the Former Ash Disposal Area
Scenarios:
1. no removal; with gamma=1 is baseline scenario
2. 90% source mass removal by excavation

na = not applicable because DNAPL in this area has zero/near zero mass of this constituent
ne = not evaluated
Cleanup times for C-56 and C-58 are for source to reach groundwater cleanup standard. Plume generally extends less than 100 m from source at these times

APPENDIX C

Sub-Appendices

Notes on REMChlor

REMChlor is a combination of two models: a source model and a plume model. The source model serves as a time-dependent mass flux boundary condition relative to the analytical plume model, where flow is assumed to be one-dimensional. The plume model simulates first order sequential decay and production of daughter products. The decay rates and parent/daughter yield coefficients are variable functions of time and distance. This approach allows for flexible simulation of enhanced plume cleanup that may be temporary in time, limited in space, and which may have different effects on the various daughter products generated.

Three-dimensional multiphase flow simulations (Falta et al., 2005) suggest that the source mass/source discharge relationship depends largely on the correlation between the DNAPL distribution and the soil permeability. This means that if most of the contaminant mass is located in a highly permeable zone, then most of it must be removed before the average discharge drops. This leads to relatively rapid depletion of the source by dissolution, with little dissolved-phase tailing.

A simulation in which the DNAPL distribution was correlated with low permeability produces the reverse result. When most of the contaminant is trapped in low permeability material, removing the small amount from the high permeability zones will have a large effect on the contaminant discharge. This includes a rapid initial drop in discharge with source mass reduction, followed by extensive tailing because the source is never completely depleted by dissolution (Falta et al., 2005).

The source mass/source discharge relationships can be empirically approximated by a simple power function (Rao et al., 2001; Rao and Jawitz, 2003; Parker and Park, 2004; Zhu and Sykes, 2004; Falta et al., 2005). The exponent, Γ (gamma, which is a function of grain-size), determines the shape of the source discharge response to the change in source mass. Field and laboratory data suggest that a Γ value of one is reasonable in most cases, but theoretical analyses indicate that a range of Γ values are possible, depending mainly on the correlation of the contamination distribution to the permeability.

An important characteristic of source zones with Γ greater than or equal to one, is that the source is never completely depleted because the rate of discharge from the source drops as fast or faster than the rate of mass depletion of the source. When Γ is less than one, the source has a finite life, and the source discharge eventually is equal to zero. This generally leads to a correlation between higher Γ values and longer times for contaminants to reach cleanup criteria. However, when the source mass to area ratio is small and the decay rates are large an inverse relation between Γ and cleanup time is observed. This is generally the case for the C-series compounds (C-56 and C-58) detected at the Site.

The model assumes a constant groundwater pore velocity in the *x* direction, with longitudinal, transverse, and vertical dispersion. The solute can be retarded by adsorption, but the different solutes involved in coupled reactions must have the same retardation factor. Additional model assumptions are presented below:

- The model assumes a homogeneous and constant groundwater velocity with flow in one direction.
- The contaminant source mass balance assumes that the contaminant discharge is a power function of the remaining contaminant mass using an exponent Γ.
- The model assumes that biocleanup reactions in the plume can be described by first order decay reactions. The biogeochemical conditions that control these reactions may not be well represented by first order reactions, and there is considerable uncertainty in values of field scale decay rates.
- All of the dissolved solutes (parent and daughter compounds) are assumed to have the same retardation coefficient, so they move at the same velocity.
- First order decay rates are a function of time and distance from the source (*x*), but they do not depend on the *y* or *z* coordinates. This means that a specified reaction zone will extend over the entire model domain in the *y* and *z* directions.

- The model uses a conventional advection-dispersion formulation, and is not able to account for transient diffusion into low permeability zones in the plume. Diffusion of contaminants into low permeability zones may result in plume rebound after the source is depleted to back diffusion.

- Transverse and vertical dispersion are approximated using the Domenico (1987) method. This can lead to errors in the concentration distributions, particularly when large dispersion coefficients are used.

CALIBRATION

Model calibration was performed to demonstrate that the model can adequately reproduce observed conditions from the site. Flow model calibrations are generally based on comparing modeled generated heads to observed heads. However, because of the simple flow regime at the site (near uniform gradient and little variation in hydraulic conductivity), flow information was simply entered into the model incorporated into the Darcy velocity (hydraulic conductivity x hydraulic gradient, Table M2).

Transport calibration is generally evaluated by comparing the model's ability to reproduce the plume development. At this site the observed concentration data are limited so there was more reliance on bracketing behavior based on literature values for transport parameters. The model predicts a short time frame for the CVOC plumes to travel from the source areas to reach White Lake (e.g. Former Fine Chemical Product Area - 10 to 20 years) because they are only slightly retarded. C-56 is also predicted to have a relatively fast travel time. However, C-58 is expected to more tightly bind to aquifer materials (Table M-3 shows the Kd for C-58 is 35 times greater than C-56). Neither C-56 nor C-58 has reached White Lake indicating they are degrading or in the case of C-58, is moving very slowly and degrading. The model predicts that neither should extend more several hundred meters from the DNAPL source areas and this has been confirmed by the lack of C-56 or C-58 in downgradient wells based on their rapid decay rates (See Table M-4) even though C-56 is relatively mobile.

The parameter Γ (gamma) determines the rate at which the source depletes. Although the field data showing concentrations are limited to just a few wells near the source areas, a Γ value of 1 is consistent with the observed concentrations. For example PCE concentrations at MW-95-03 over an 8 year period showed a 22% percent decline while the model predicts a 35% decline. The gamma value of 1 is consistent with middle age to older sites and has been observed at other DNAPL sites.

REMChlor predicts CVOC plumes would quickly reach White Lake with similar concentrations extending from the source area towards the lake due to little retardation and degradation. C-56 is predicted to not travel far due to degradation while C-58 moves slower but also decays rapidly resulting in limited plumes developing. All of these predicted behaviors have been confirmed by field observations.

SUMMARY

The REMChlor input parameters and a summary of the output data are summarized in tables M1-M5. Table M1 summarizes the source area data, M2 presents the aquifer properties, M3 is the chemical characteristics of each of the constituents, M4 lists the decay rates of the constituents and their breakdown products, and M5 summarizes the time to reach the groundwater cleanup standard at each of the four source area for the constituents.

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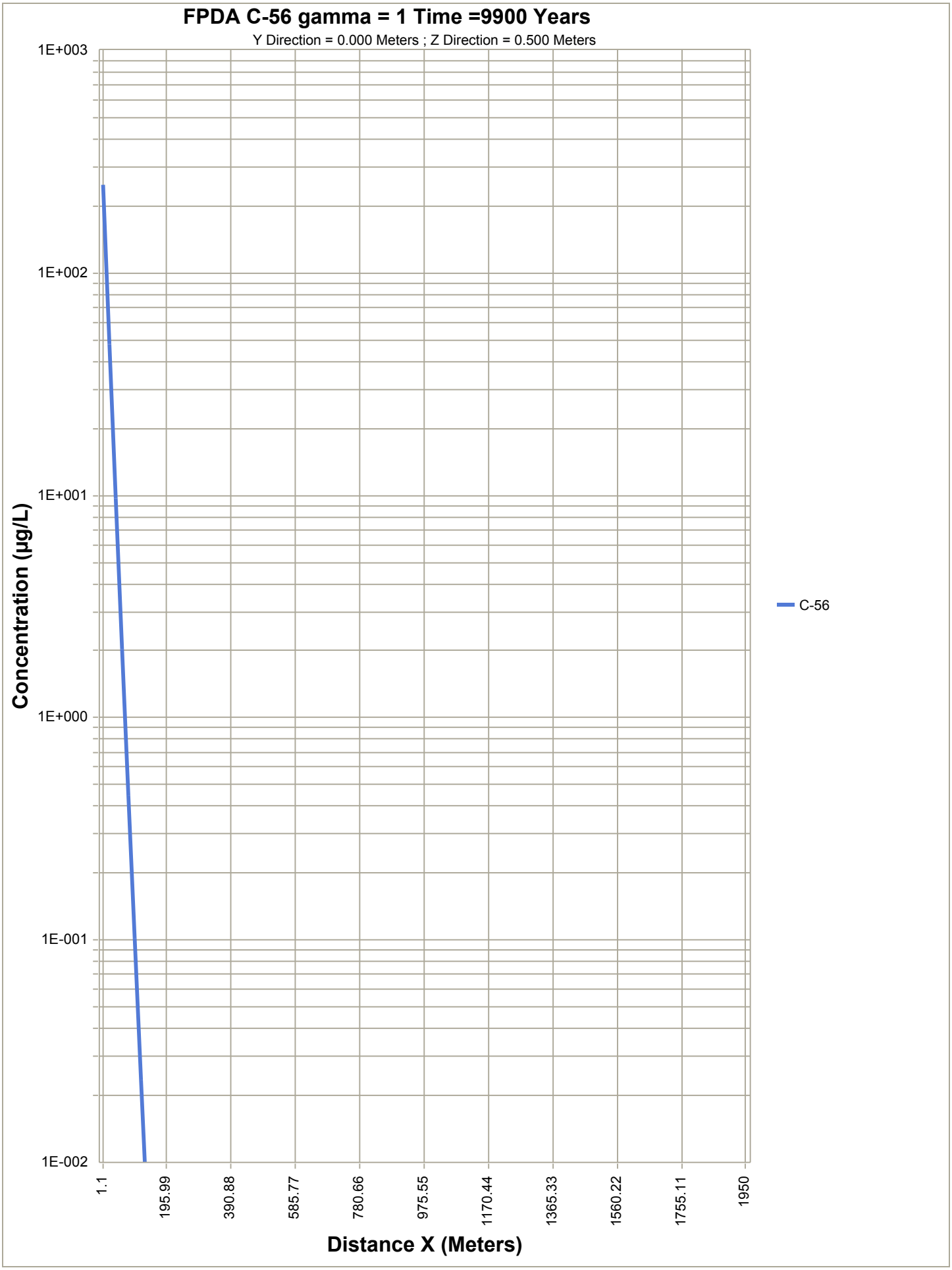
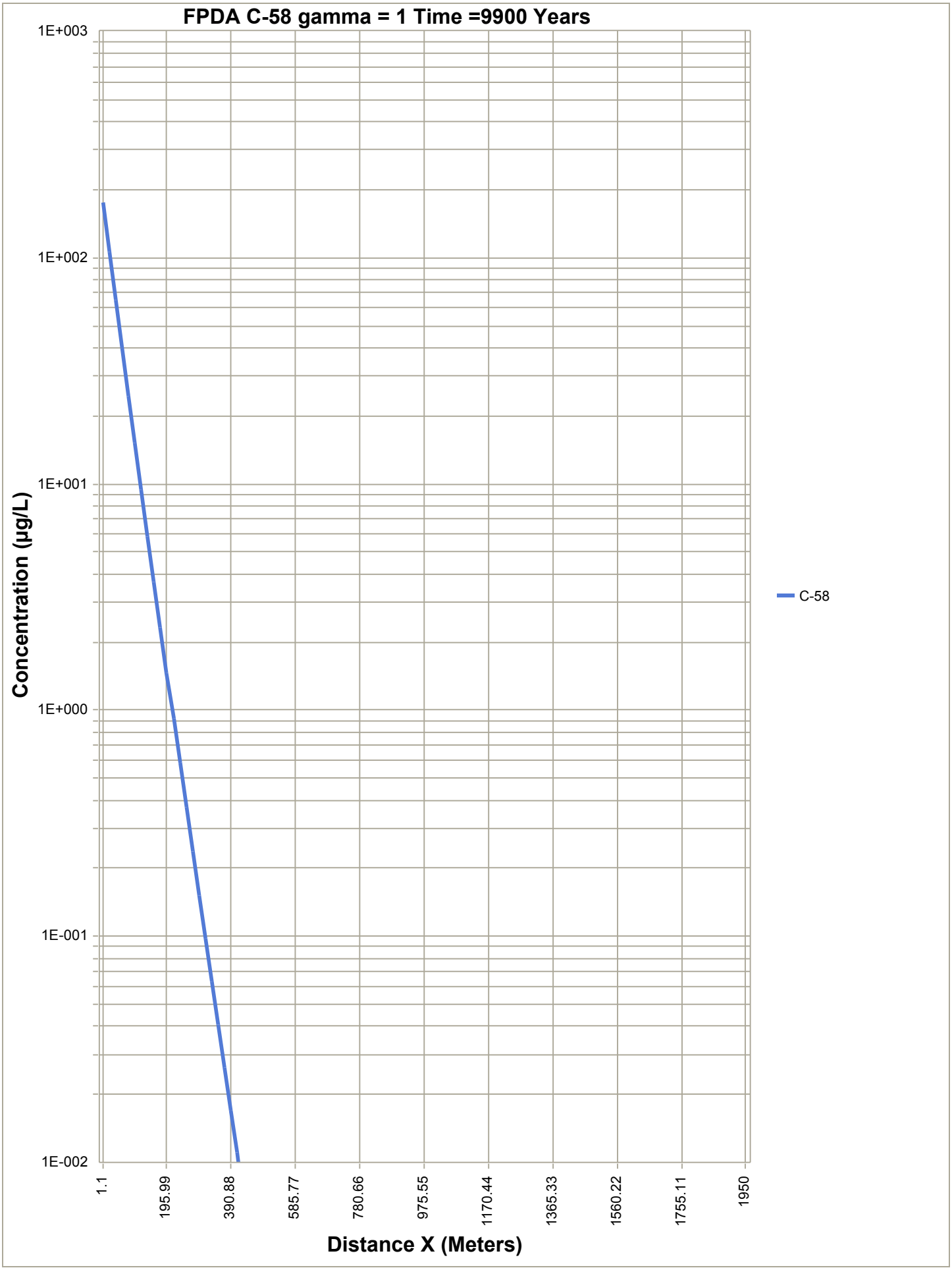
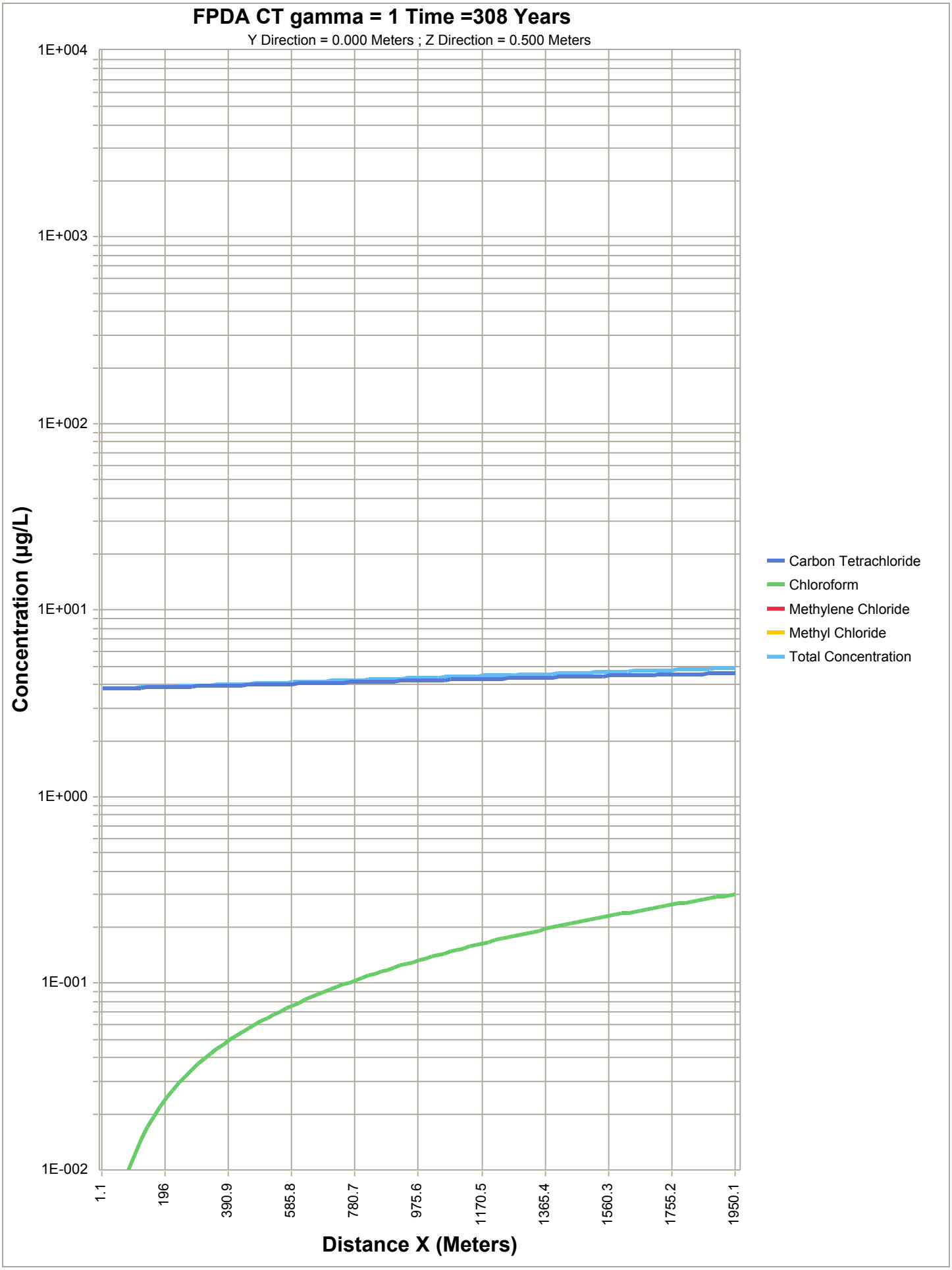
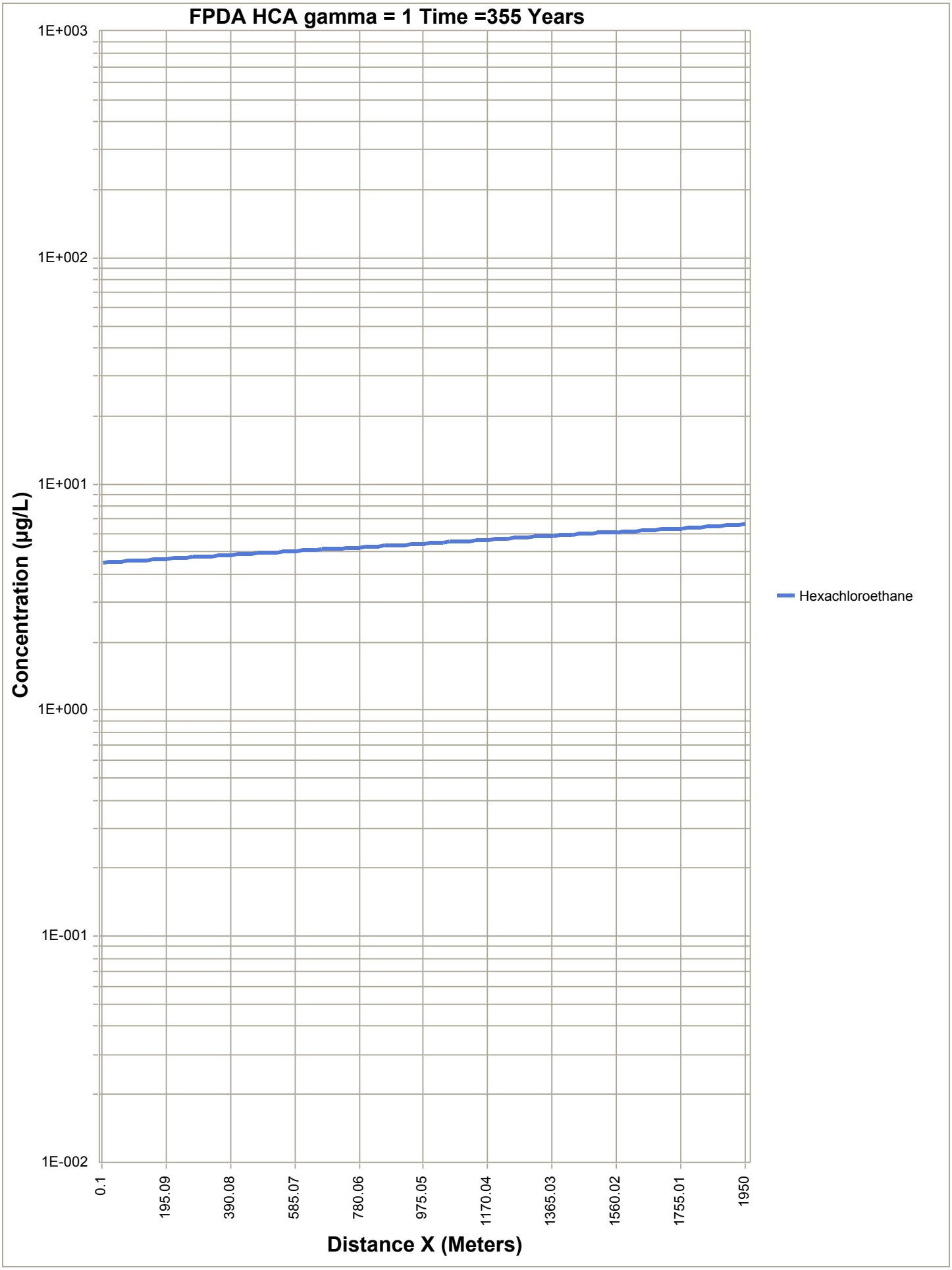
M1

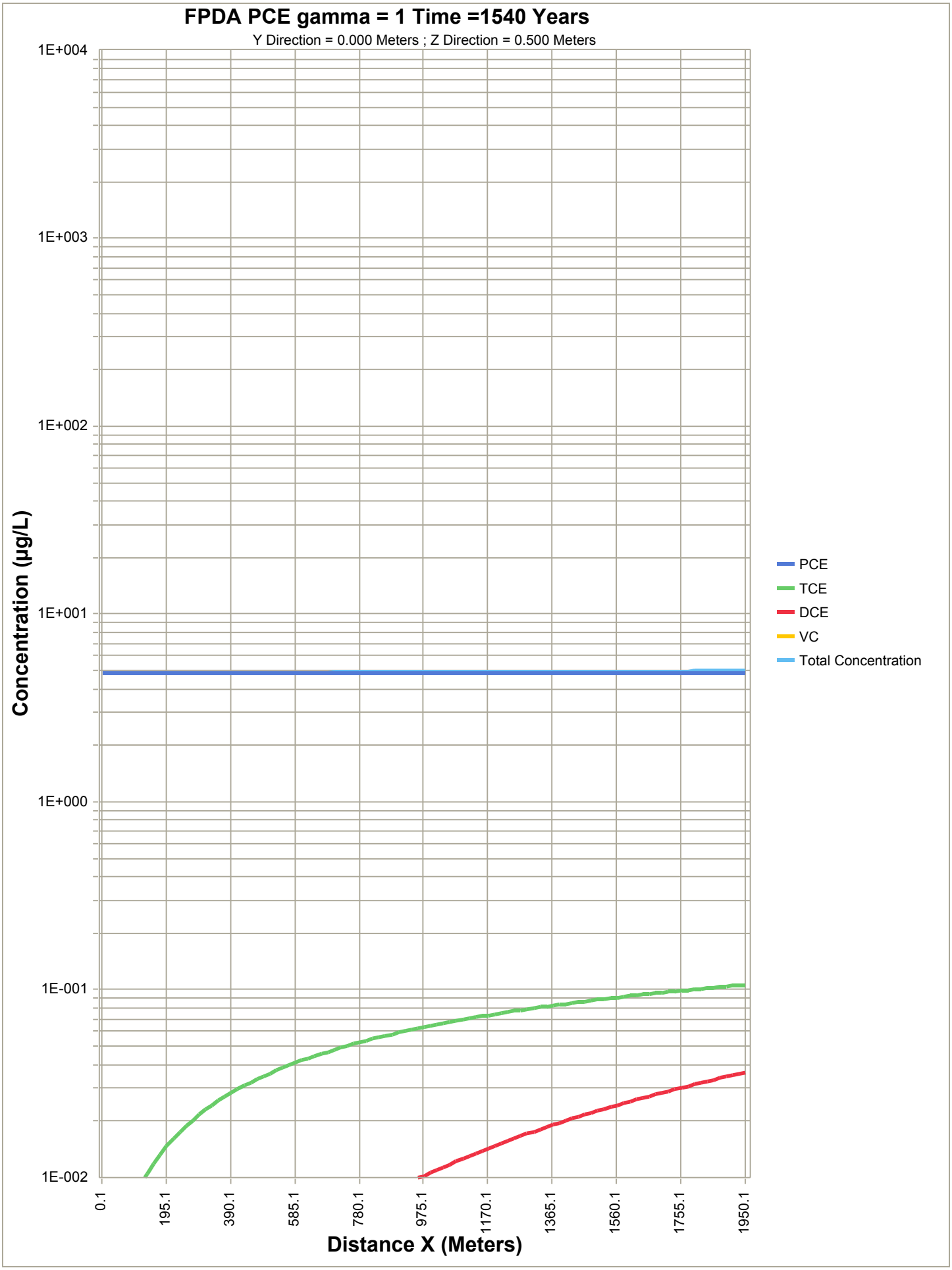
FPDA Source Area
Gamma = 1 (Baseline – Sand)


FPDA C-56 gamma = 1 Time =9900 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
1.1
195.99
390.88
585.77
780.66
975.55
1170.44
1365.33
1560.22
1755.11
1950
Distance X (Meters)
C-56


FPDA C-58 gamma = 1 Time =9900 Years
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
1.1
195.99
390.88
585.77
780.66
975.55
1170.44
1365.33
1560.22
1755.11
1950
Distance X (Meters)
C-58

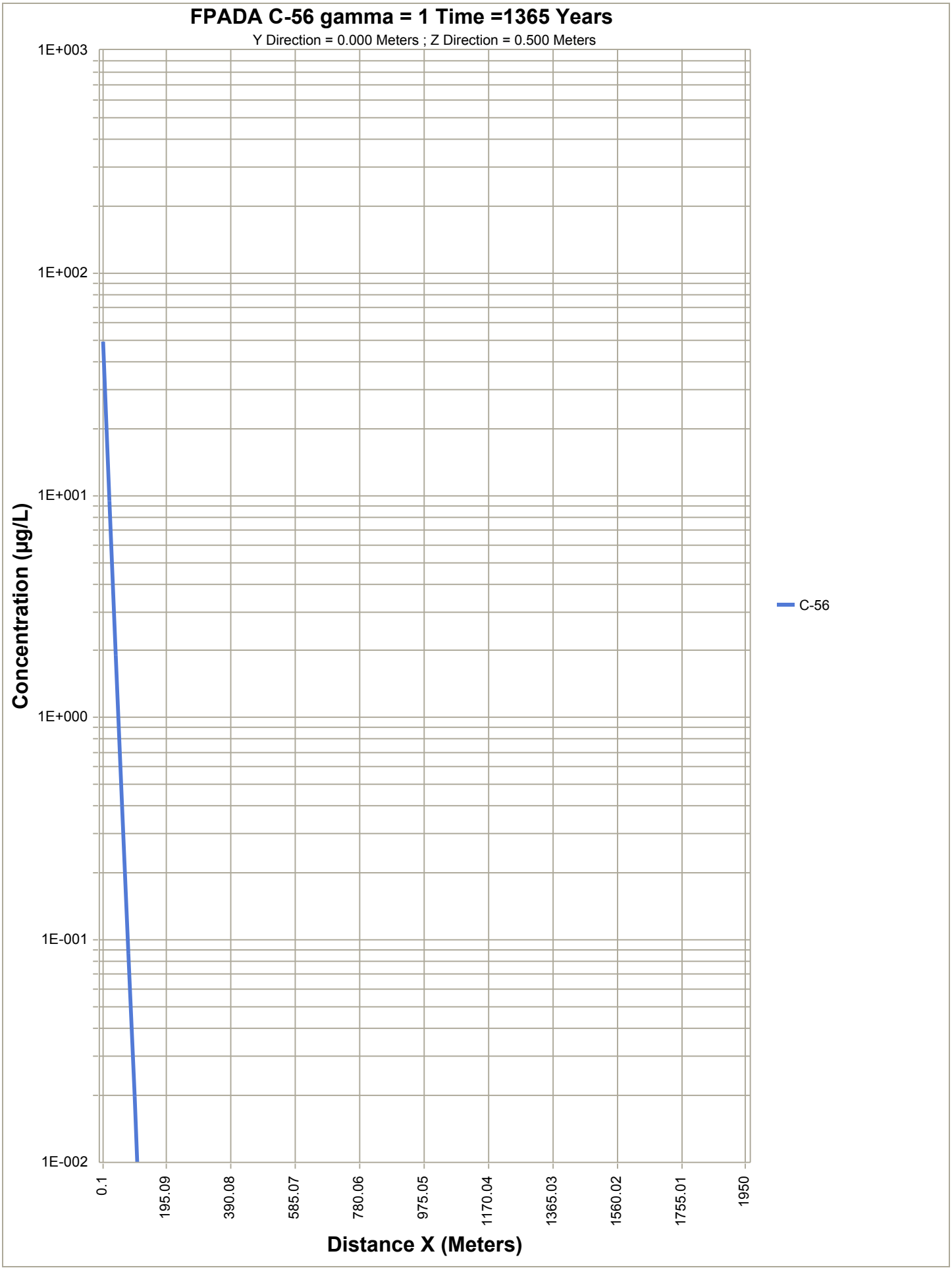

FPDA CT gamma = 1 Time =308 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
1.1
196
390.9
585.8
780.7
975.6
1170.5
1365.4
1560.3
1755.2
1950.1
Distance X (Meters)
Carbon Tetrachloride
Chloroform
Methylene Chloride
Methyl Chloride
Total Concentration

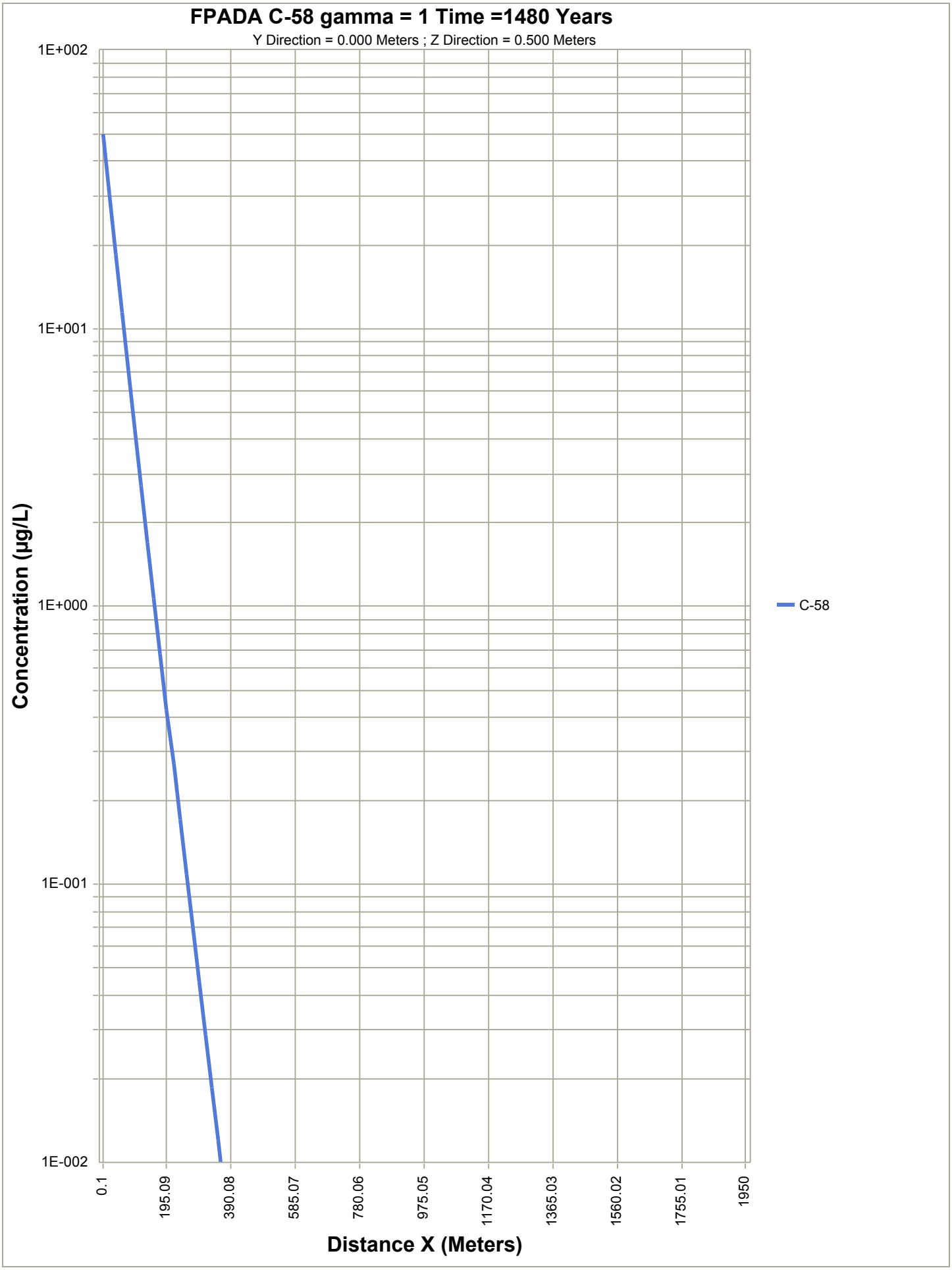

FPDA HCA gamma = 1 Time =355 Years
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
Hexachloroethane


FPDA PCE gamma = 1 Time =1540 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
0.1
195.1
390.1
585.1
780.1
975.1
1170.1
1365.1
1560.1
1755.1
1950.1
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

M2

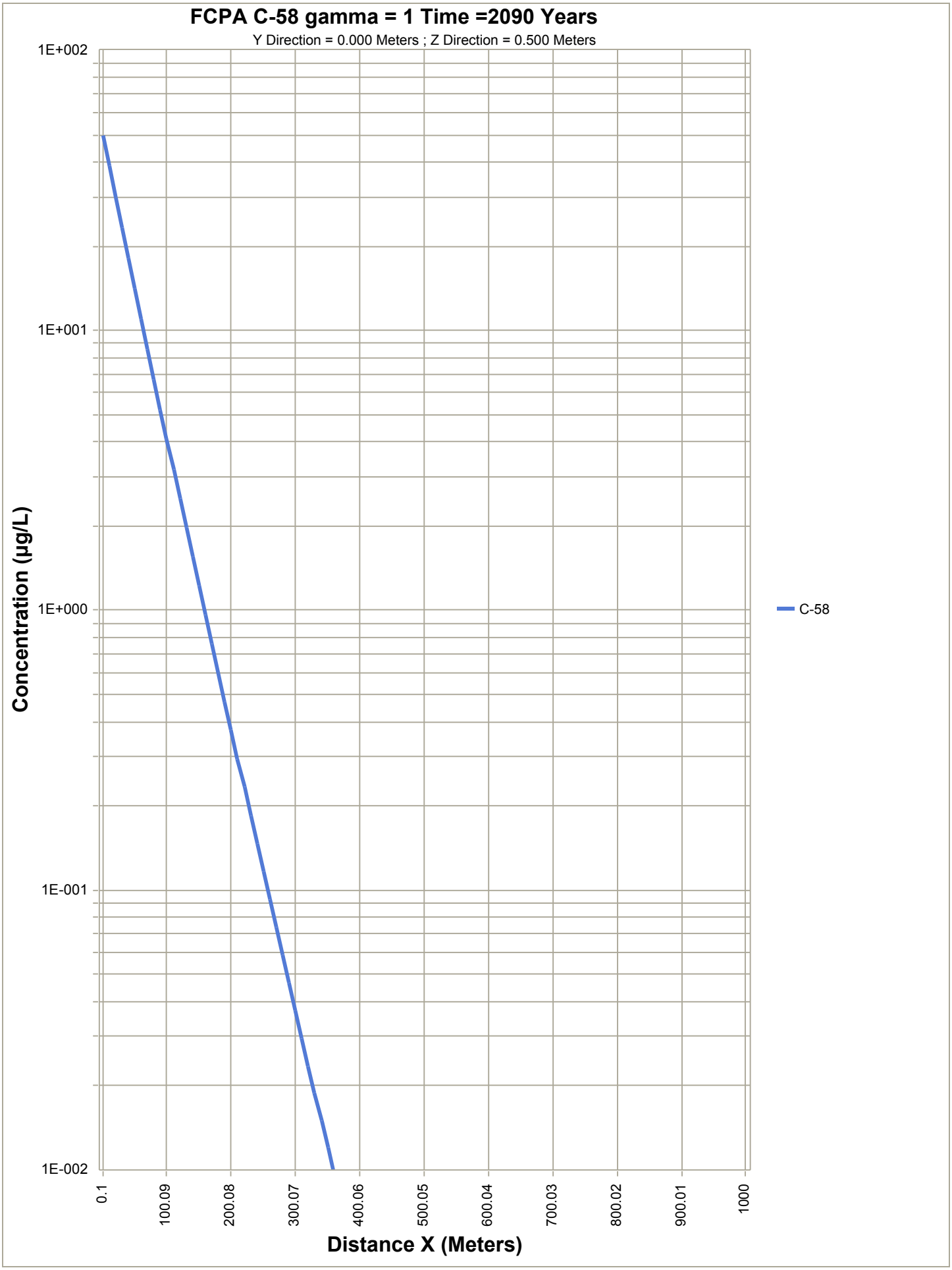
FPADA Source Area
Gamma = 1 (Baseline – Sand)

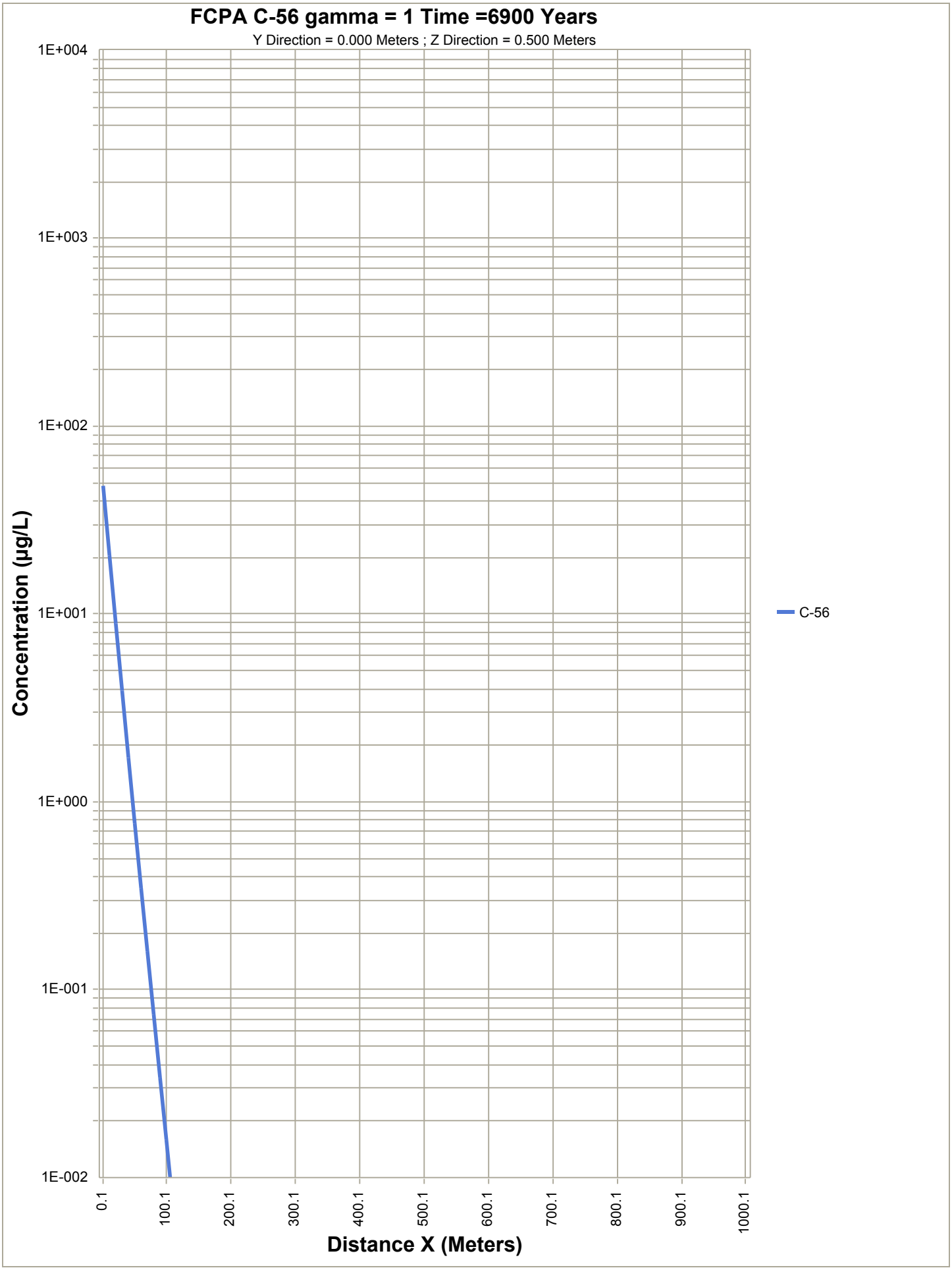

FPADA C-56 gamma = 1 Time =1365 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
C-56

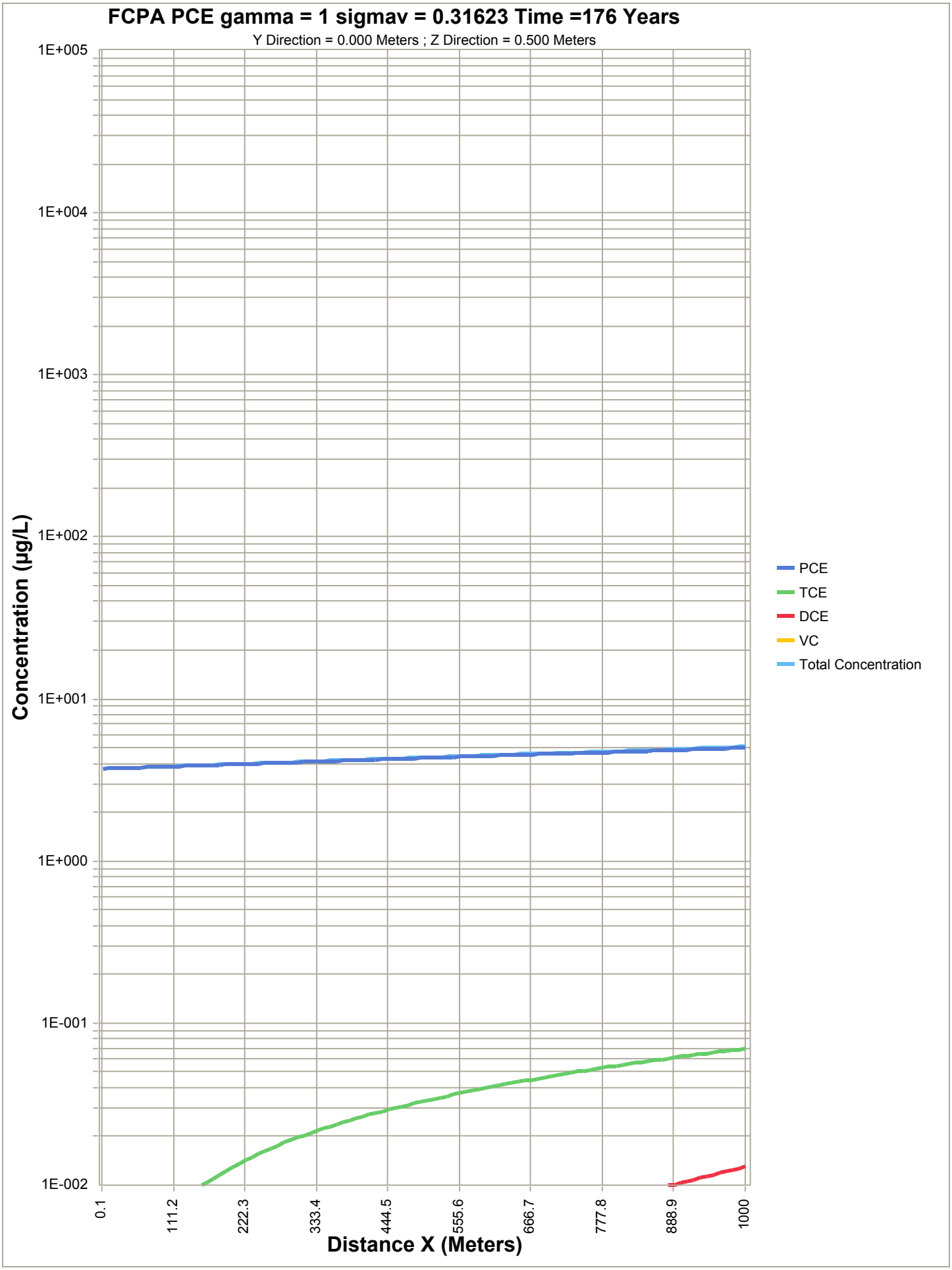

FPADA C-58 gamma = 1 Time =1480 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
C-58

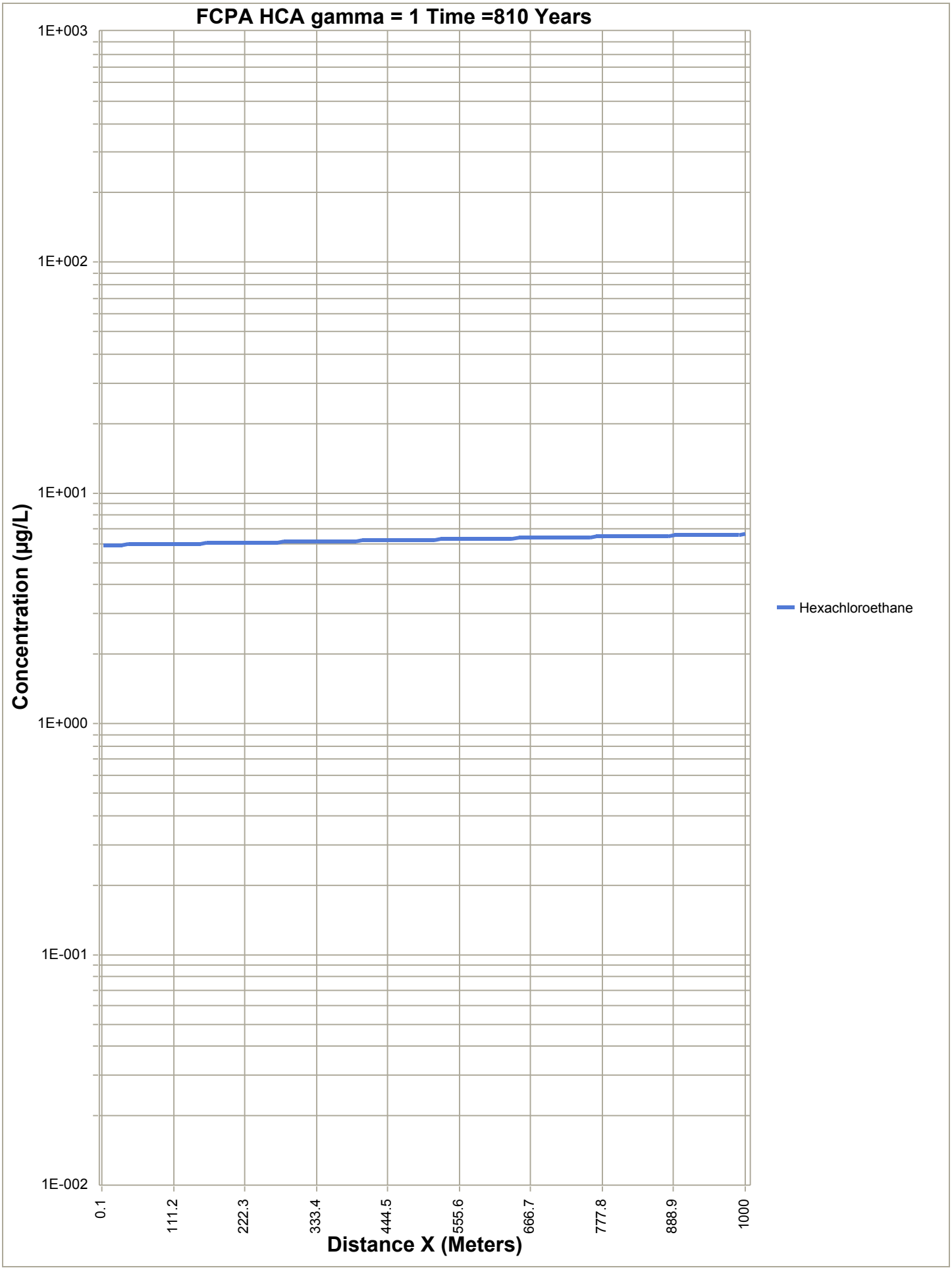
M3

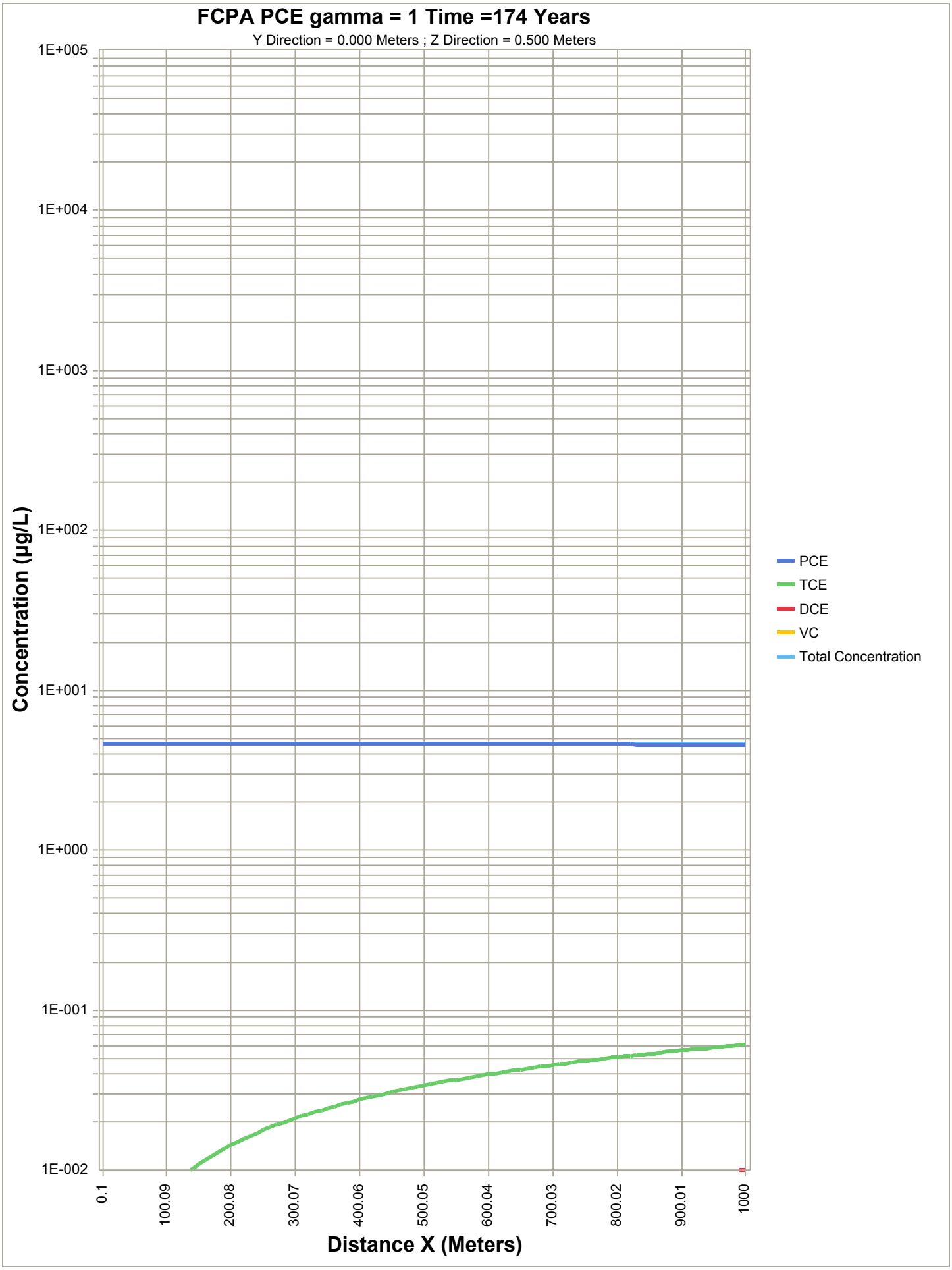
FCPA Source Area
Gamma = 1 (Baseline – Sand)


FCPA C-58 gamma = 1 Time =2090 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
100.09
200.08
300.07
400.06
500.05
600.04
700.03
800.02
900.01
1000
Distance X (Meters)
C-58


FCPA C-56 gamma = 1 Time =6900 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
100.1
200.1
300.1
400.1
500.1
600.1
700.1
800.1
900.1
1000.1
Distance X (Meters)
C-56

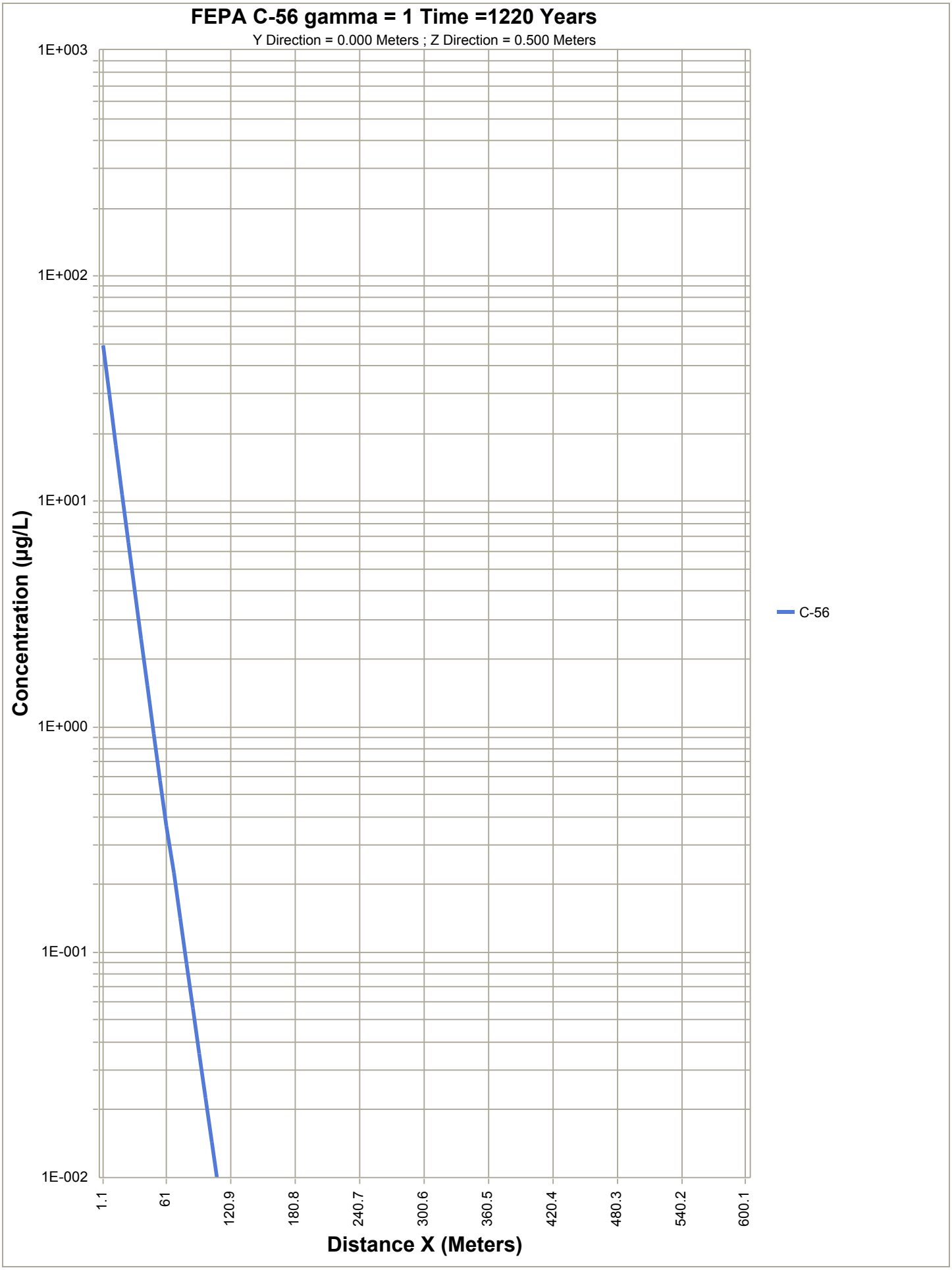

FCPA PCE gamma = 1 sigmav = 0.31623 Time =176 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+005
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
0.1
111.2
222.3
333.4
444.5
555.6
666.7
777.8
888.9
1000
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

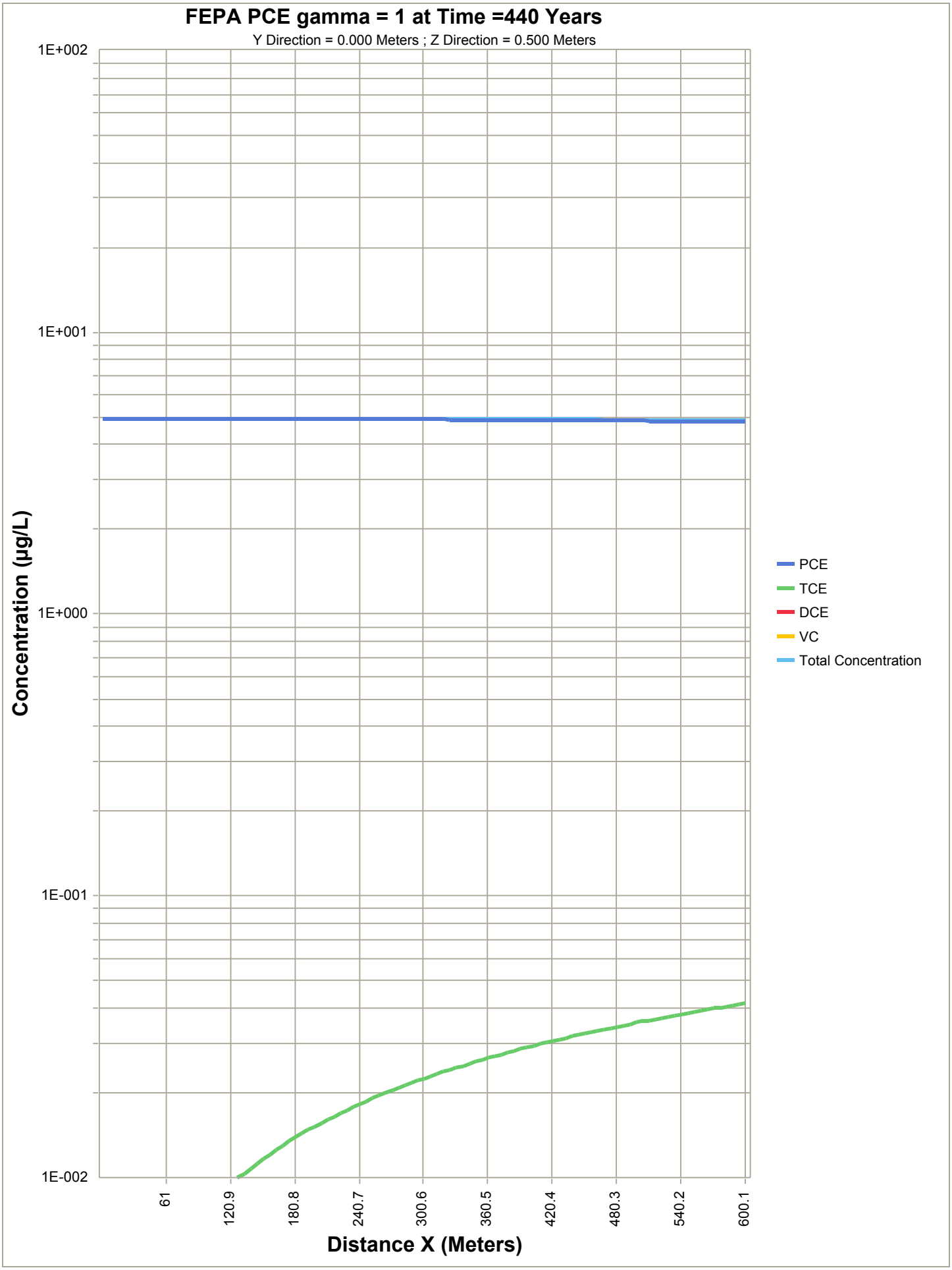

FCPA HCA gamma = 1 Time =810 Years
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
111.2
222.3
333.4
444.5
555.6
666.7
777.8
888.9
1000
Distance X (Meters)
Hexachloroethane


FCPA PCE gamma = 1 Time =174 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+005
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
0.1
100.09
200.08
300.07
400.06
500.05
600.04
700.03
800.02
900.01
1000
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

M4

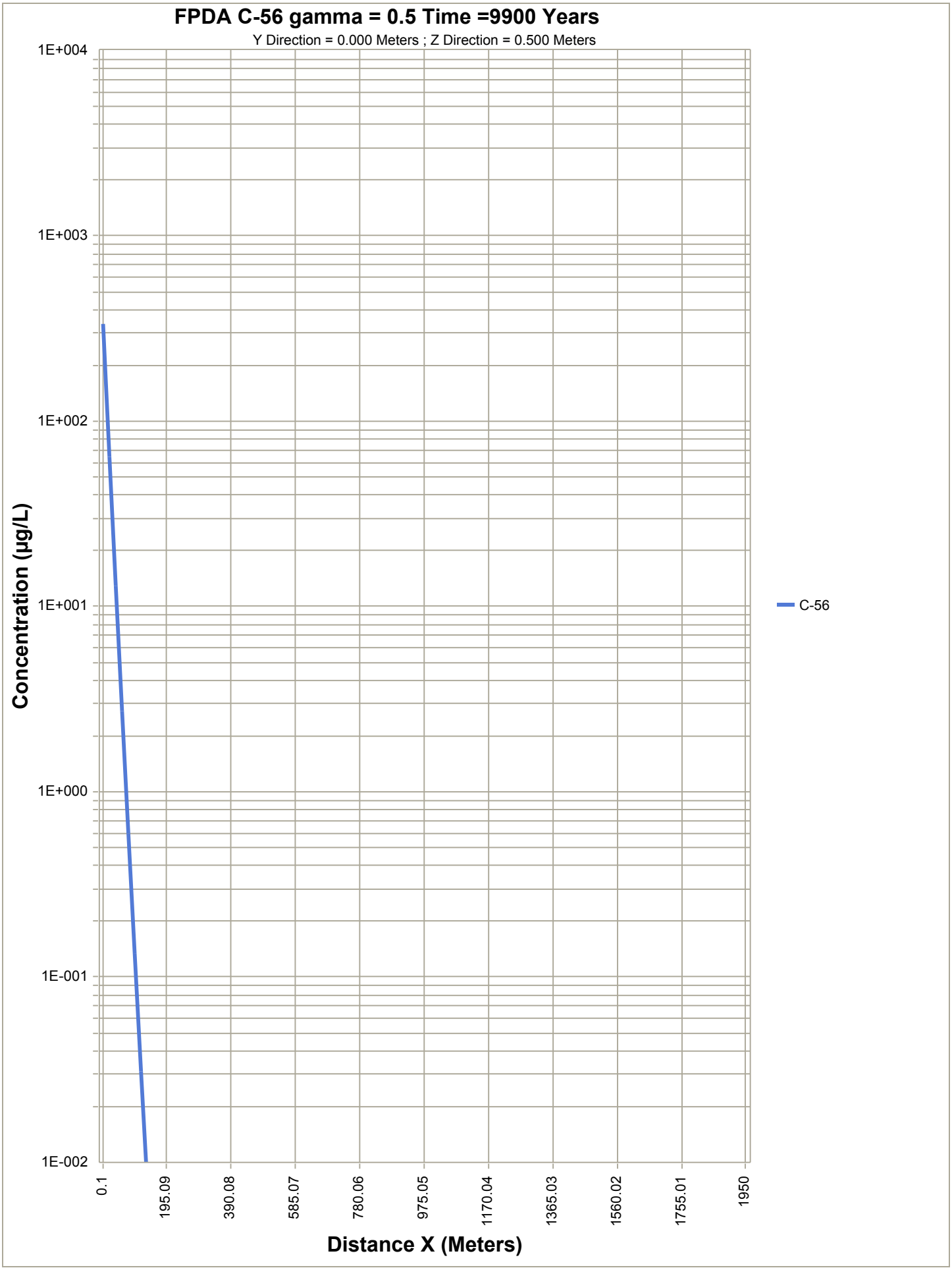
FEPA Source Area
Gamma = 1 (Baseline – Sand)

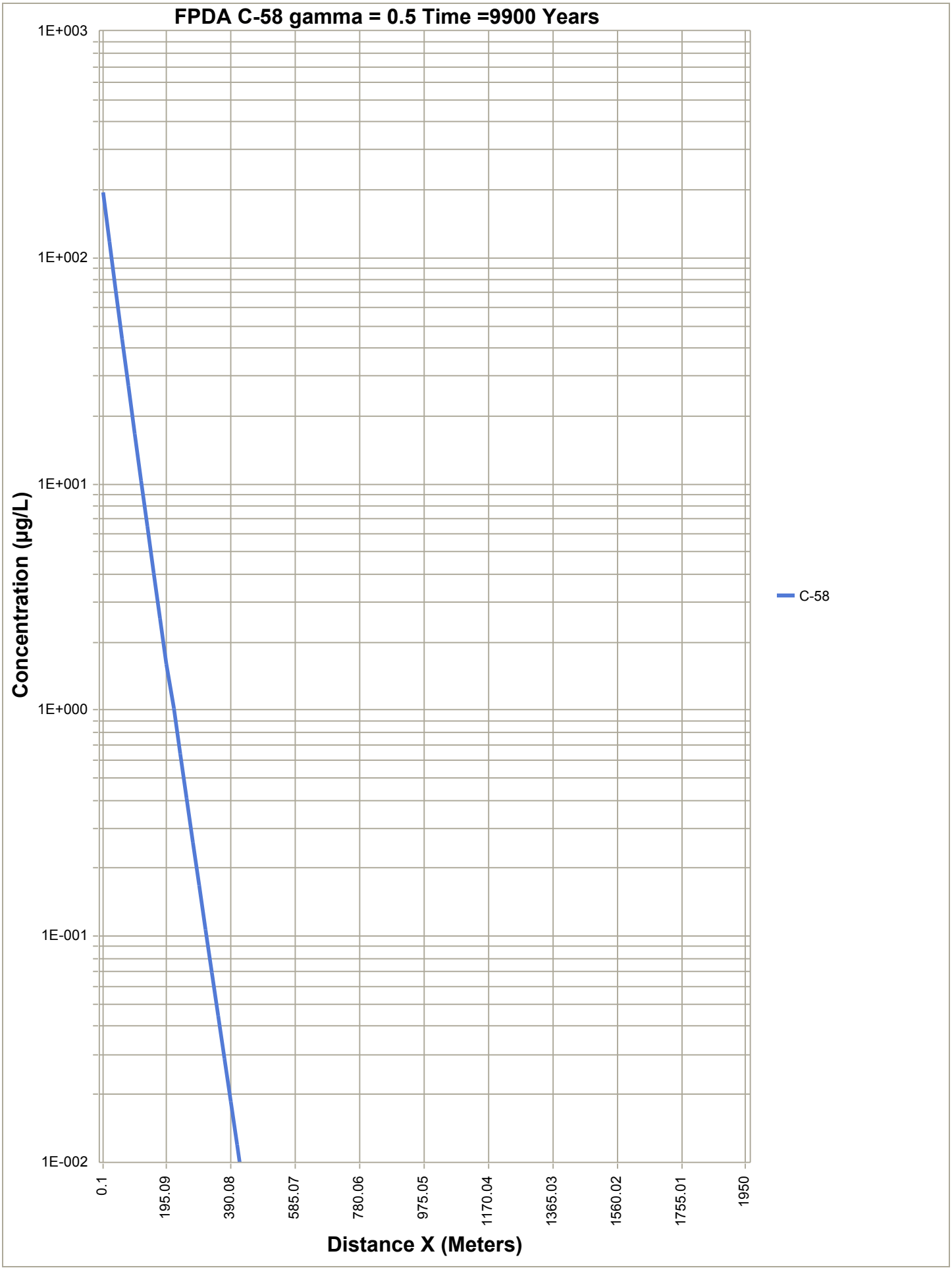

FEPA C-56 gamma = 1 Time =1220 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
1.1
61
120.9
180.8
240.7
300.6
360.5
420.4
480.3
540.2
600.1
Distance X (Meters)
C-56

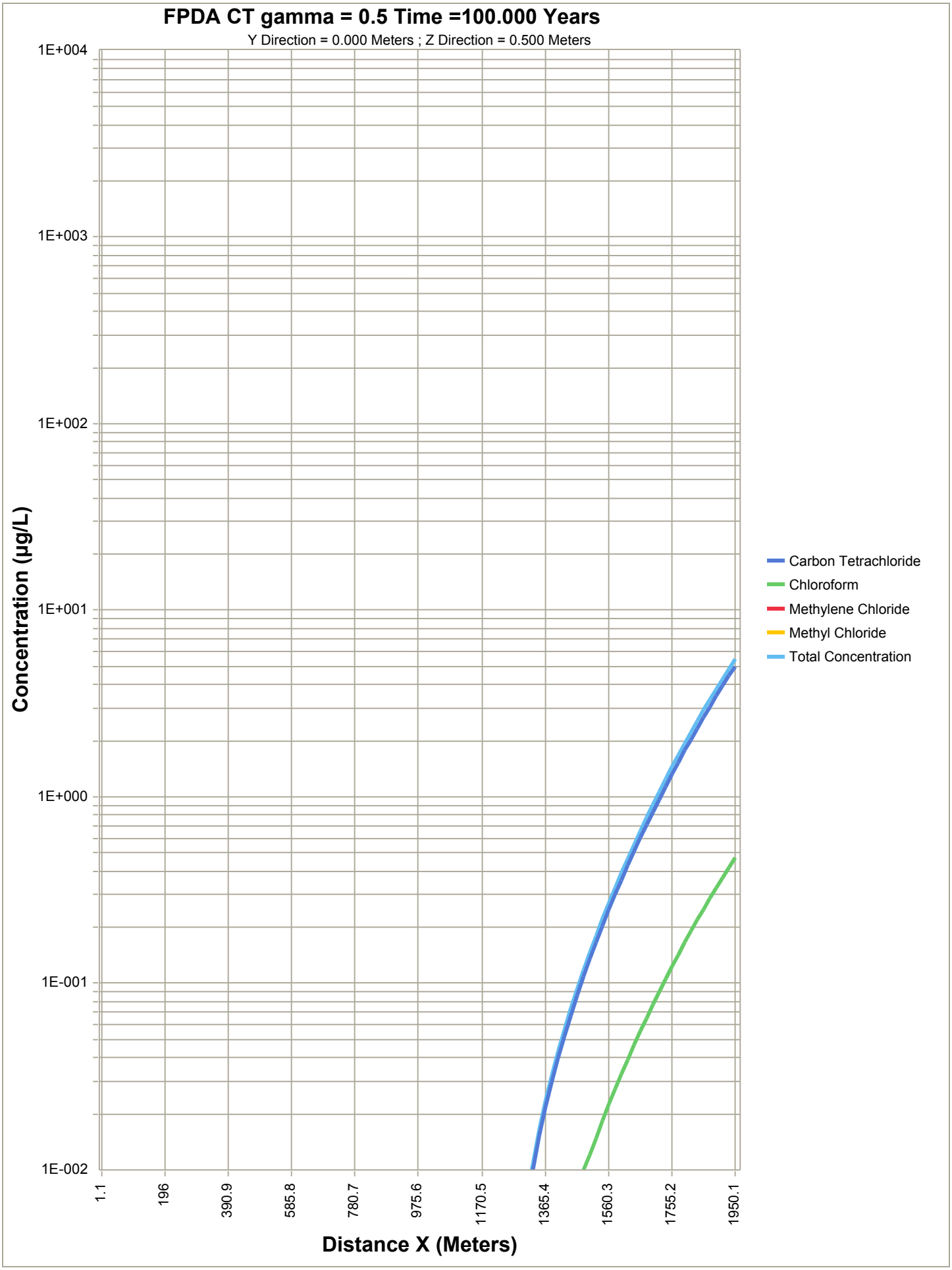

FEPA PCE gamma = 1 at Time =440 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
61
120.9
180.8
240.7
300.6
360.5
420.4
480.3
540.2
600.1
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

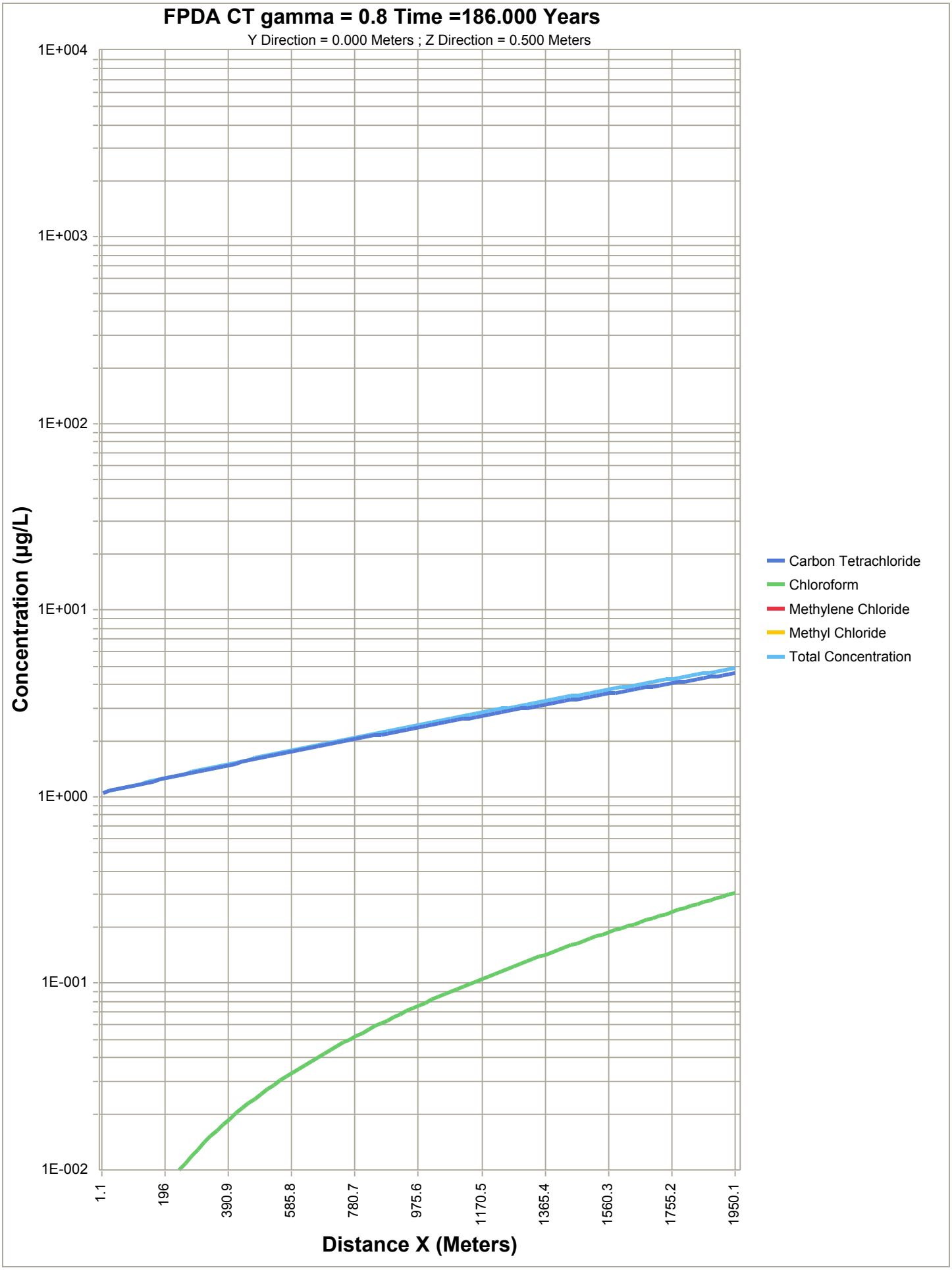
M5

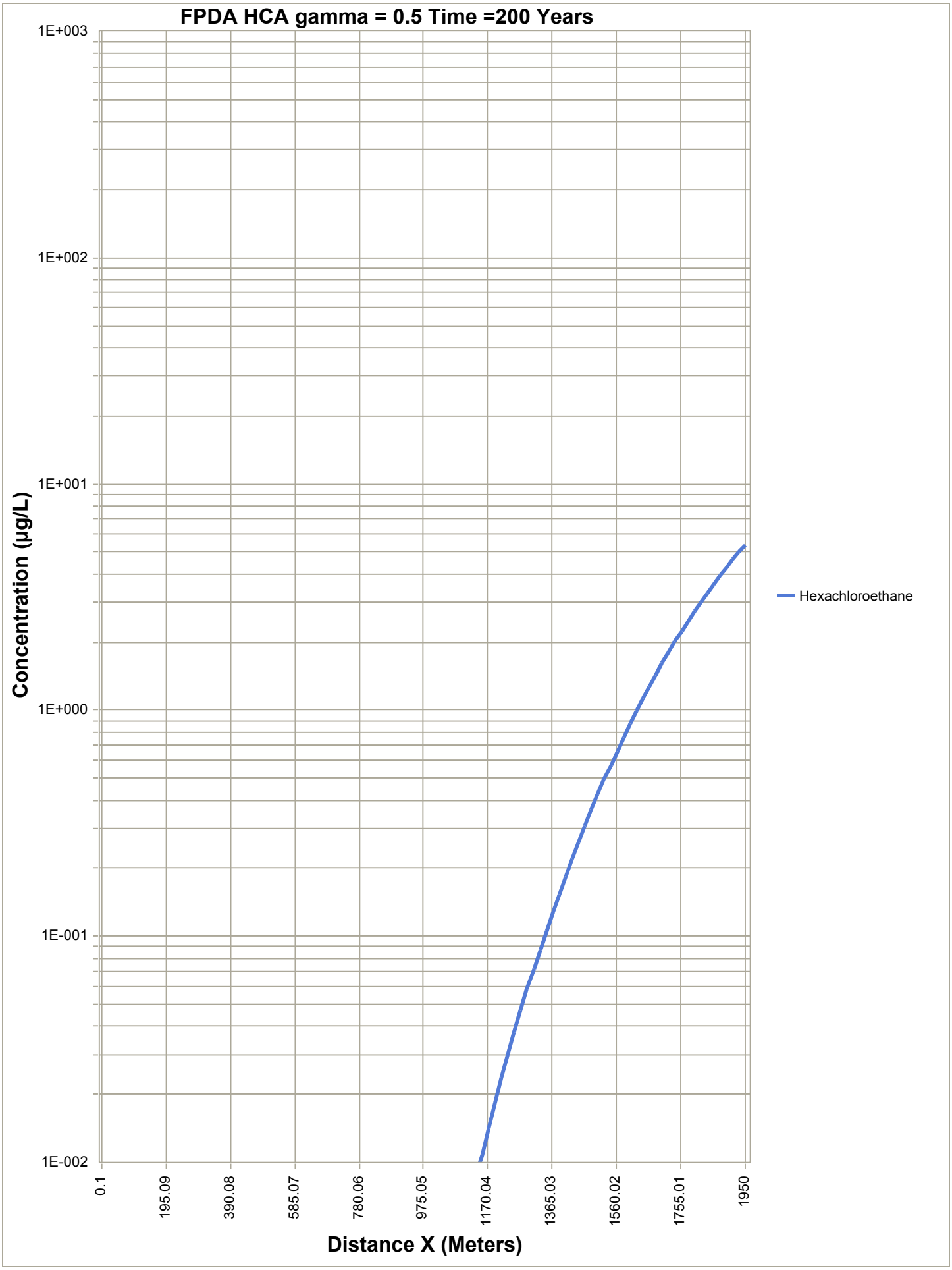
FPDA Source Area
Gamma = 0.5, 0.8

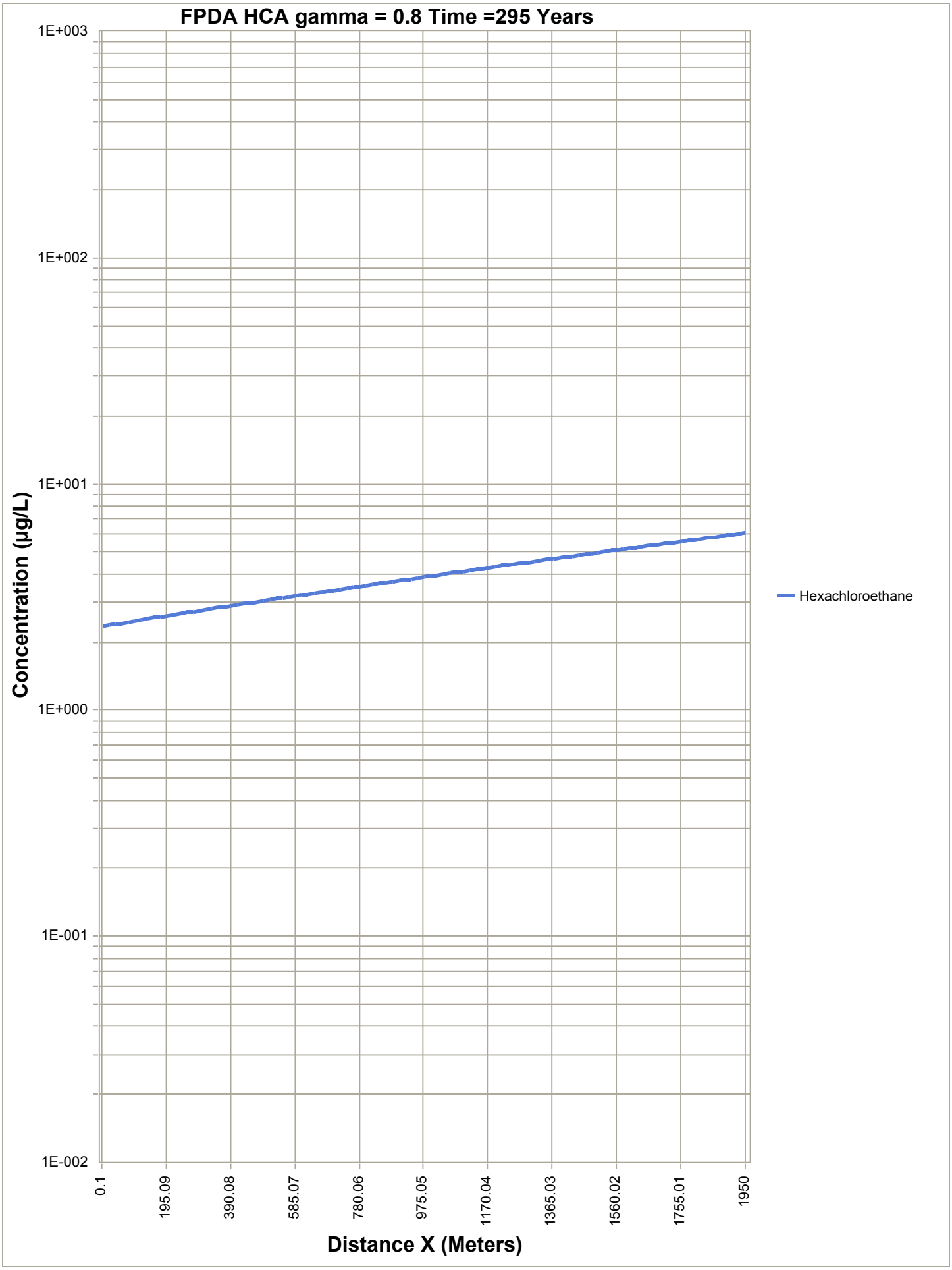

FPDA C-56 gamma = 0.5 Time =9900 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
C-56

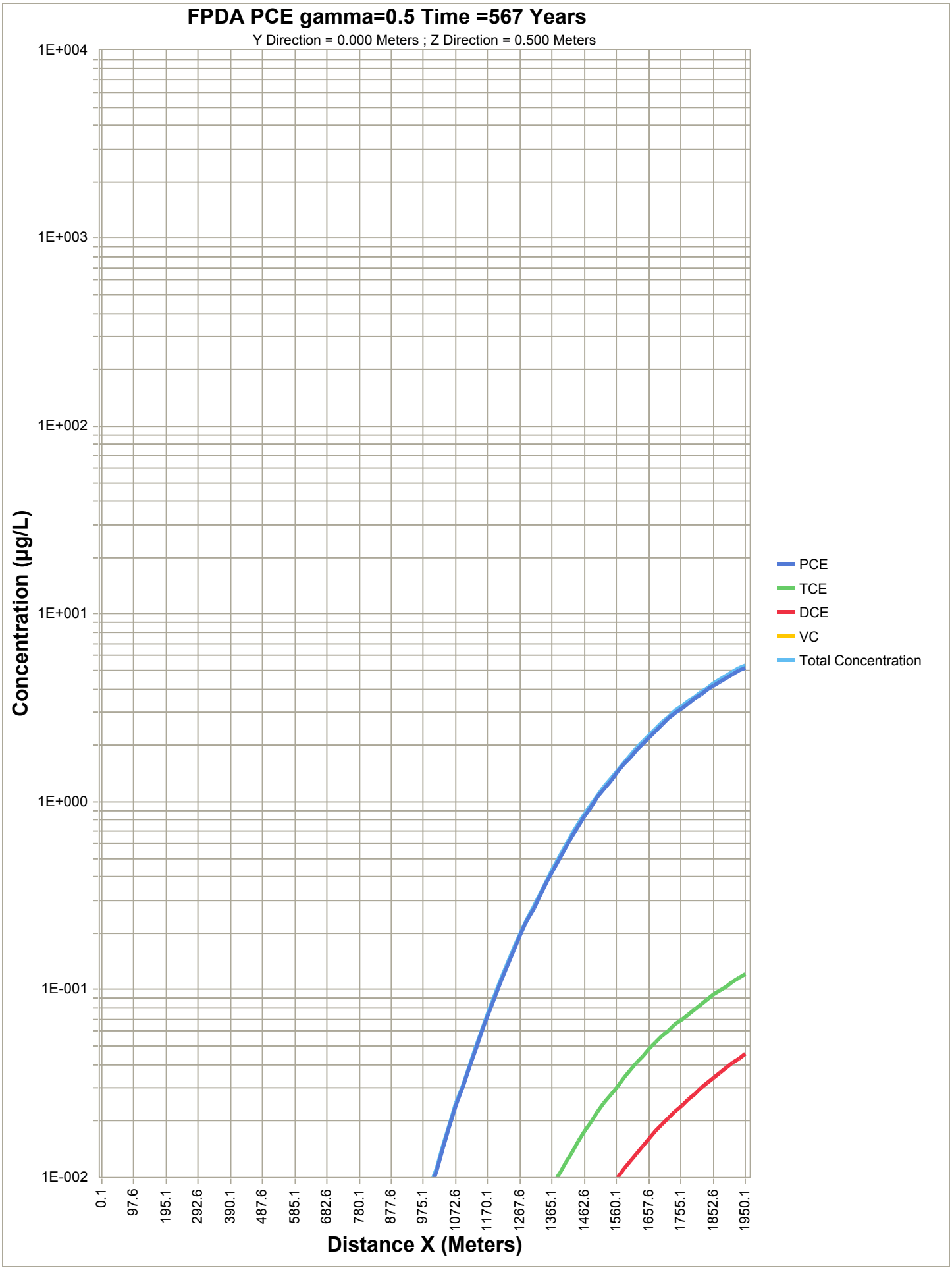

FPDA C-58 gamma = 0.5 Time =9900 Years
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
C-58

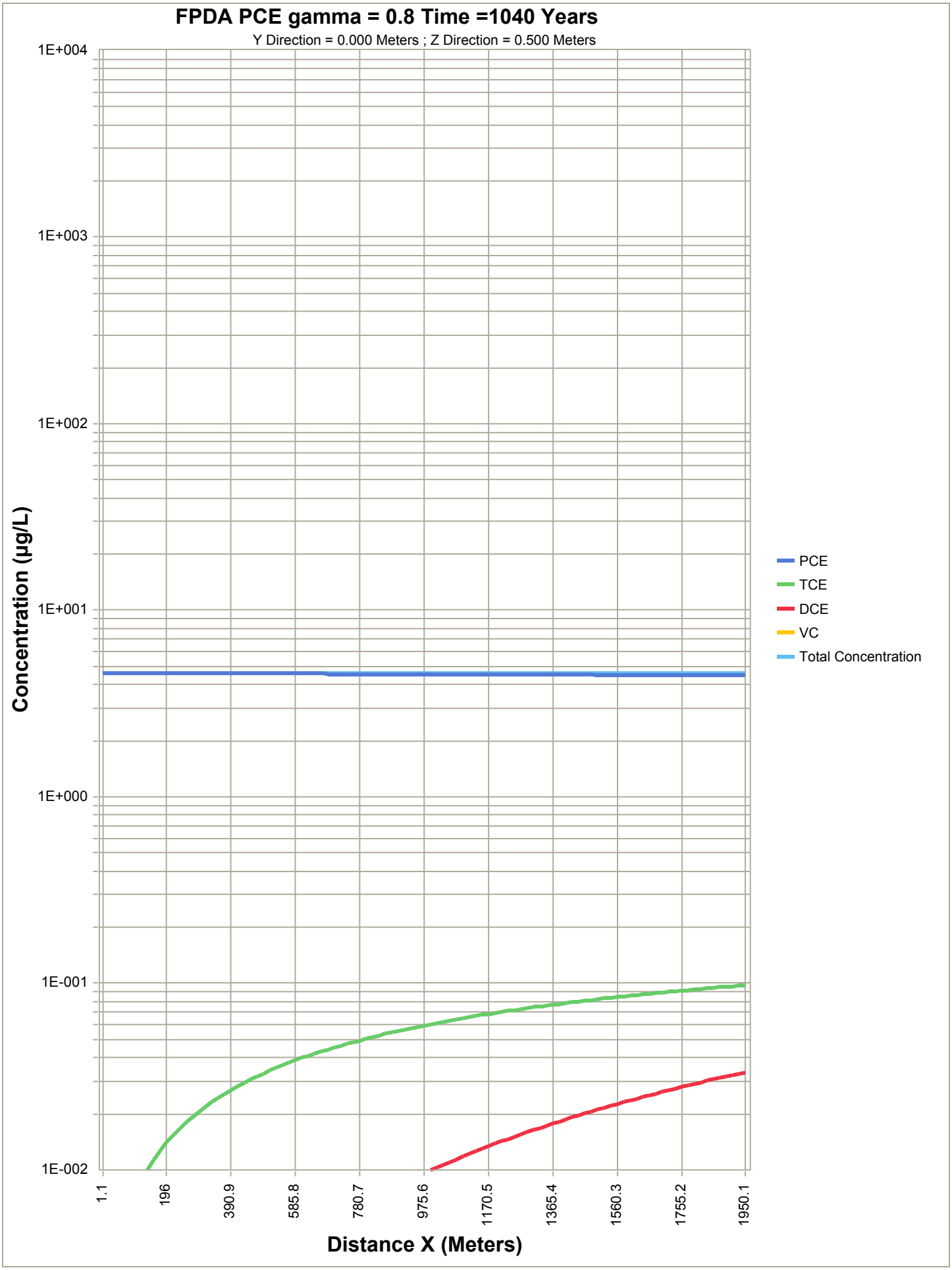

FPDA CT gamma = 0.5 Time =100.000 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
1.1
196
390.9
585.8
780.7
975.6
1170.5
1365.4
1560.3
1755.2
1950.1
Distance X (Meters)
Carbon Tetrachloride
Chloroform
Methylene Chloride
Methyl Chloride
Total Concentration


FPDA CT gamma = 0.8 Time =186.000 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
1.1
196
390.9
585.8
780.7
975.6
1170.5
1365.4
1560.3
1755.2
1950.1
Distance X (Meters)
Carbon Tetrachloride
Chloroform
Methylene Chloride
Methyl Chloride
Total Concentration


FPDA HCA gamma = 0.5 Time =200 Years
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
Hexachloroethane

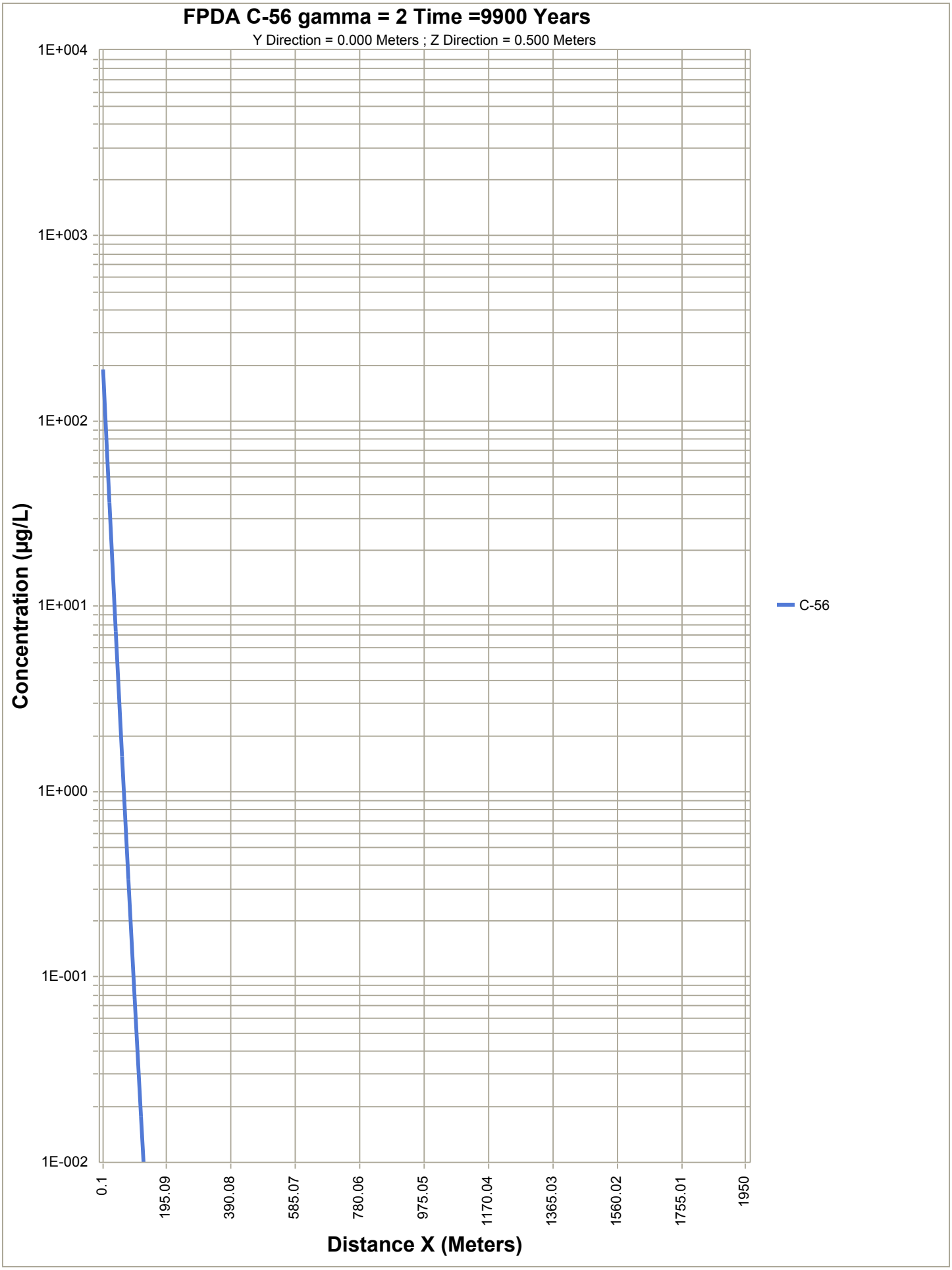

FPDA HCA gamma = 0.8 Time =295 Years
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
Hexachloroethane

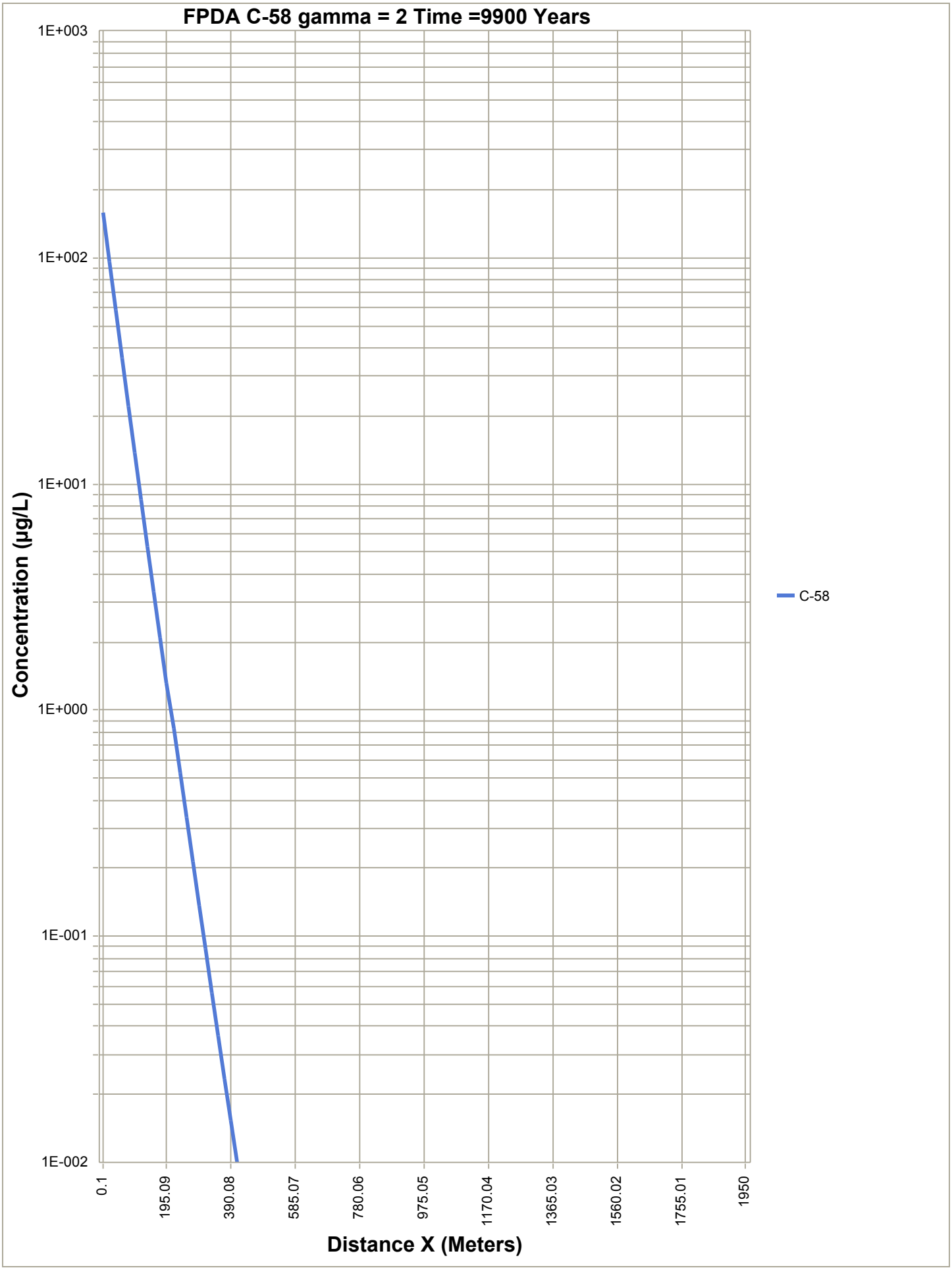

FPDA PCE gamma=0.5 Time =567 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
0.1
97.6
195.1
292.6
390.1
487.6
585.1
682.6
780.1
877.6
975.1
1072.6
1170.1
1267.6
1365.1
1462.6
1560.1
1657.6
1755.1
1852.6
1950.1
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

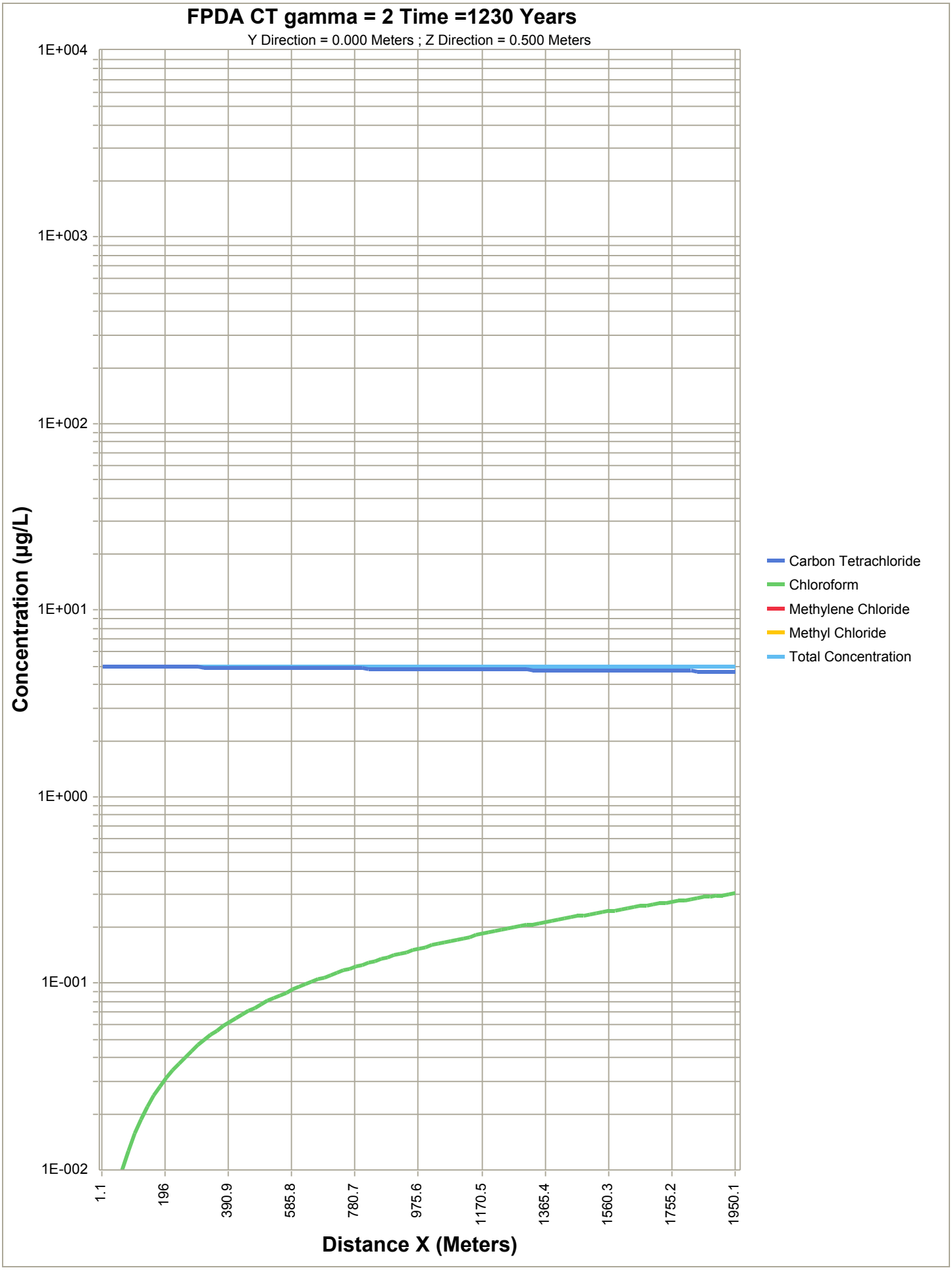

FPDA PCE gamma = 0.8 Time =1040 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
1.1
196
390.9
585.8
780.7
975.6
1170.5
1365.4
1560.3
1755.2
1950.1
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

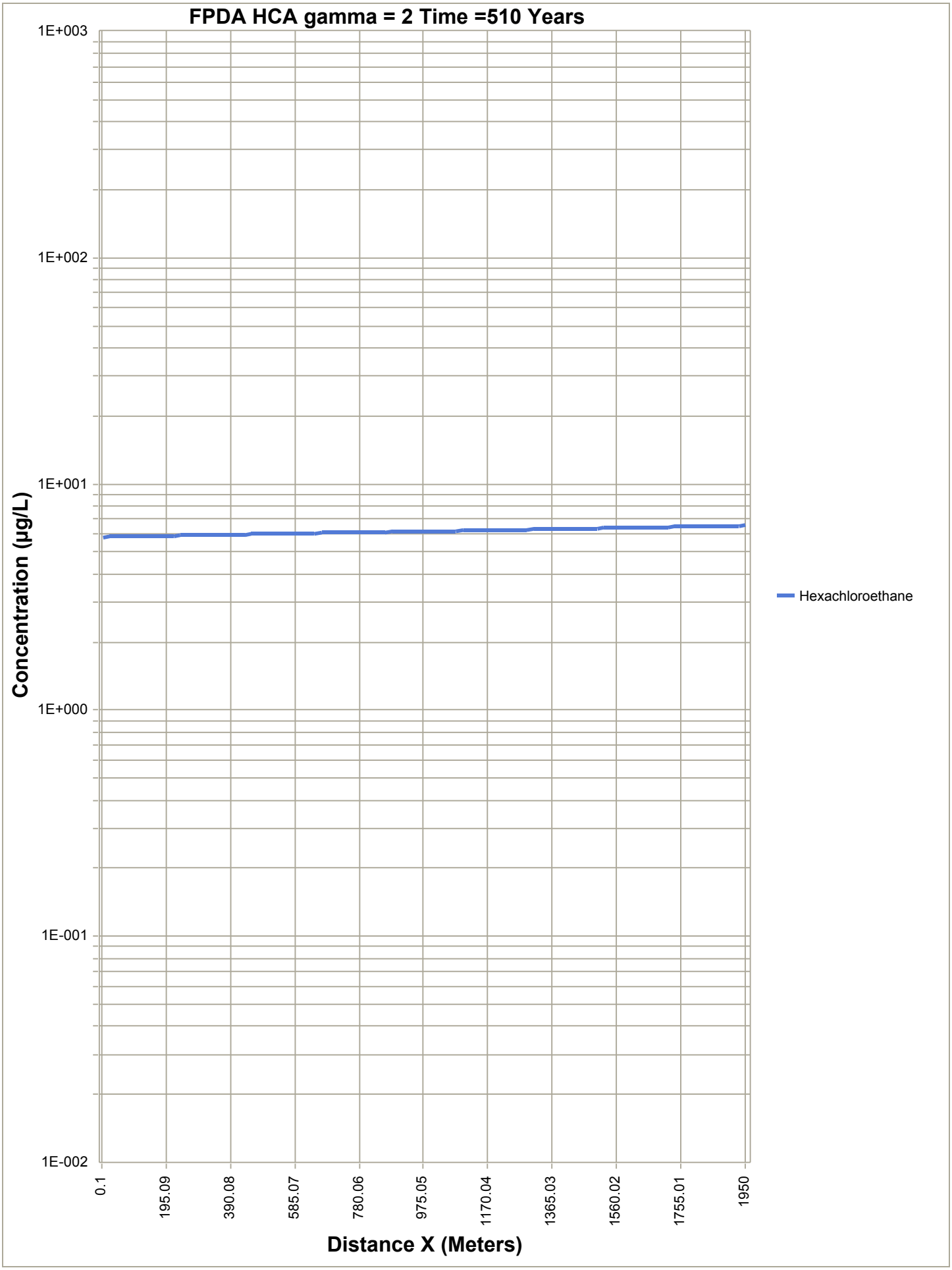
M6

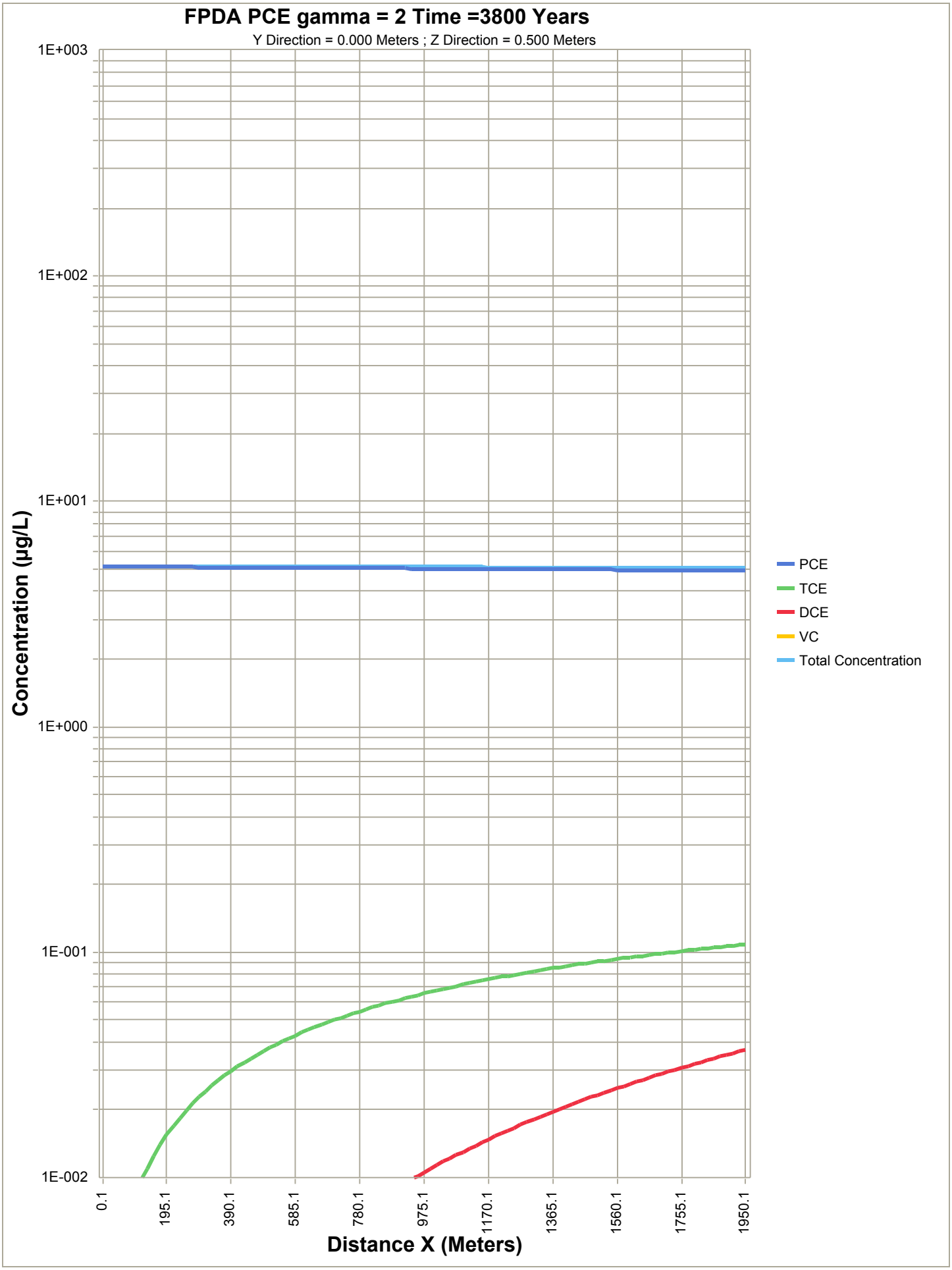
FPDA Source Area
Gamma = 2


FPDA C-56 gamma = 2 Time =9900 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
C-56


FPDA C-58 gamma = 2 Time =9900 Years
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
C-58

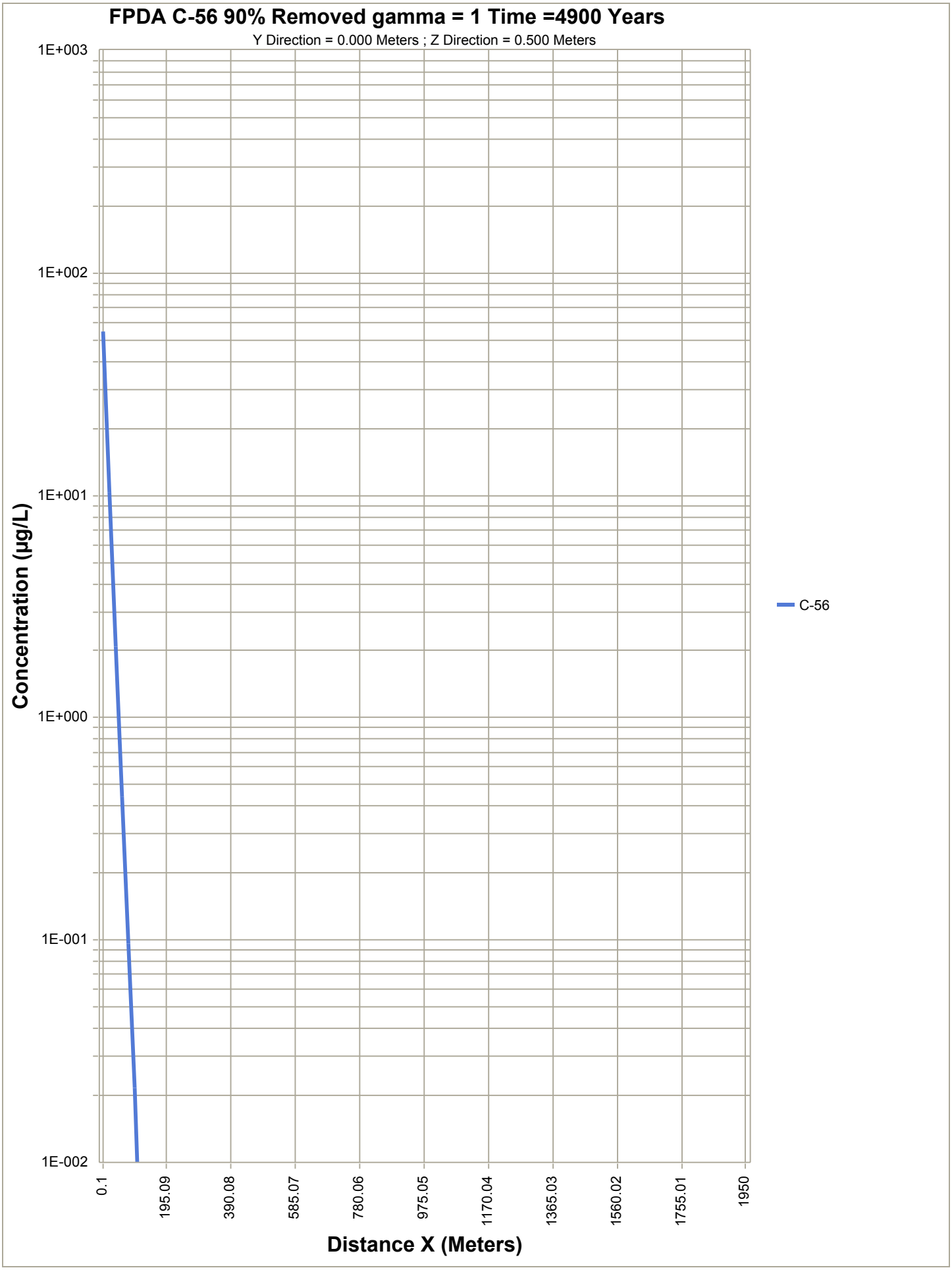

FPDA CT gamma = 2 Time =1230 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
1.1
196
390.9
585.8
780.7
975.6
1170.5
1365.4
1560.3
1755.2
1950.1
Distance X (Meters)
Carbon Tetrachloride
Chloroform
Methylene Chloride
Methyl Chloride
Total Concentration

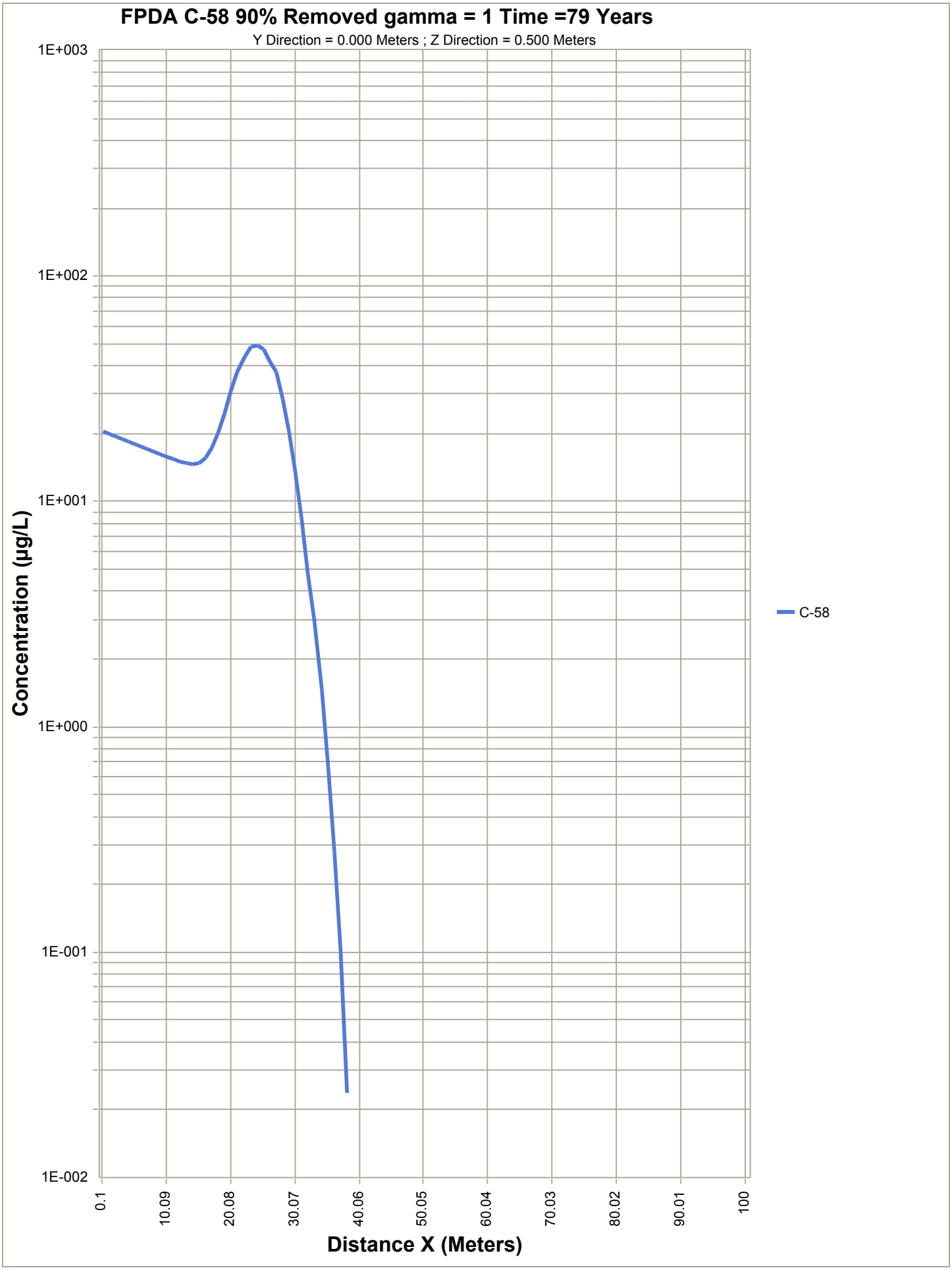

FPDA HCA gamma = 2 Time =510 Years
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
Hexachloroethane

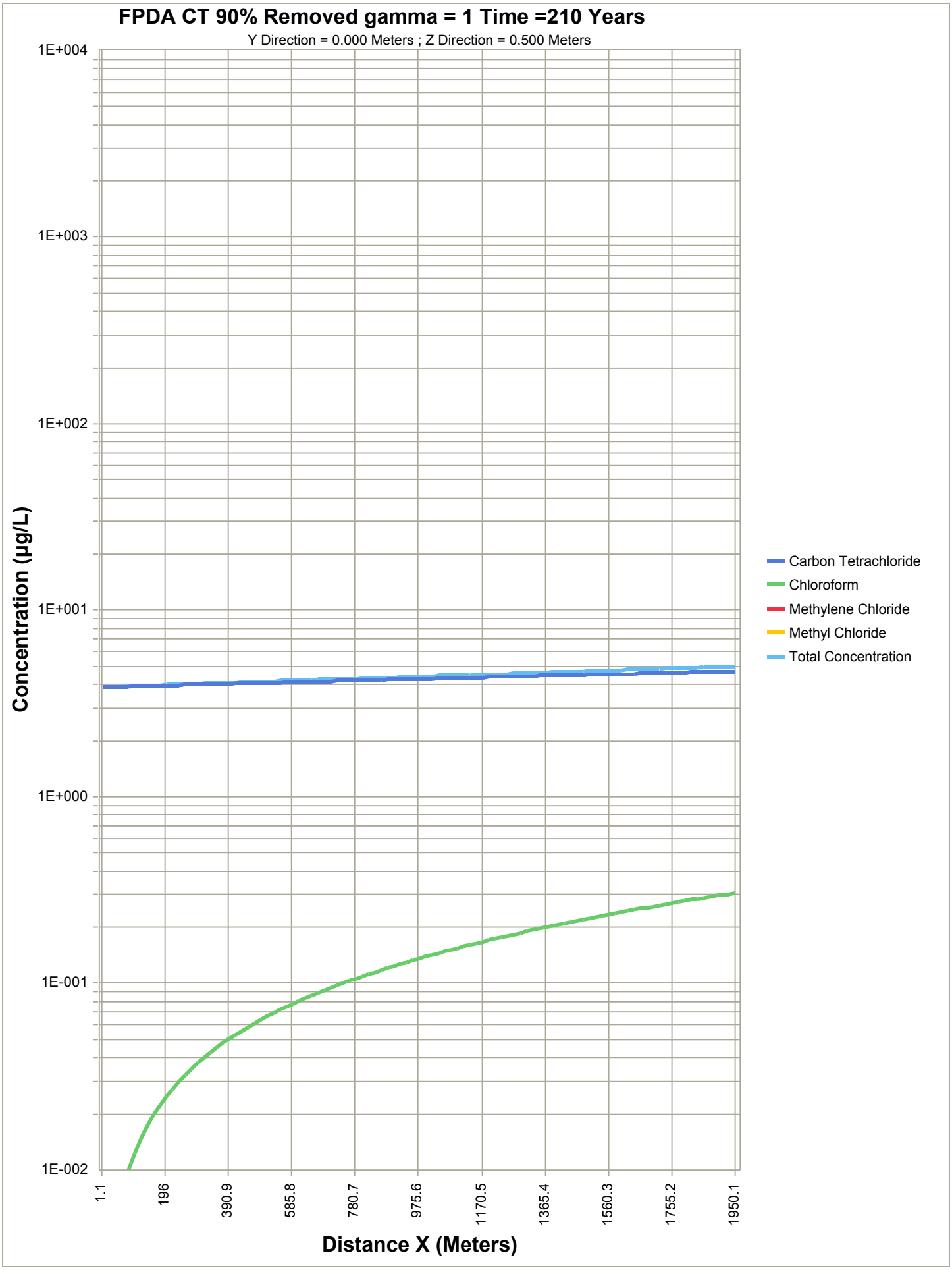

FPDA PCE gamma = 2 Time =3800 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.1
390.1
585.1
780.1
975.1
1170.1
1365.1
1560.1
1755.1
1950.1
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

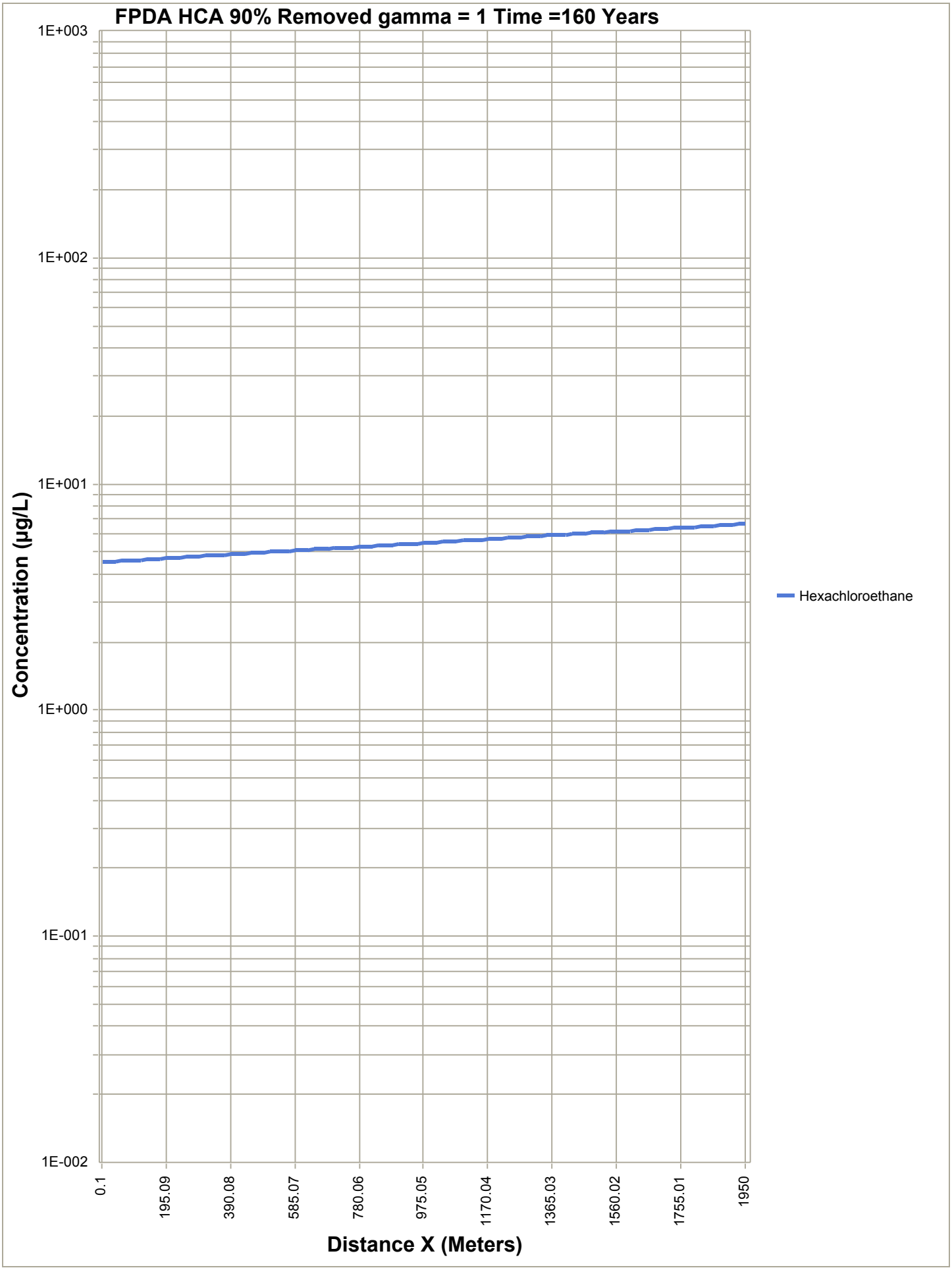
M7

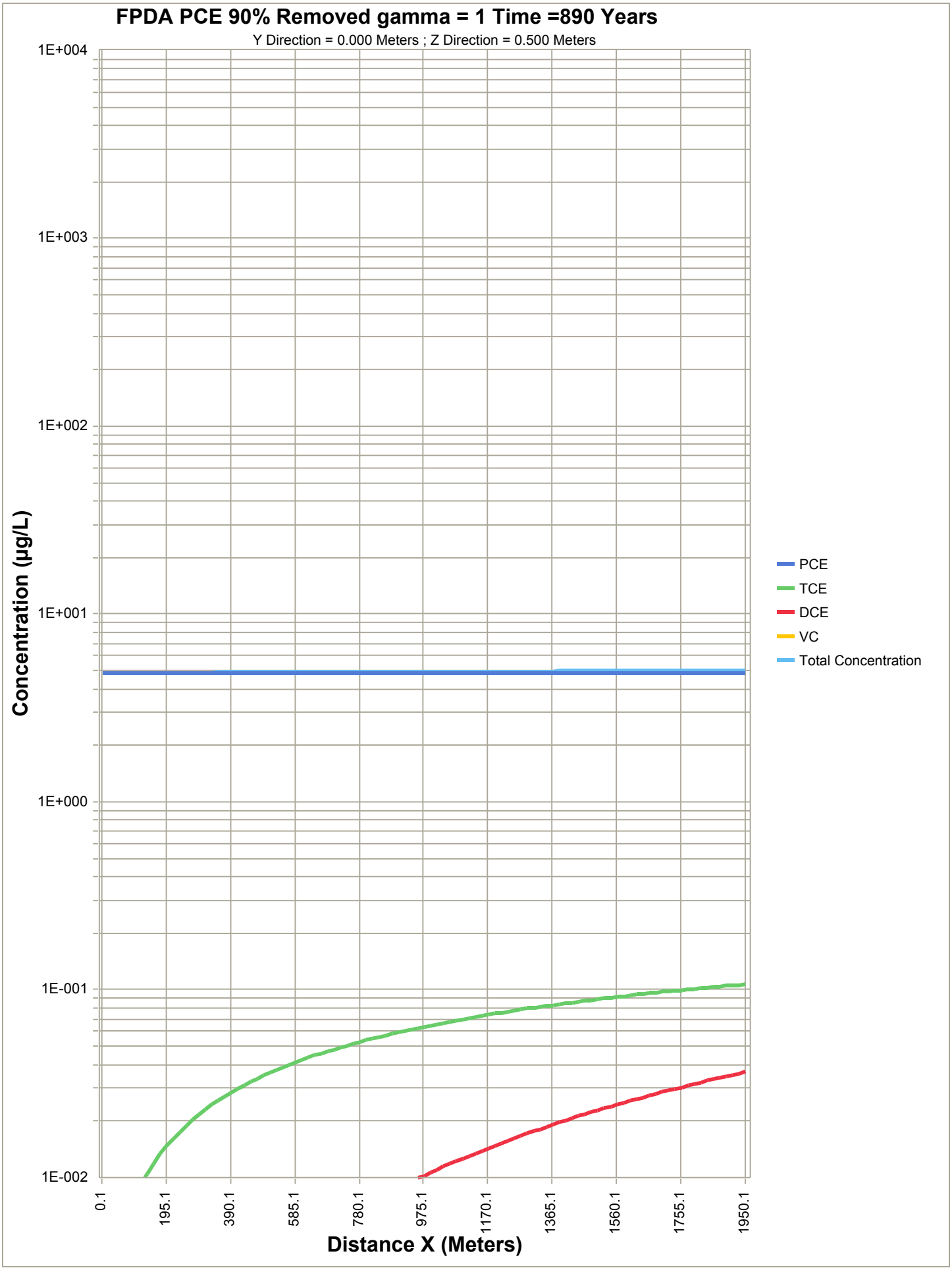
FPDA Source Area
90% Source Removal


FPDA C-56 90% Removed gamma = 1 Time =4900 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
C-56


FPDA C-58 90% Removed gamma = 1 Time =79 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
10.09
20.08
30.07
40.06
50.05
60.04
70.03
80.02
90.01
100
Distance X (Meters)
C-58

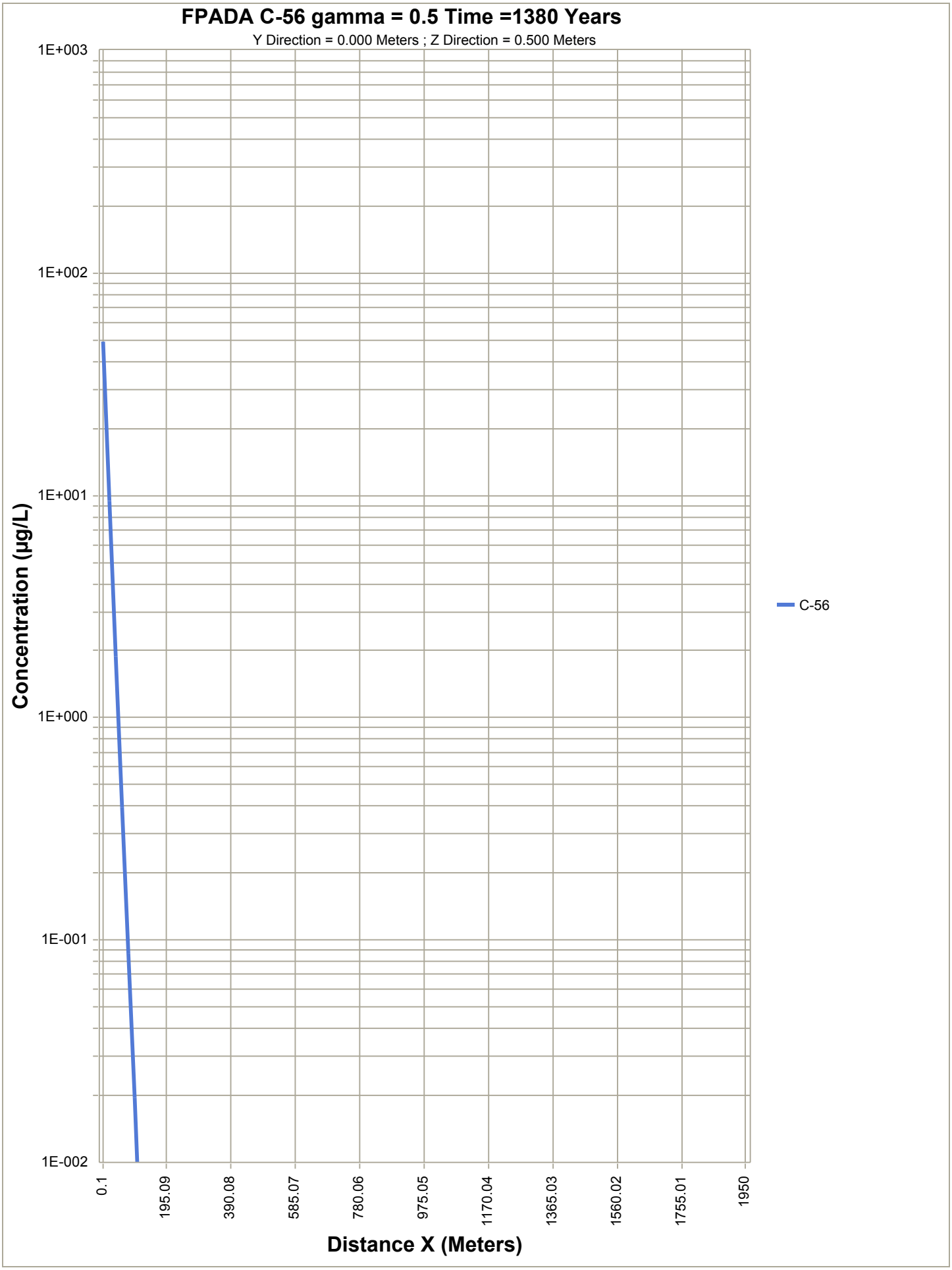

FPDA CT 90% Removed gamma = 1 Time =210 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
1.1
196
390.9
585.8
780.7
975.6
1170.5
1365.4
1560.3
1755.2
1950.1
Distance X (Meters)
Carbon Tetrachloride
Chloroform
Methylene Chloride
Methyl Chloride
Total Concentration

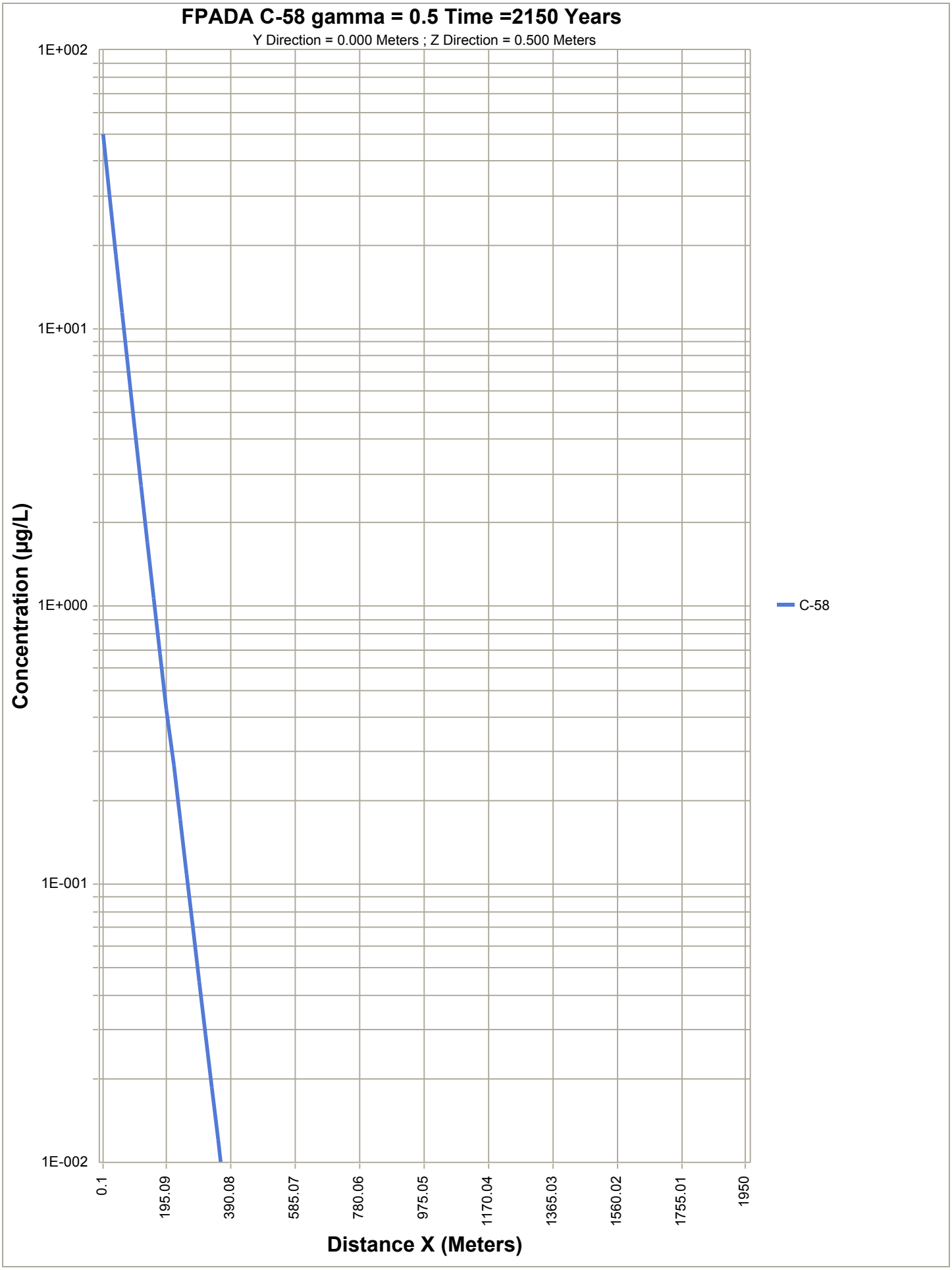

FPDA HCA 90% Removed gamma = 1 Time =160 Years
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
Hexachloroethane


FPDA PCE 90% Removed gamma = 1 Time =890 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
0.1
195.1
390.1
585.1
780.1
975.1
1170.1
1365.1
1560.1
1755.1
1950.1
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

M8

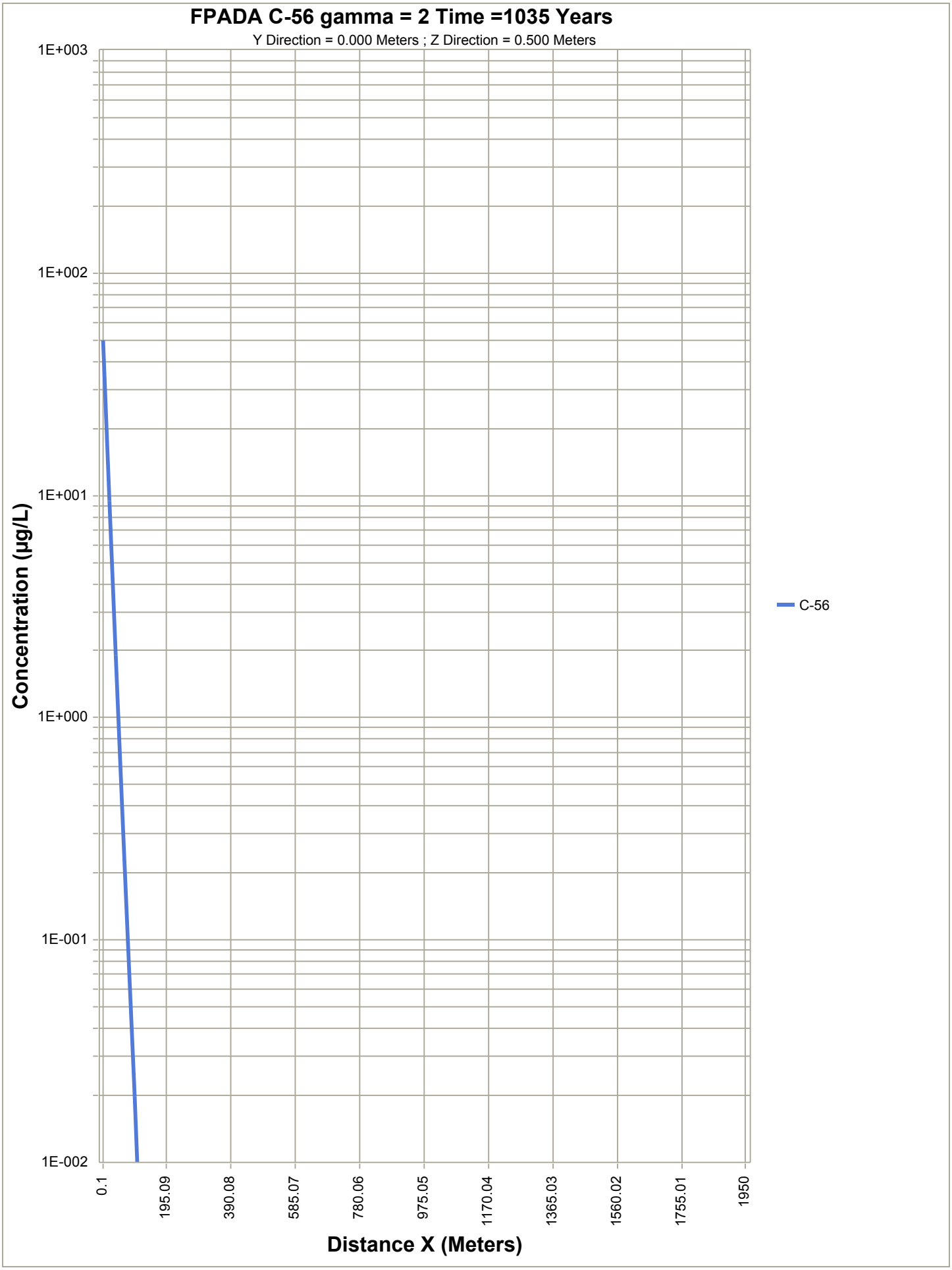
FEPA Source Area
Gamma = 0.5

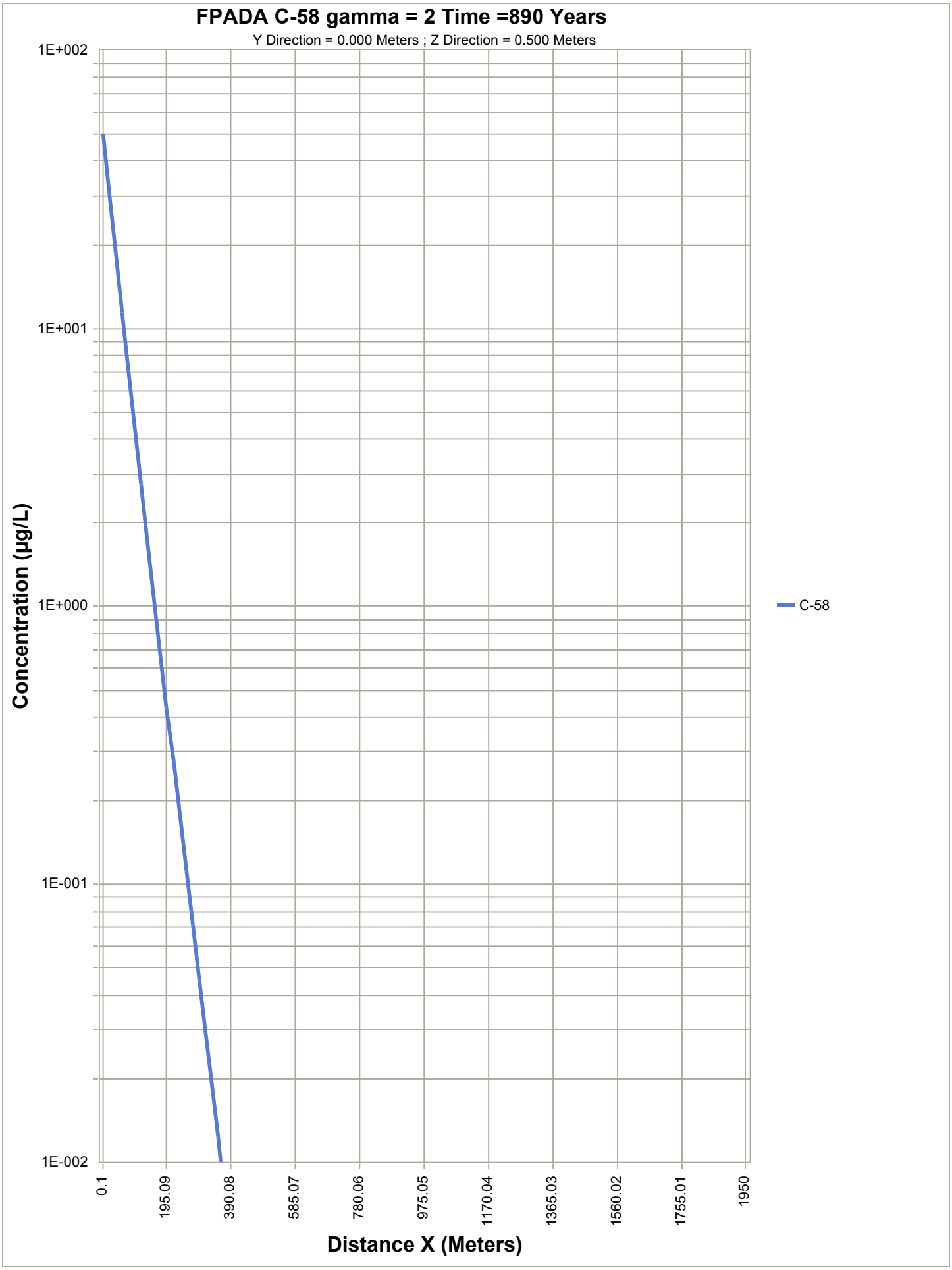

FPADA C-56 gamma = 0.5 Time =1380 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
C-56


FPADA C-58 gamma = 0.5 Time =2150 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
C-58

M9

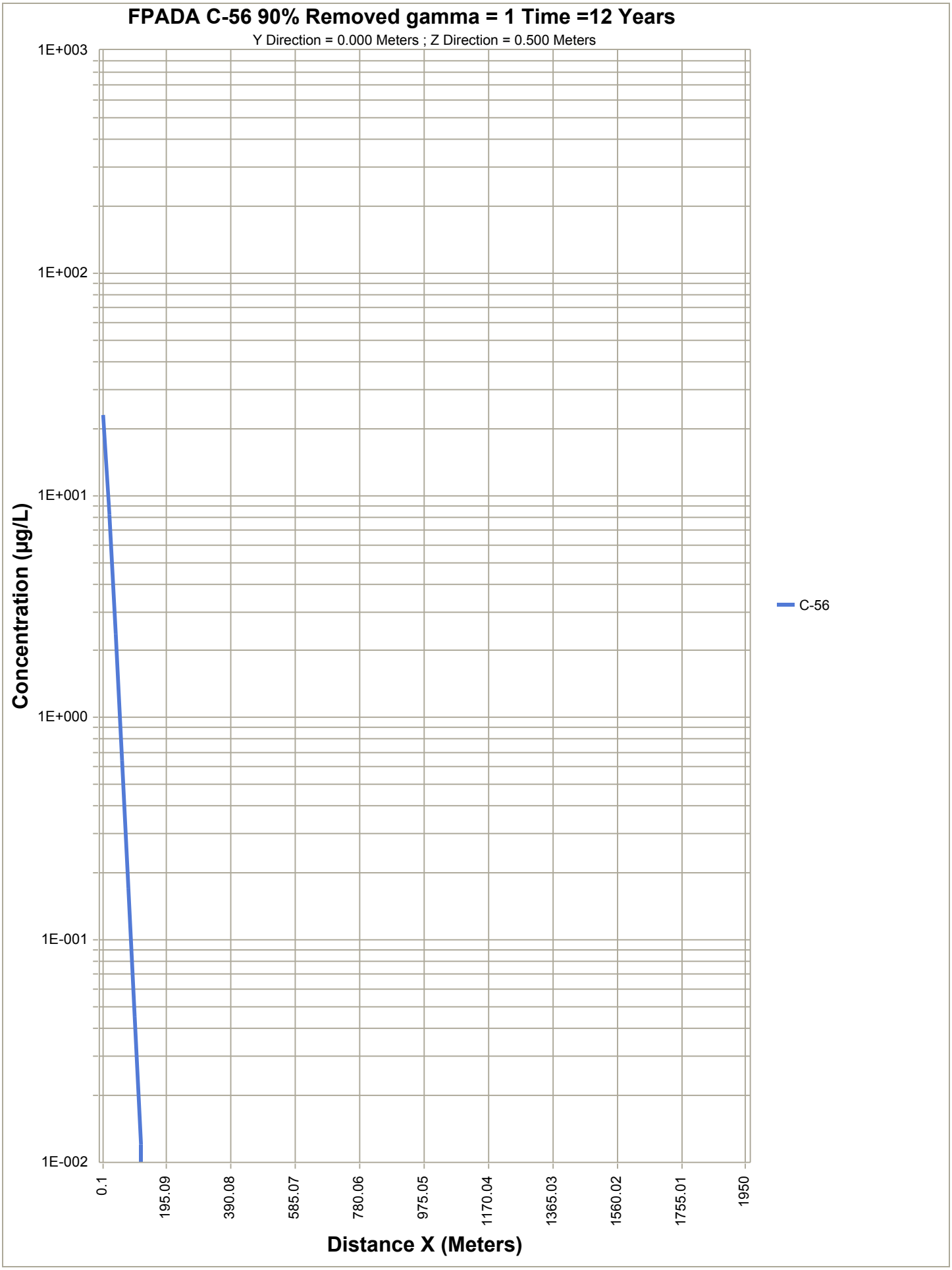
FPADA Source Area
Gamma = 2

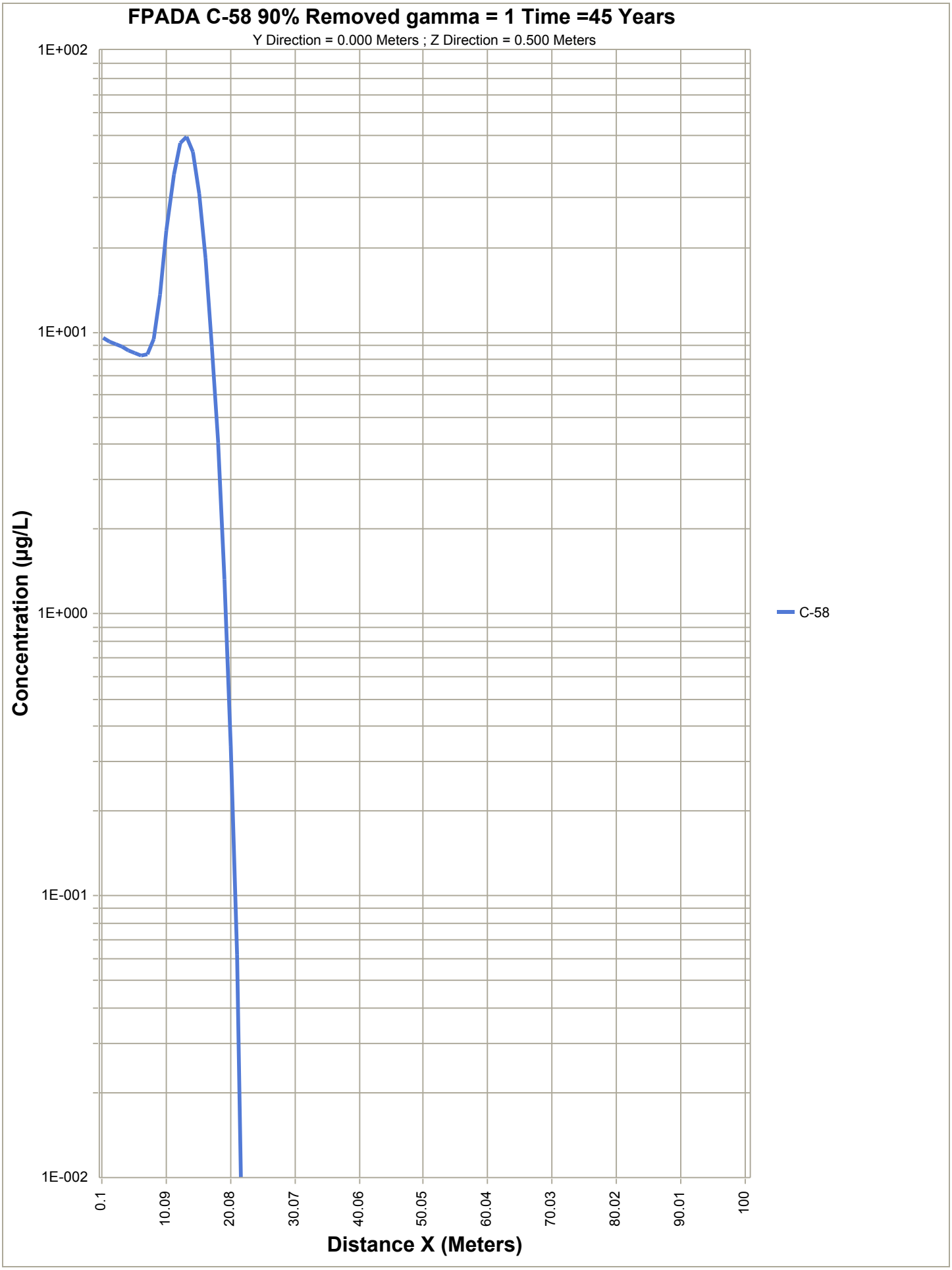

FPADA C-56 gamma = 2 Time =1035 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
C-56


FPADA C-58 gamma = 2 Time =890 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
C-58

M10

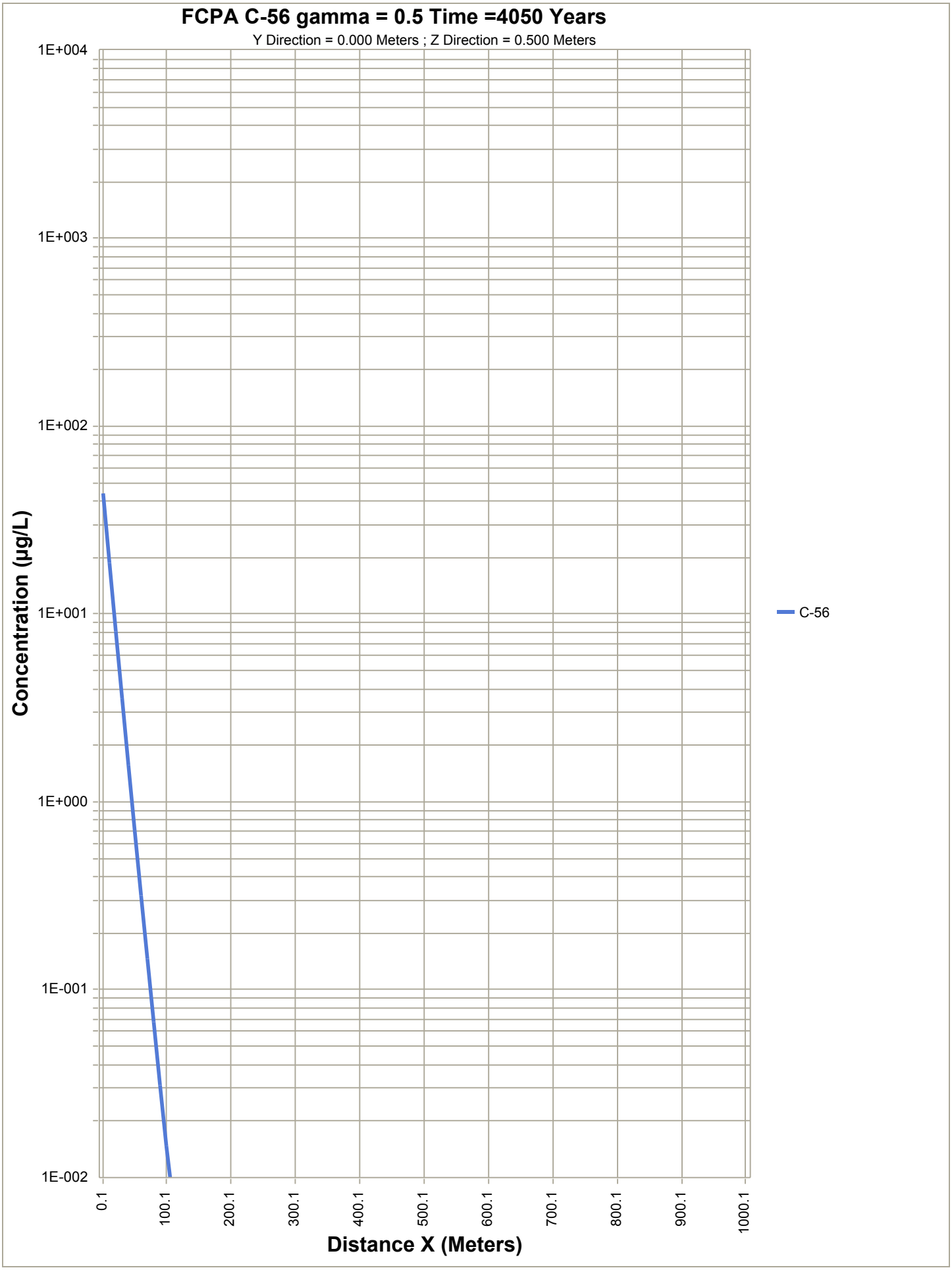
FPADA Source Area
90% Source Removal

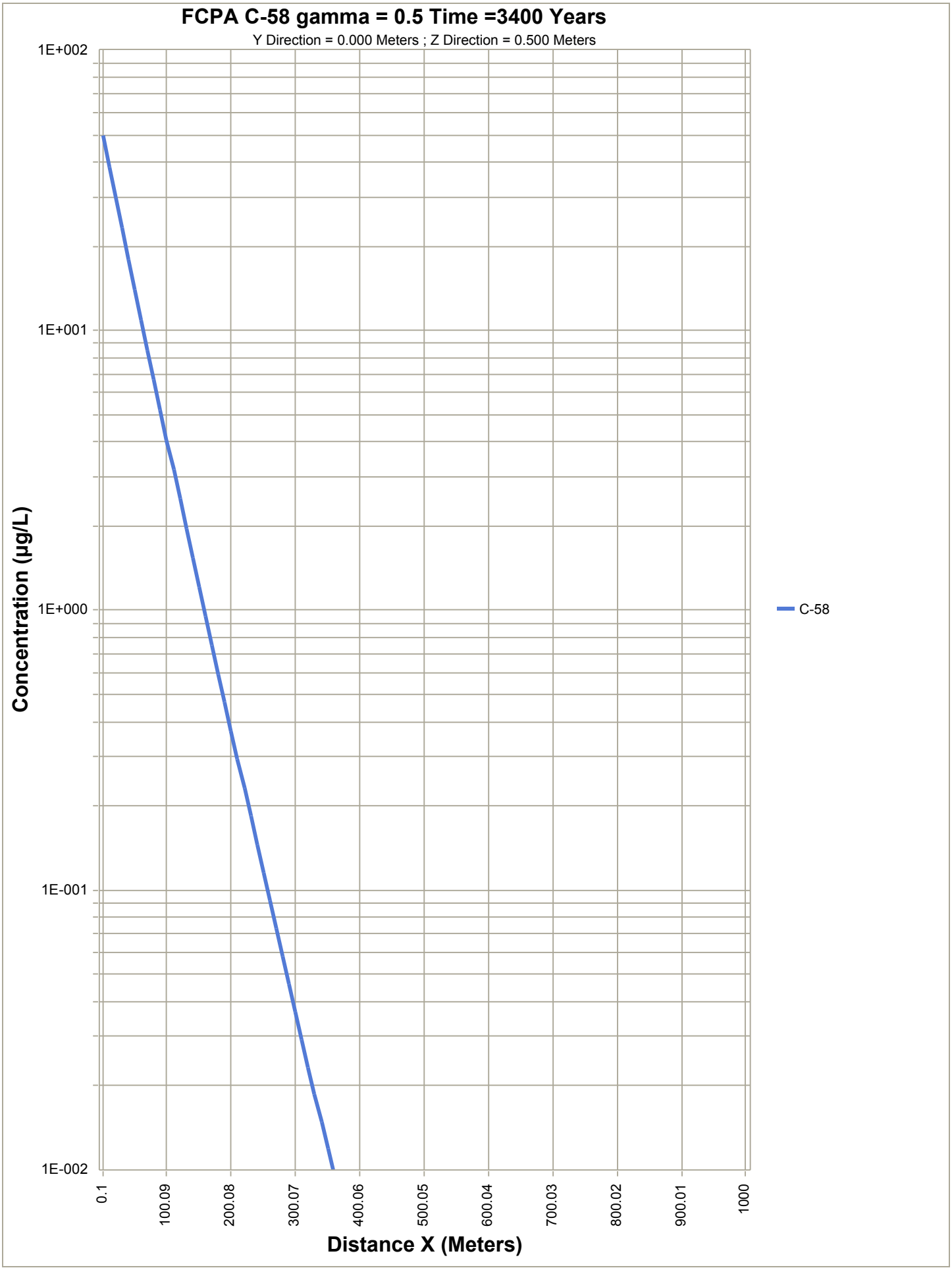

FPADA C-56 90% Removed gamma = 1 Time =12 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
195.09
390.08
585.07
780.06
975.05
1170.04
1365.03
1560.02
1755.01
1950
Distance X (Meters)
C-56

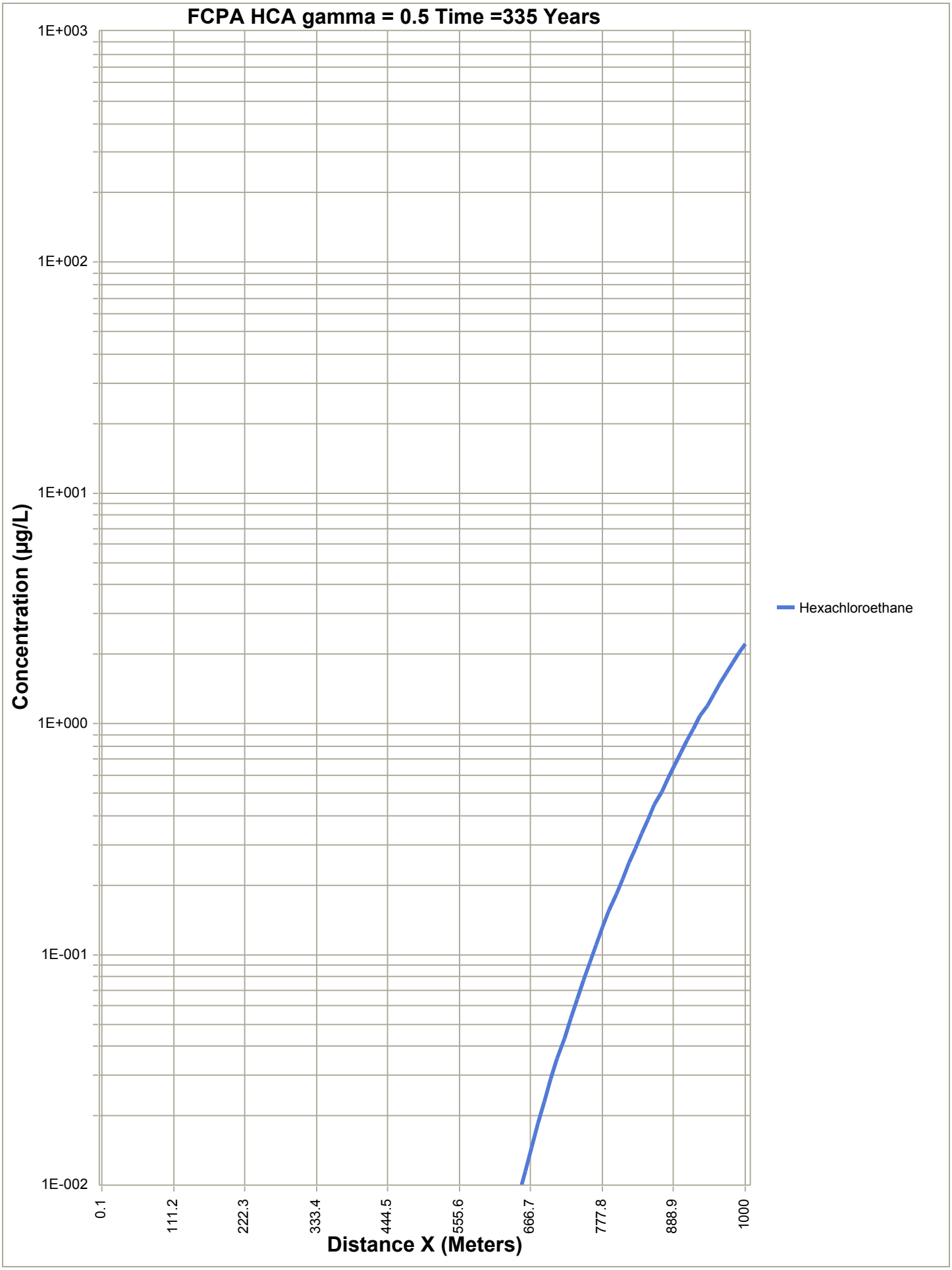

FPADA C-58 90% Removed gamma = 1 Time =45 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
10.09
20.08
30.07
40.06
50.05
60.04
70.03
80.02
90.01
100
Distance X (Meters)
C-58

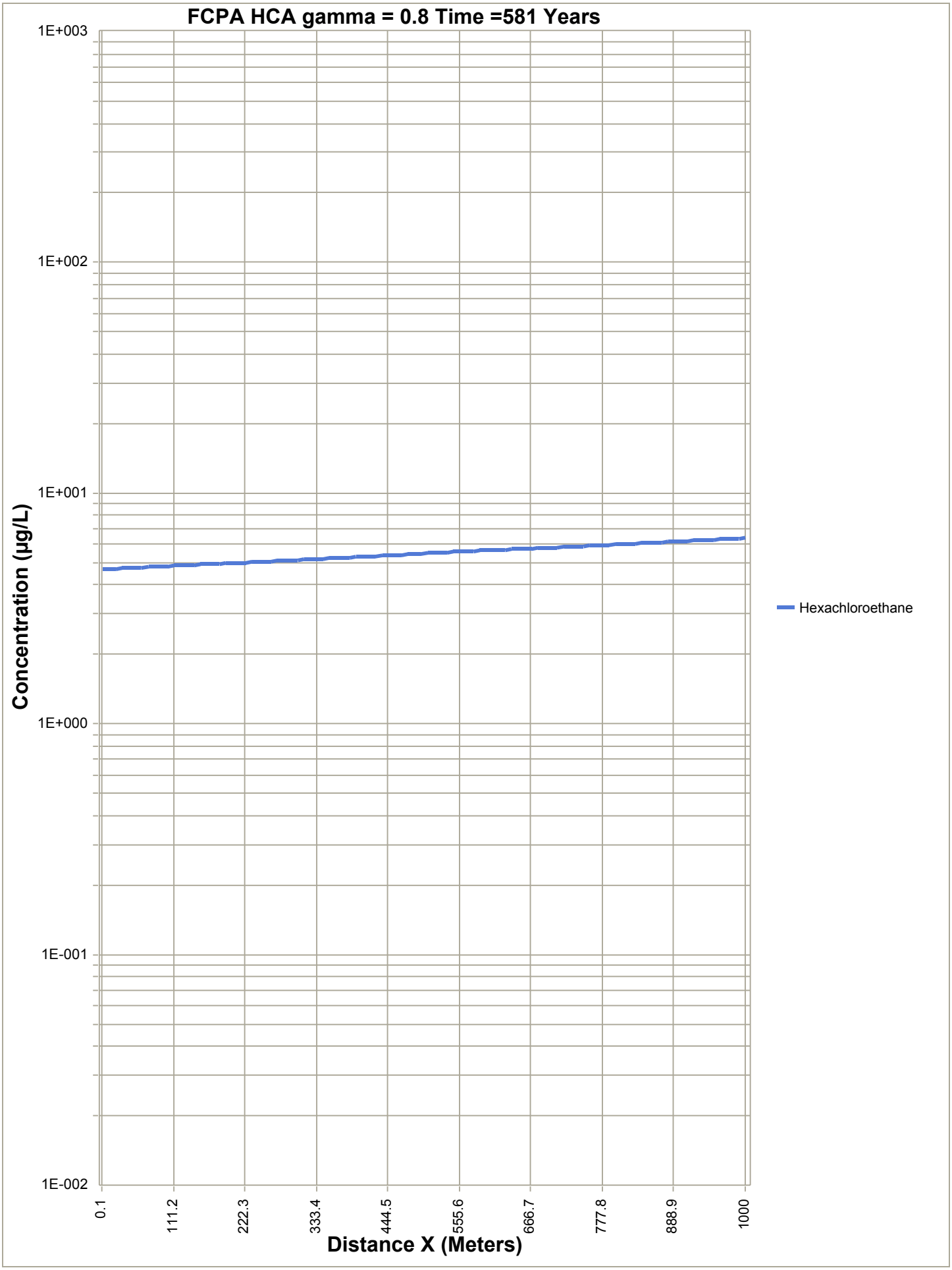
M11

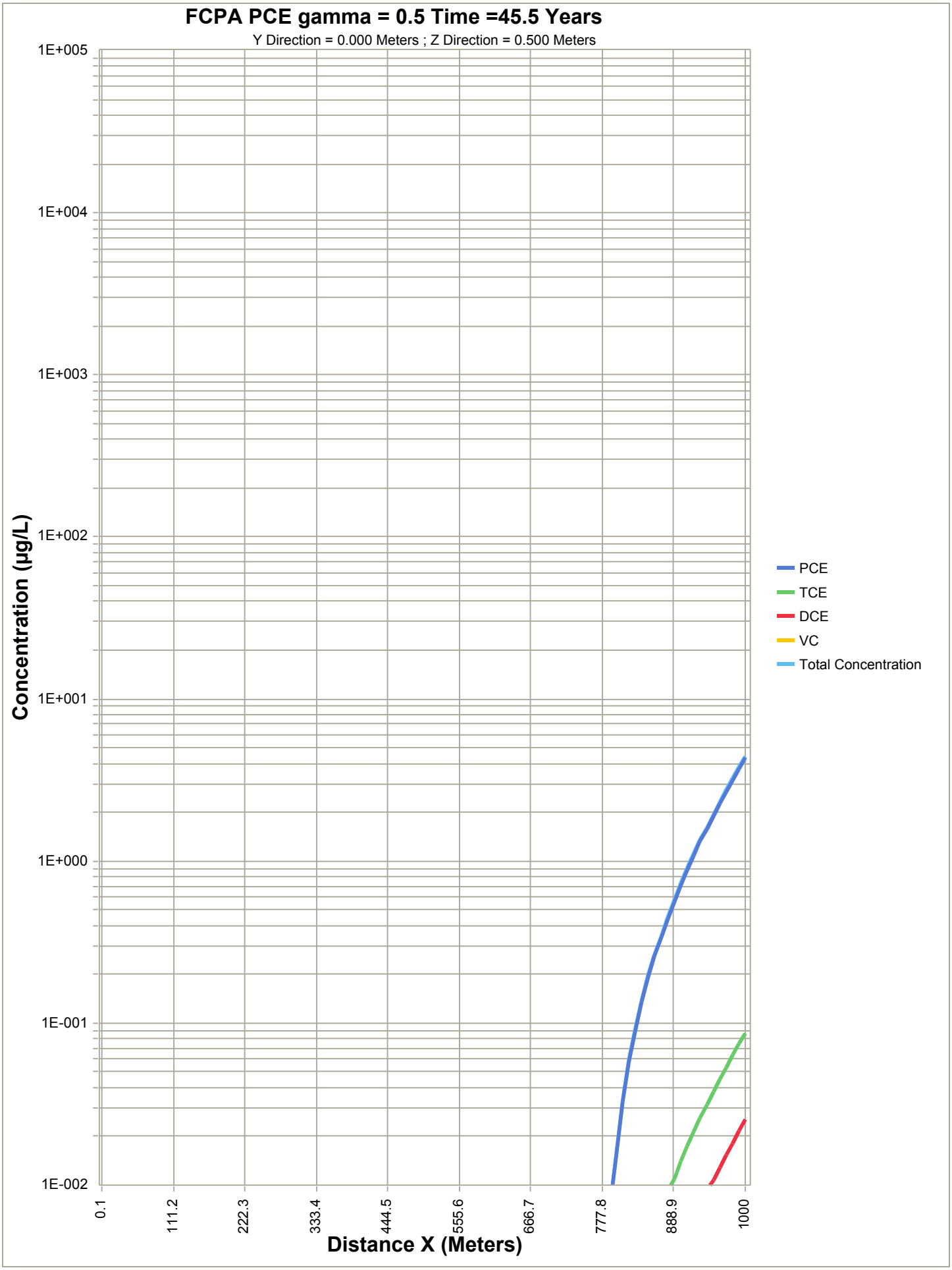
FCPA Source Area
Gamma = 0.5, 0.8

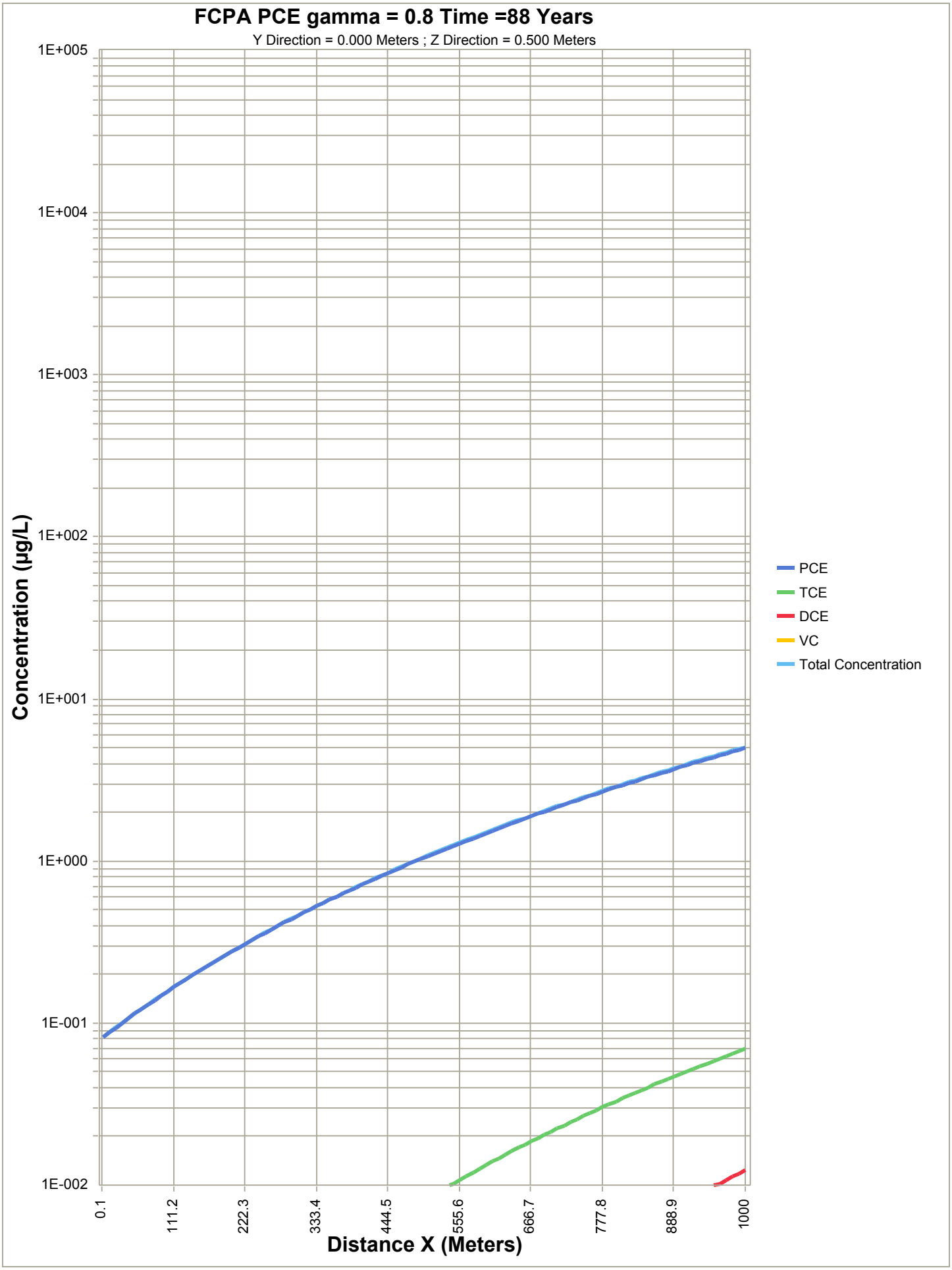

FCPA C-56 gamma = 0.5 Time =4050 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
100.1
200.1
300.1
400.1
500.1
600.1
700.1
800.1
900.1
1000.1
Distance X (Meters)
C-56


FCPA C-58 gamma = 0.5 Time =3400 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
100.09
200.08
300.07
400.06
500.05
600.04
700.03
800.02
900.01
1000
Distance X (Meters)
C-58


FCPA HCA gamma = 0.5 Time =335 Years
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
111.2
222.3
333.4
444.5
555.6
666.7
777.8
888.9
1000
Distance X (Meters)
Hexachloroethane

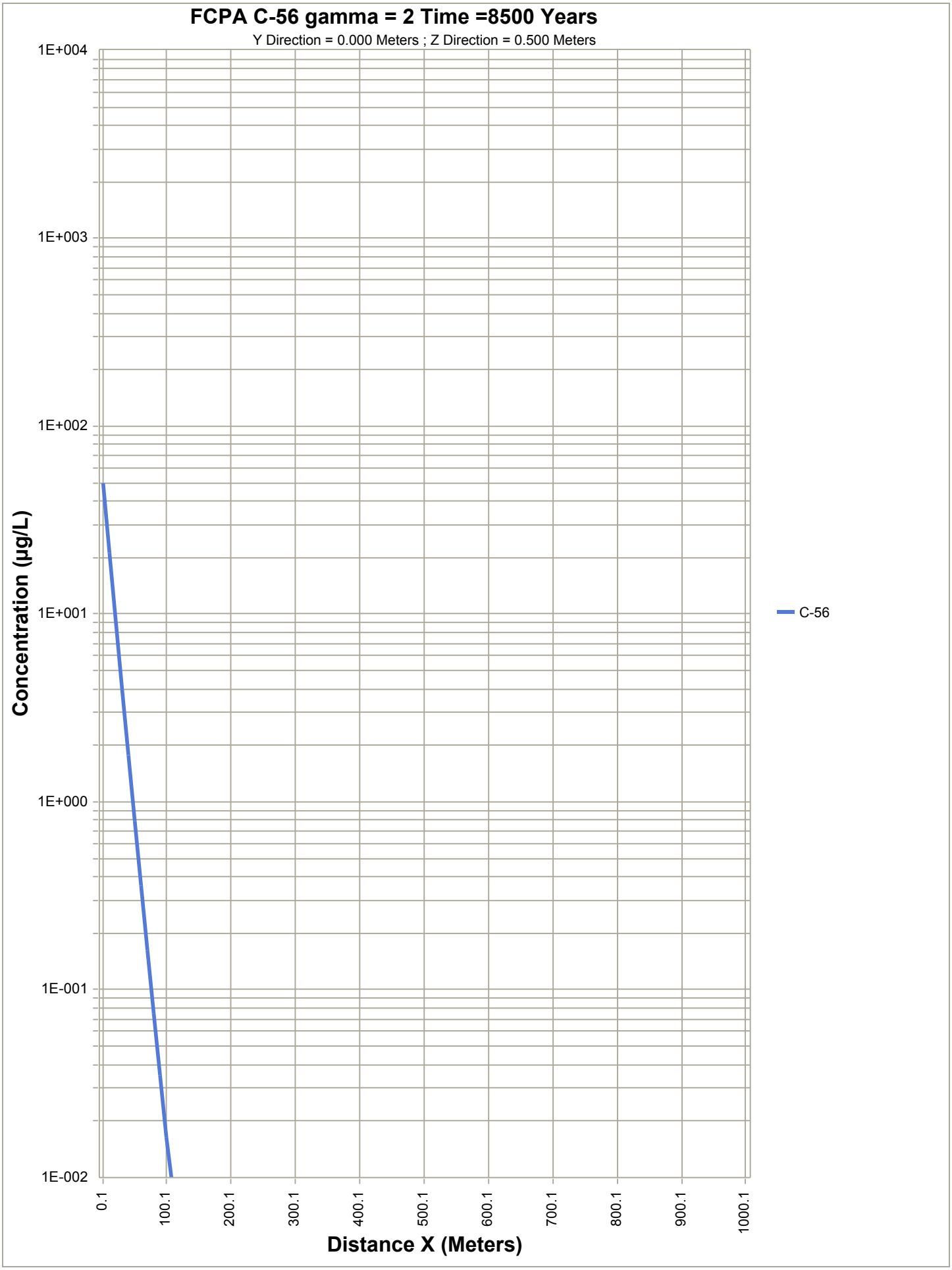

FCPA HCA gamma = 0.8 Time =581 Years
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
111.2
222.3
333.4
444.5
555.6
666.7
777.8
888.9
1000
Distance X (Meters)
Hexachloroethane

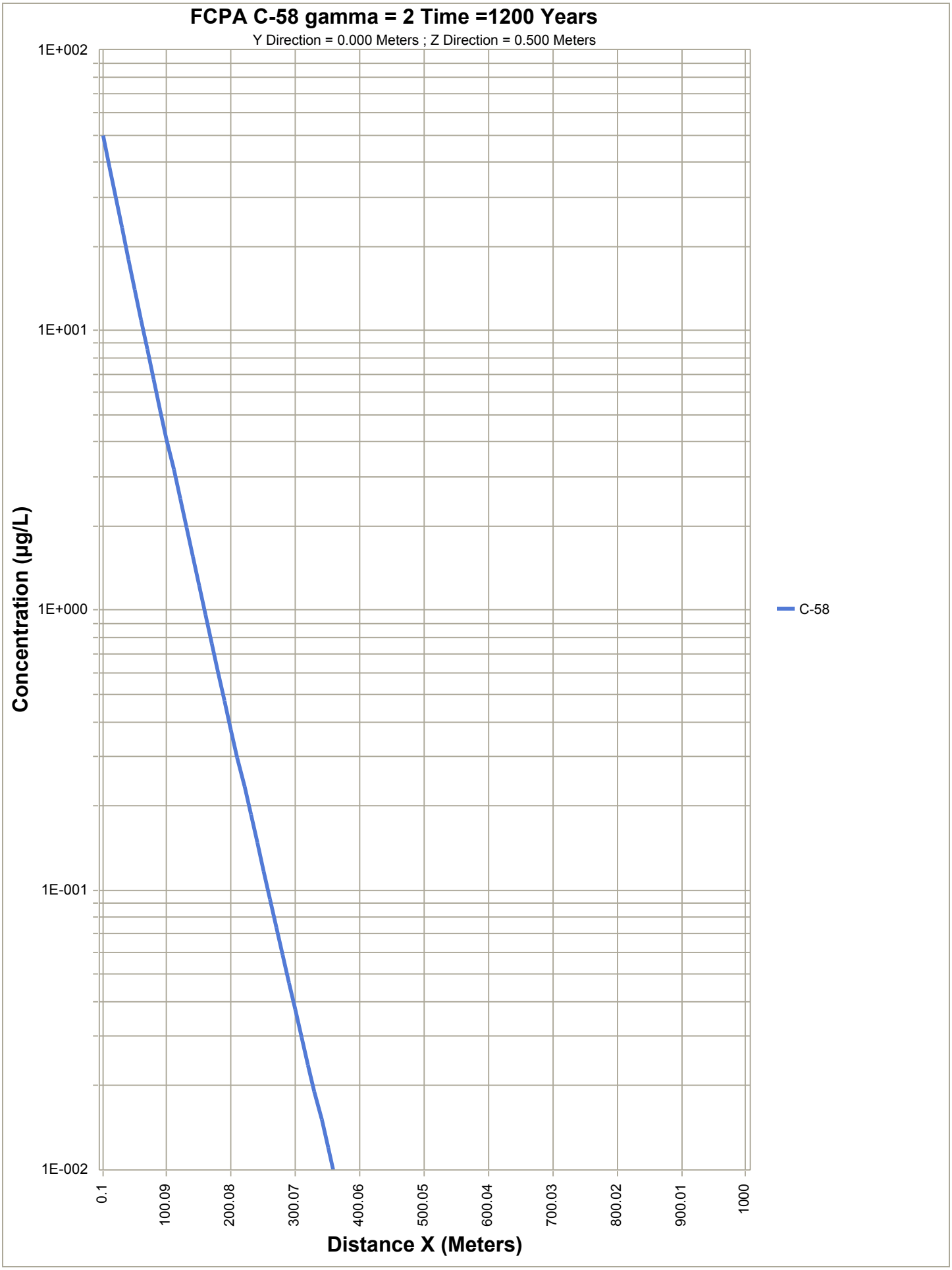

FCPA PCE gamma = 0.5 Time =45.5 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+005
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
0.1
111.2
222.3
333.4
444.5
555.6
666.7
777.8
888.9
1000
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

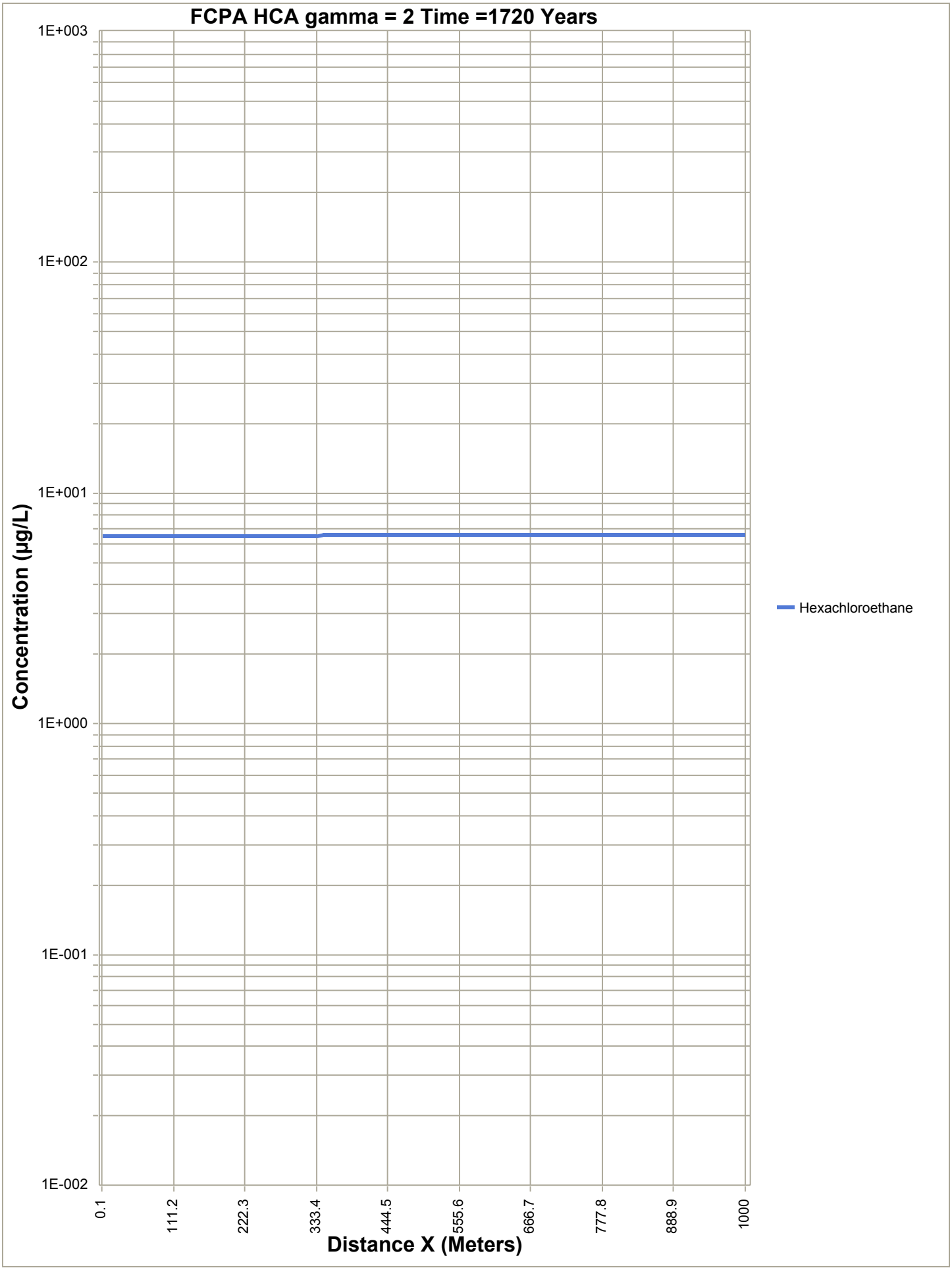

FCPA PCE gamma = 0.8 Time =88 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+005
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
0.1
111.2
222.3
333.4
444.5
555.6
666.7
777.8
888.9
1000
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

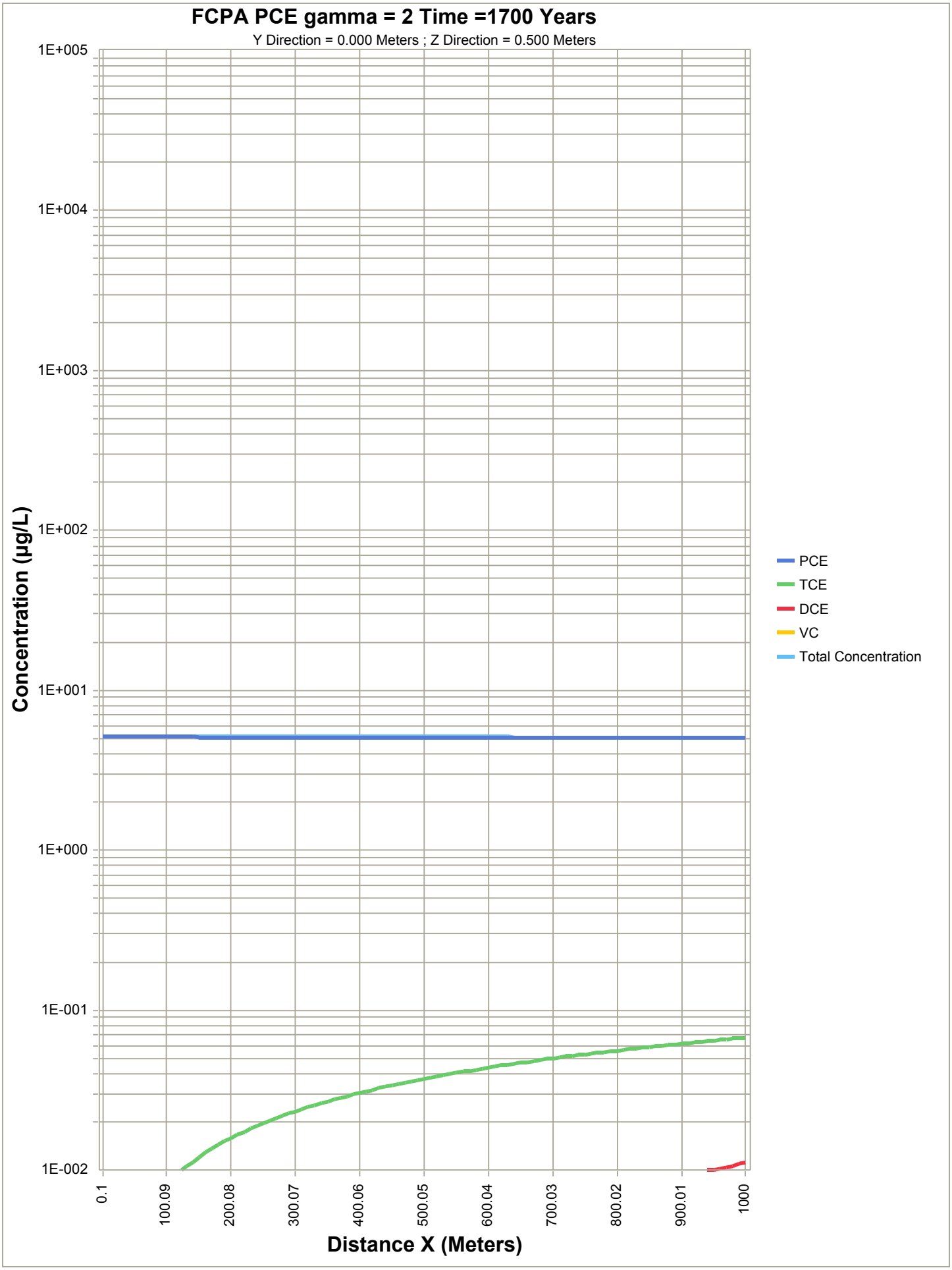
M12

FCPA Source Area
Gamma = 2


FCPA C-56 gamma = 2 Time =8500 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
100.1
200.1
300.1
400.1
500.1
600.1
700.1
800.1
900.1
1000.1
Distance X (Meters)
C-56

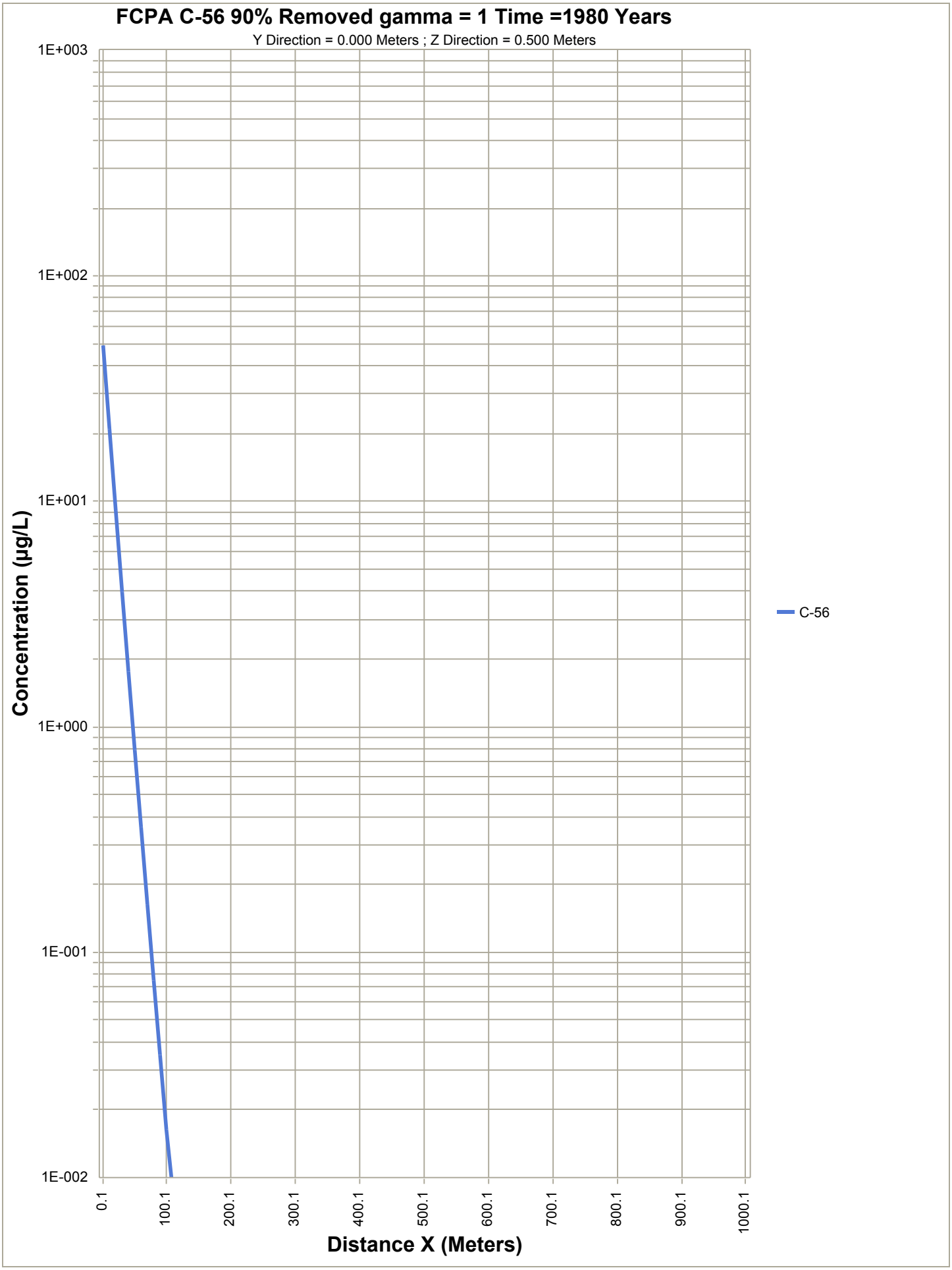

FCPA C-58 gamma = 2 Time =1200 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
100.09
200.08
300.07
400.06
500.05
600.04
700.03
800.02
900.01
1000
Distance X (Meters)
C-58

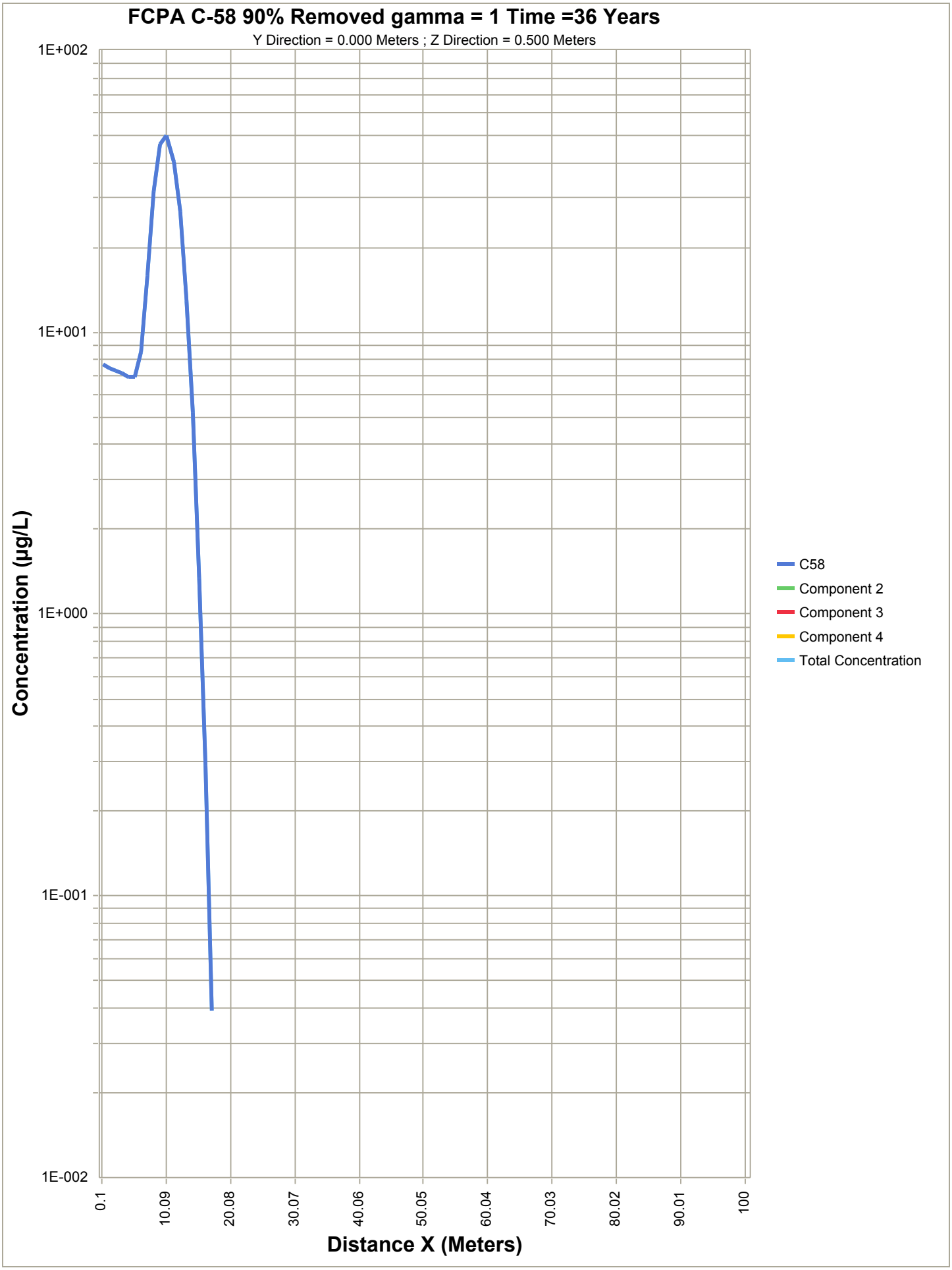

FCPA HCA gamma = 2 Time =1720 Years
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
111.2
222.3
333.4
444.5
555.6
666.7
777.8
888.9
1000
Distance X (Meters)
Hexachloroethane

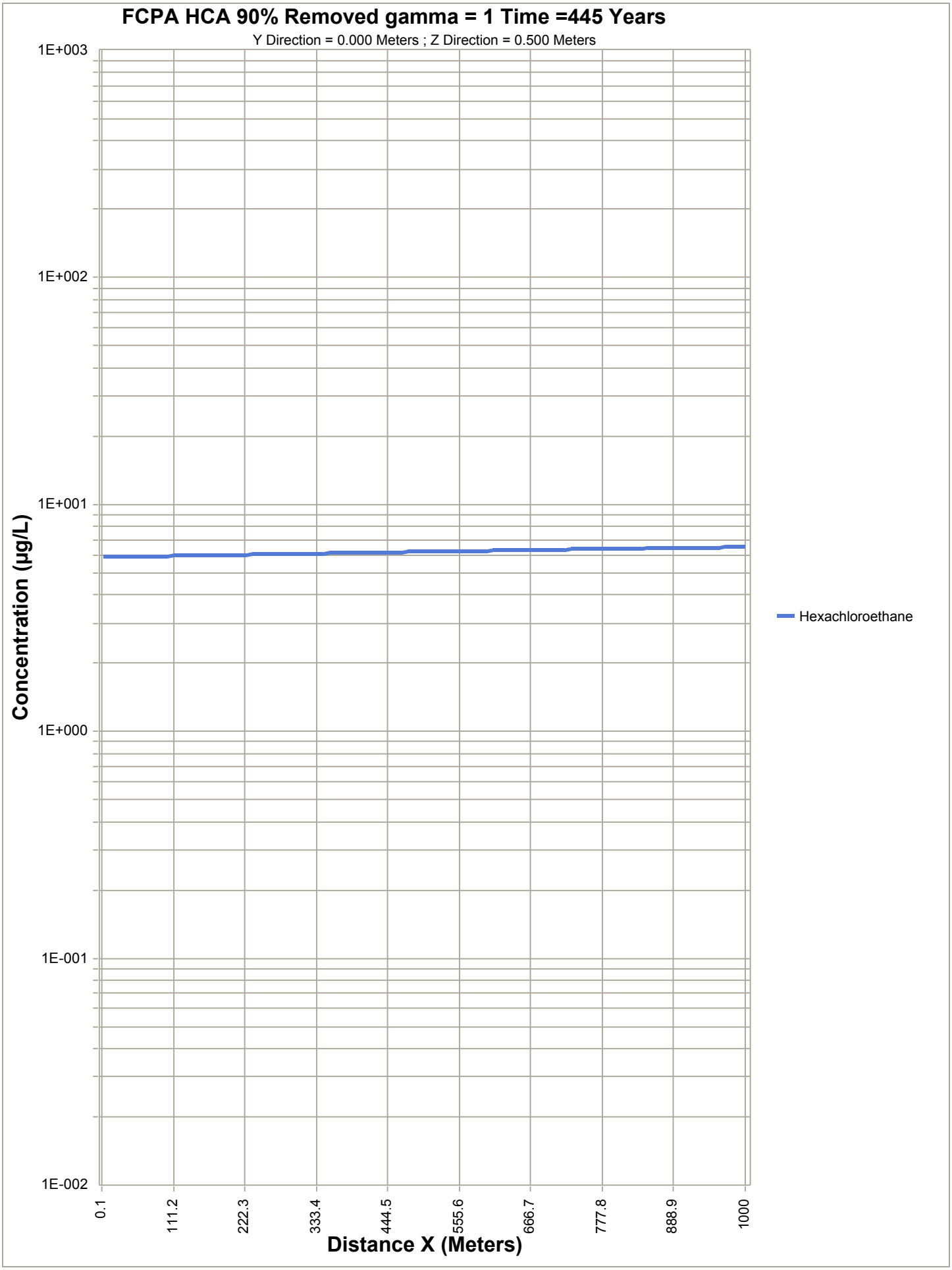

FCPA PCE gamma = 2 Time =1700 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+005
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
0.1
100.09
200.08
300.07
400.06
500.05
600.04
700.03
800.02
900.01
1000
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

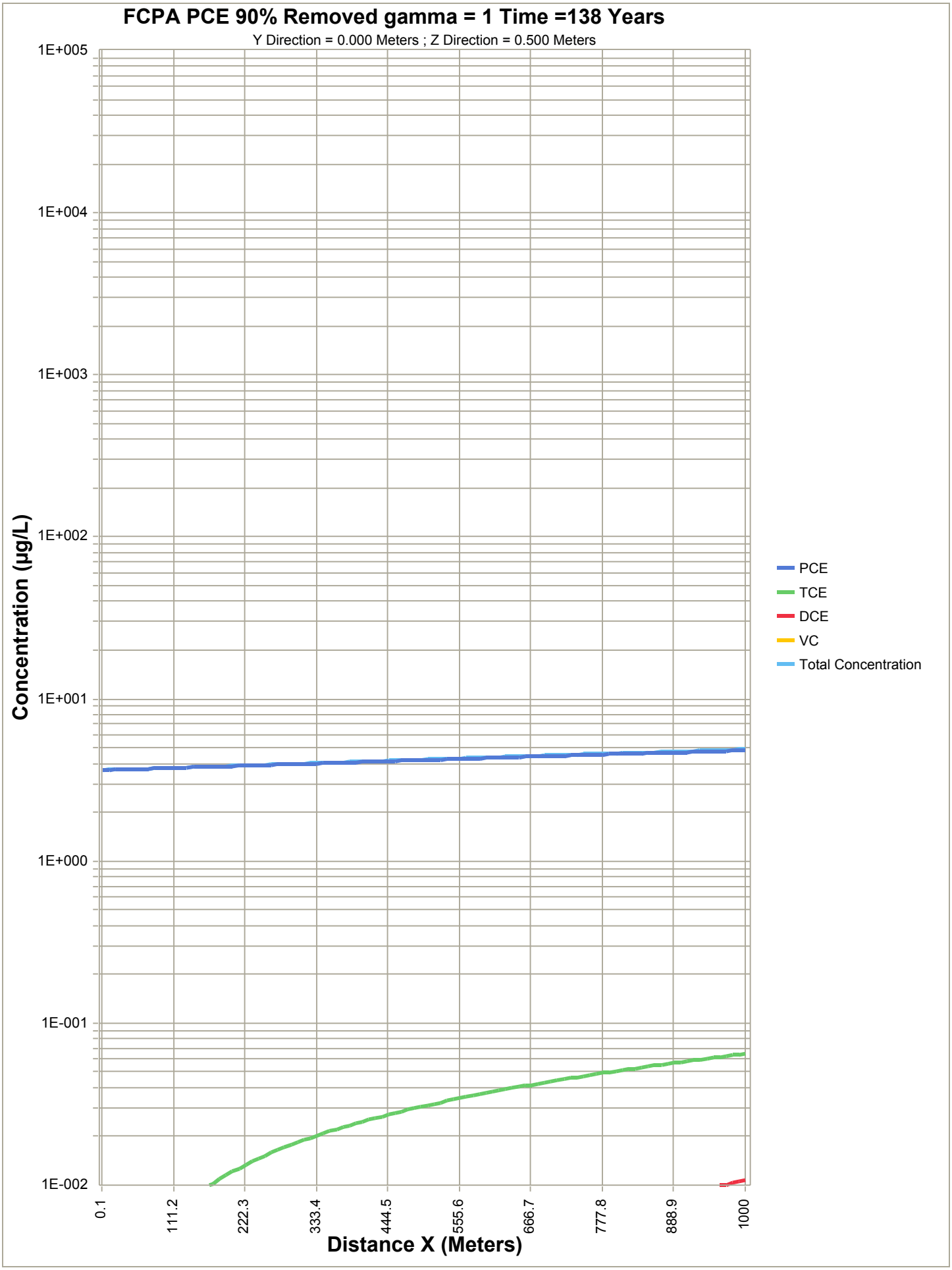
M13

FCPA Source Area
90% Source Removal


FCPA C-56 90% Removed gamma = 1 Time =1980 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
100.1
200.1
300.1
400.1
500.1
600.1
700.1
800.1
900.1
1000.1
Distance X (Meters)
C-56

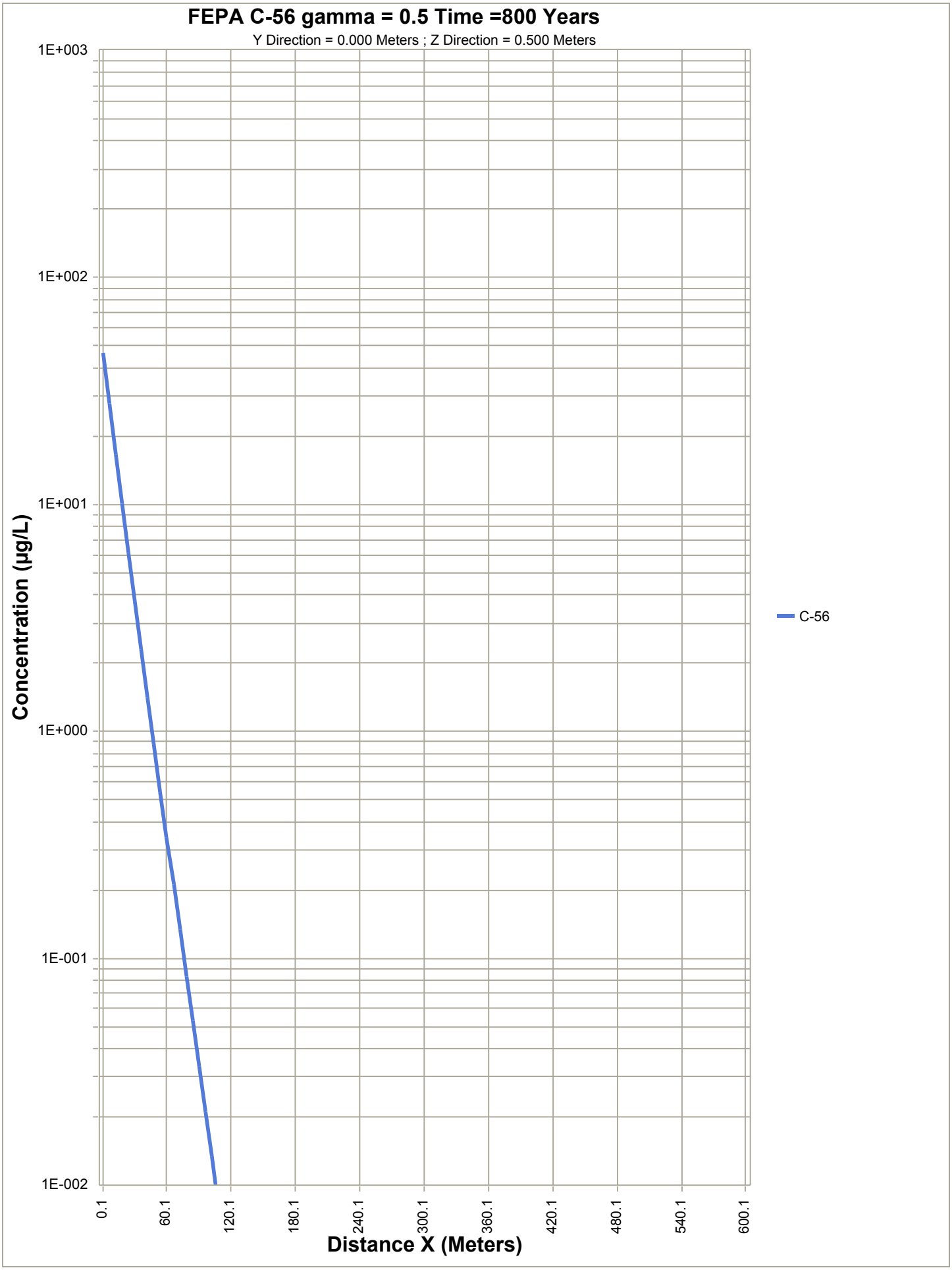

FCPA C-58 90% Removed gamma = 1 Time =36 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
10.09
20.08
30.07
40.06
50.05
60.04
70.03
80.02
90.01
100
Distance X (Meters)
C58
Component 2
Component 3
Component 4
Total Concentration

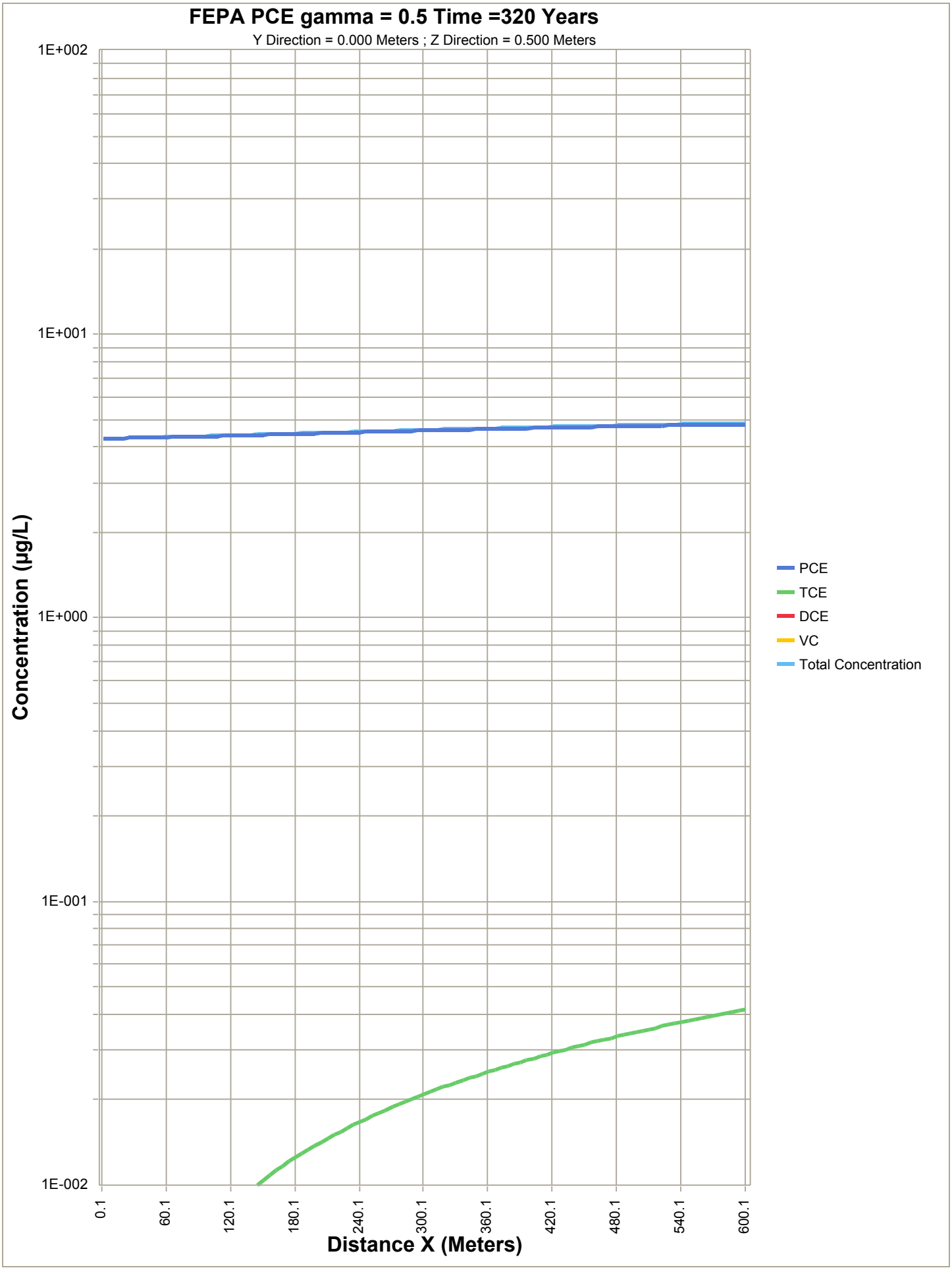

FCPA HCA 90% Removed gamma = 1 Time =445 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
111.2
222.3
333.4
444.5
555.6
666.7
777.8
888.9
1000
Distance X (Meters)
Hexachloroethane

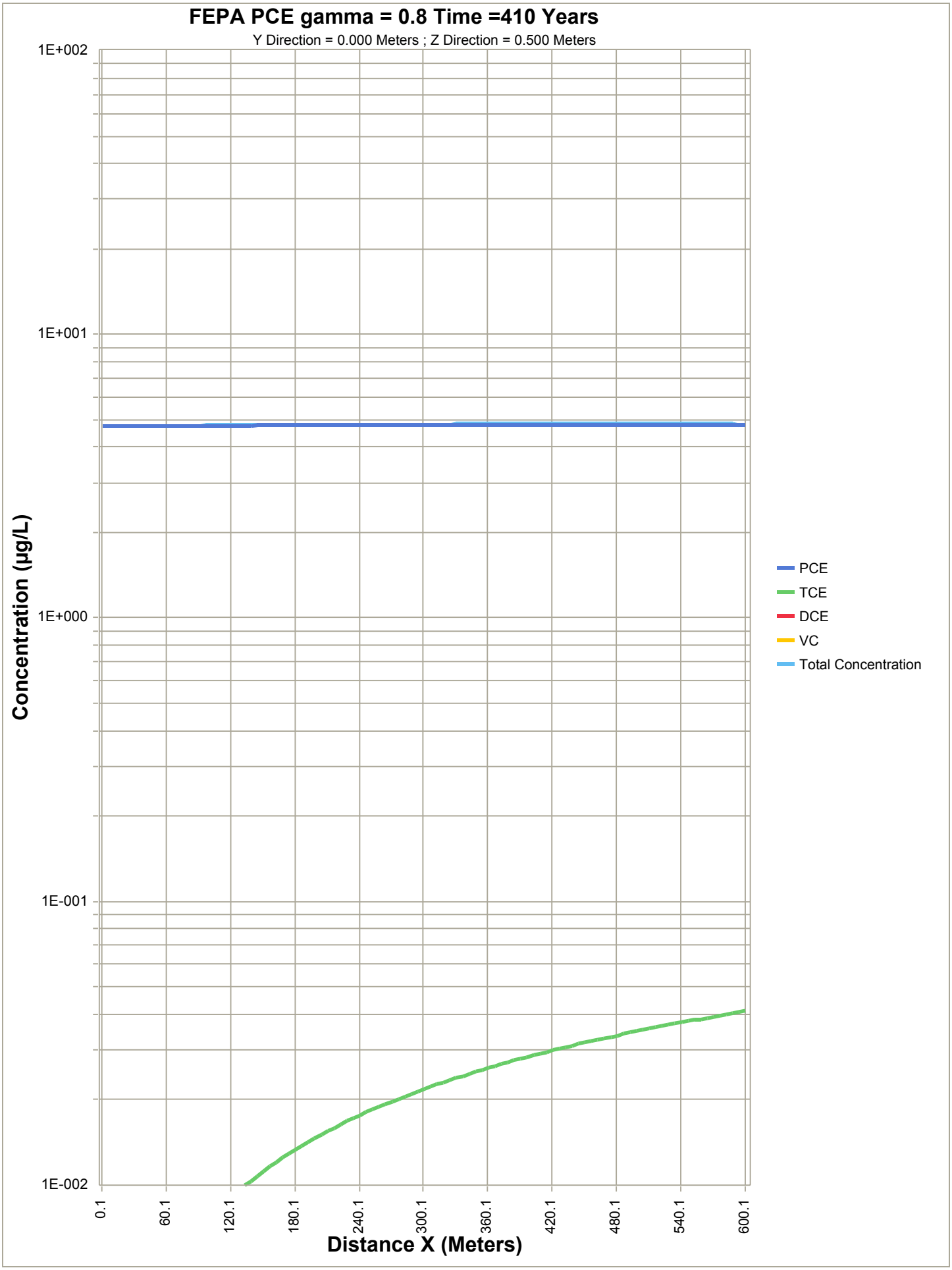

FCPA PCE 90% Removed gamma = 1 Time =138 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+005
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
0.1
111.2
222.3
333.4
444.5
555.6
666.7
777.8
888.9
1000
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

M14

FEPA Source Area
Gamma = 0.5, 0.8

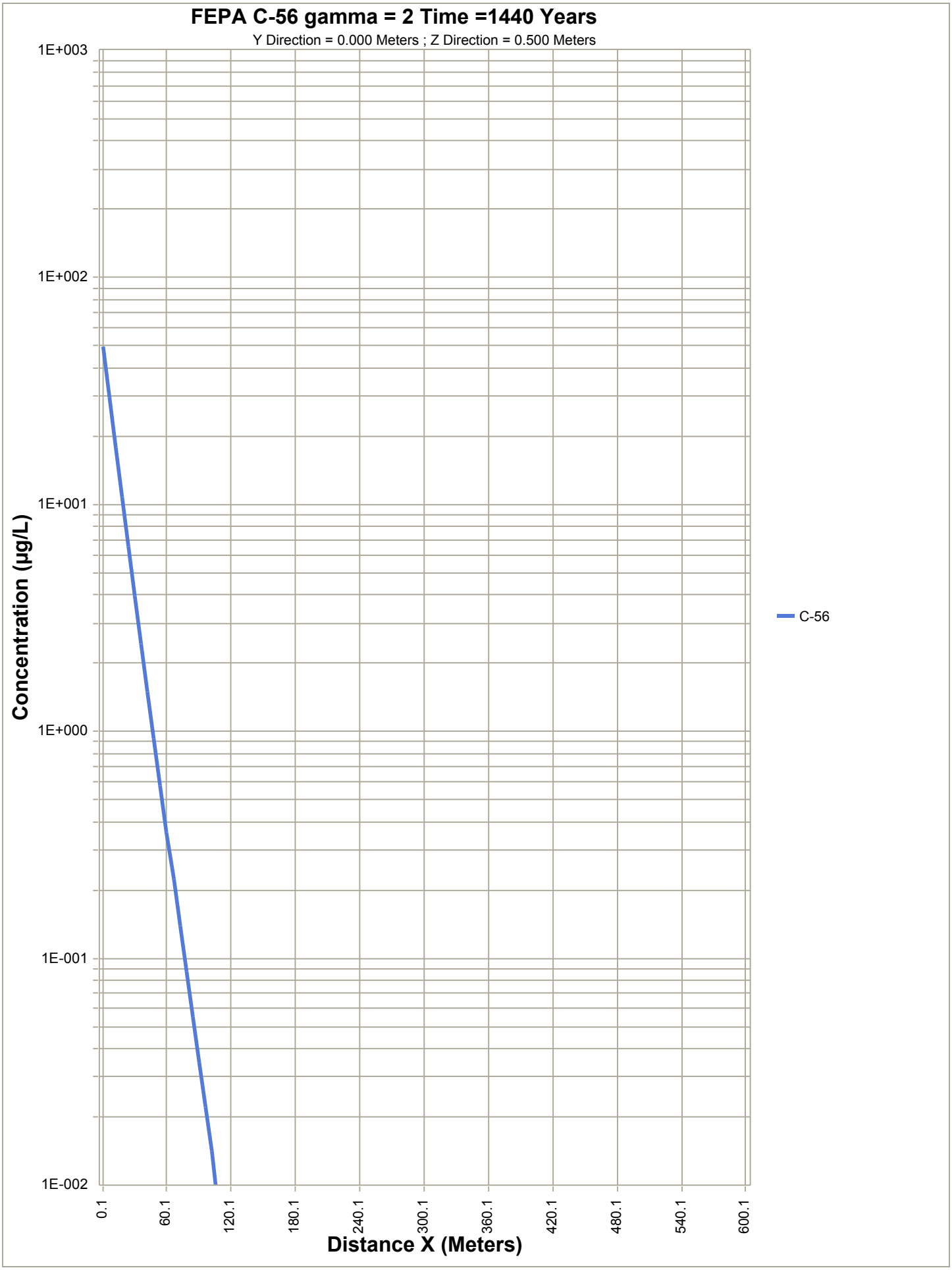

FEPA C-56 gamma = 0.5 Time =800 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
60.1
120.1
180.1
240.1
300.1
360.1
420.1
480.1
540.1
600.1
Distance X (Meters)
C-56

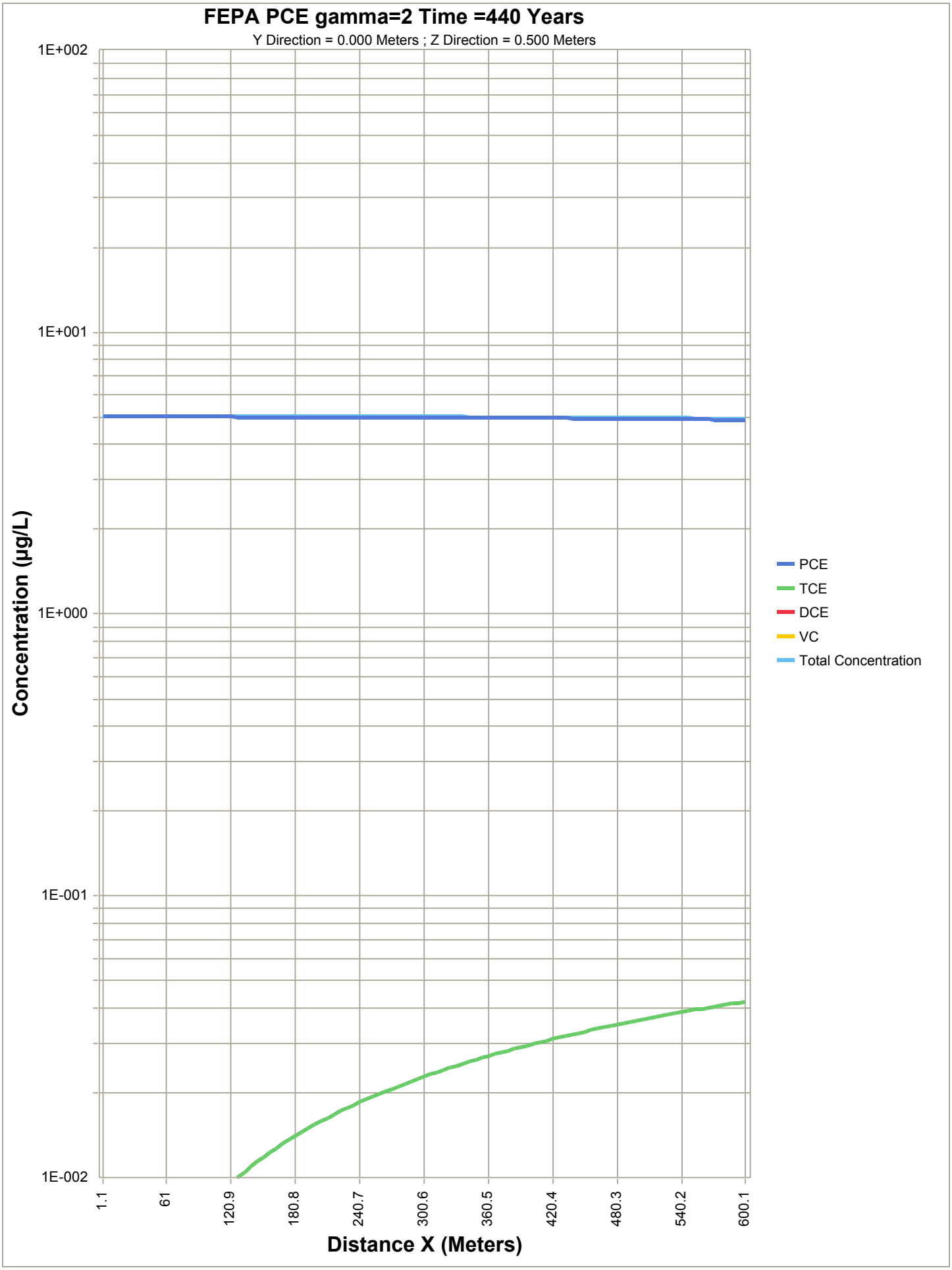

FEPA PCE gamma = 0.5 Time =320 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
60.1
120.1
180.1
240.1
300.1
360.1
420.1
480.1
540.1
600.1
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration


FEPA PCE gamma = 0.8 Time =410 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
60.1
120.1
180.1
240.1
300.1
360.1
420.1
480.1
540.1
600.1
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

M15

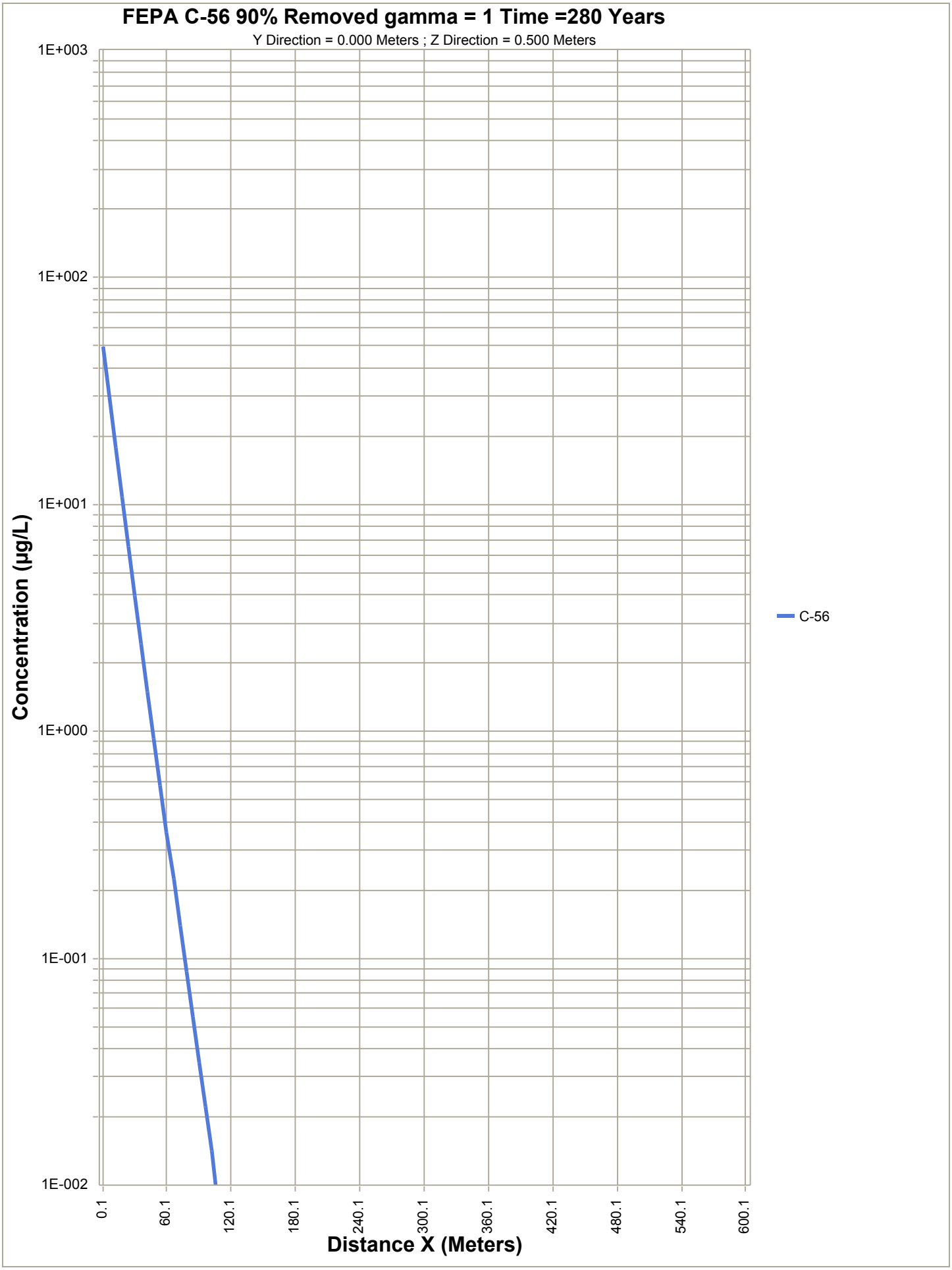
FEPA Source Area
Gamma = 2l

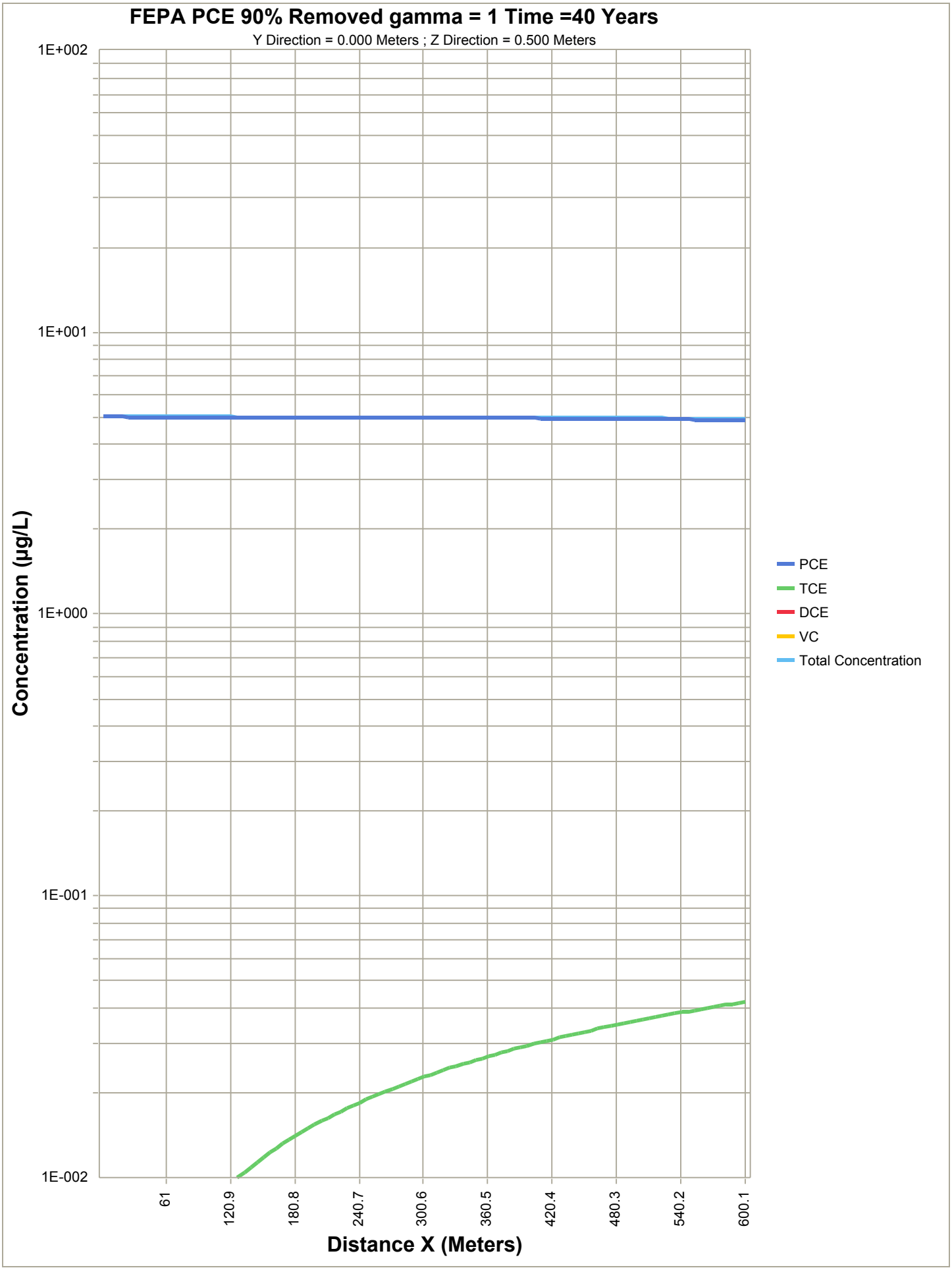

FEPA C-56 gamma = 2 Time =1440 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
60.1
120.1
180.1
240.1
300.1
360.1
420.1
480.1
540.1
600.1
Distance X (Meters)
C-56


FEPA PCE gamma=2 Time =440 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
1.1
61
120.9
180.8
240.7
300.6
360.5
420.4
480.3
540.2
600.1
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

M16

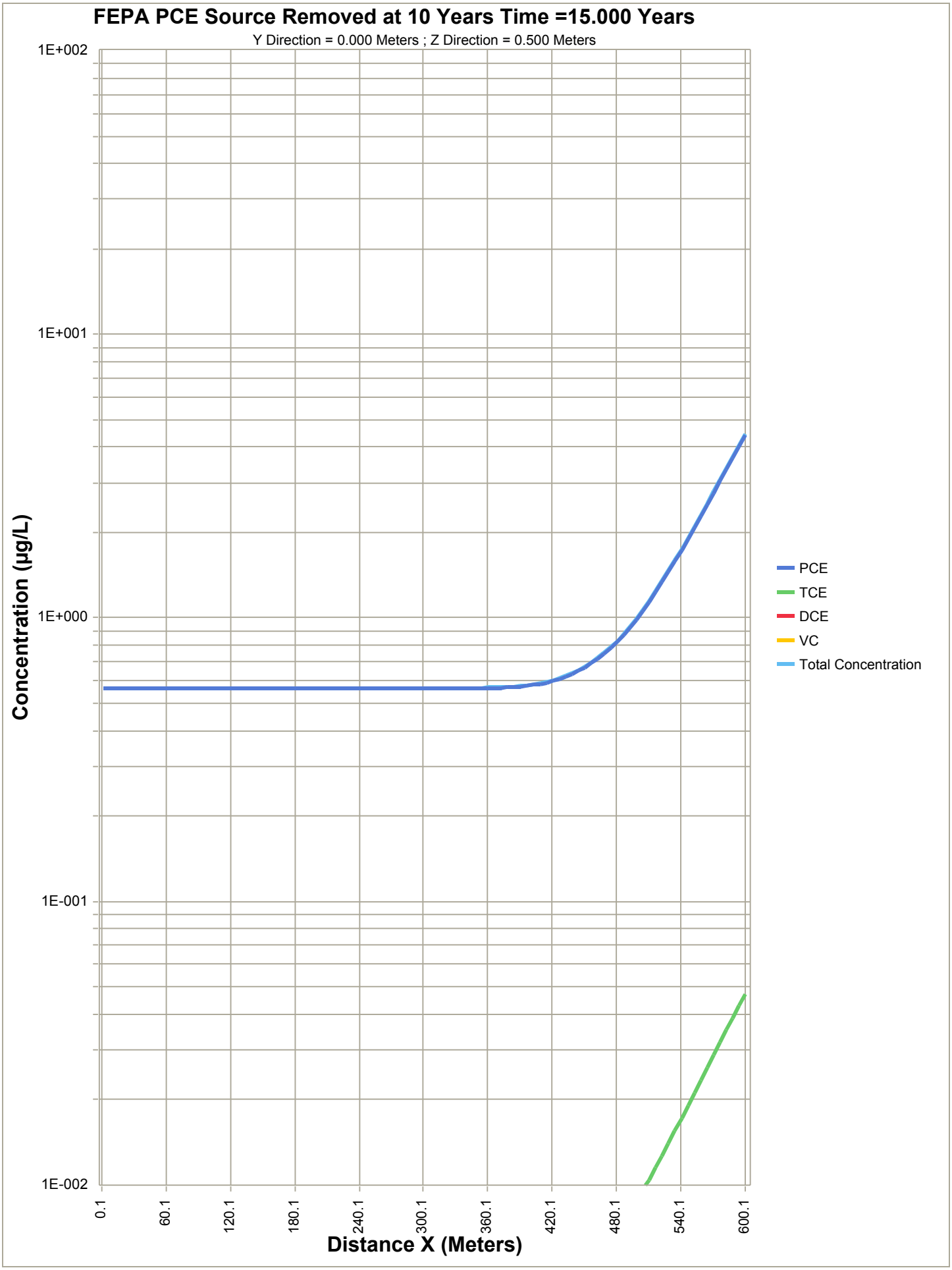
FEPA Source Area
90% Source Removal

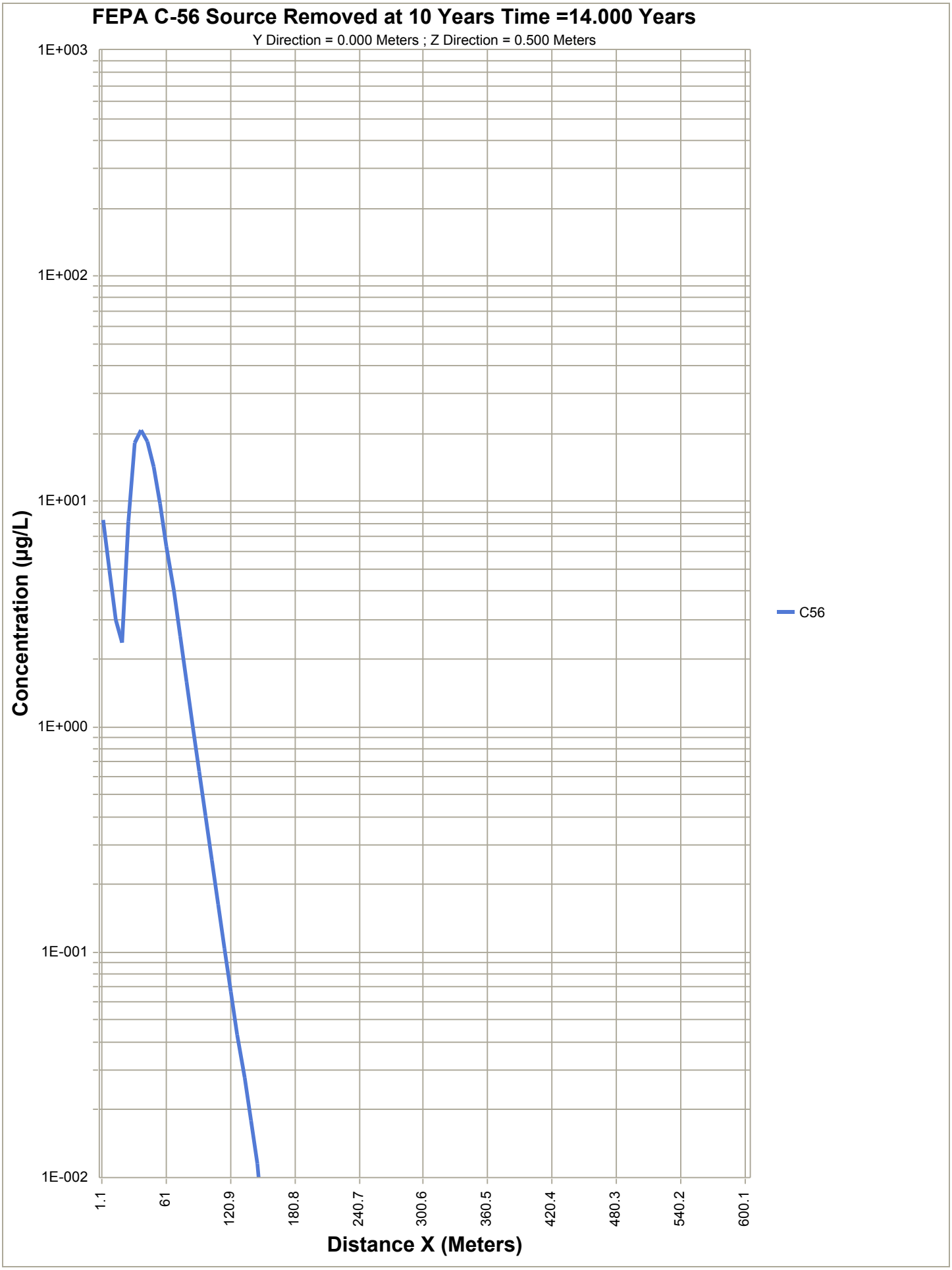

FEPA C-56 90% Removed gamma = 1 Time =280 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
60.1
120.1
180.1
240.1
300.1
360.1
420.1
480.1
540.1
600.1
Distance X (Meters)
C-56

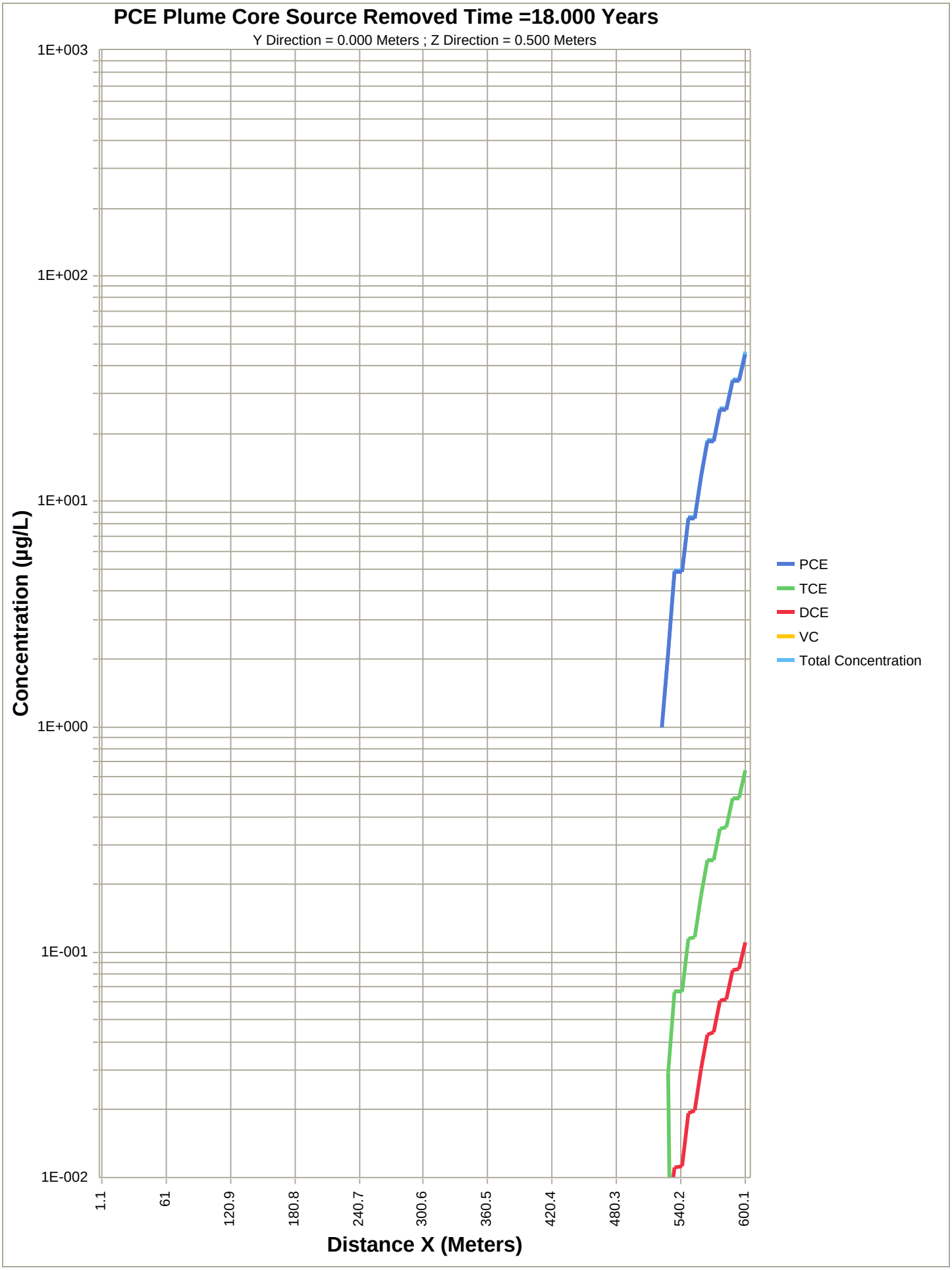

FEPA PCE 90% Removed gamma = 1 Time =40 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
61
120.9
180.8
240.7
300.6
360.5
420.4
480.3
540.2
600.1
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

M17

Proposed Pump and Treat Area
100% Source Removal


FEPA PCE Source Removed at 10 Years Time =15.000 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
0.1
60.1
120.1
180.1
240.1
300.1
360.1
420.1
480.1
540.1
600.1
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration


FEPA C-56 Source Removed at 10 Years Time =14.000 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
Concentration (µg/L)
1.1
61
120.9
180.8
240.7
300.6
360.5
420.4
480.3
540.2
600.1
Distance X (Meters)
C56


PCE Plume Core Source Removed Time =18.000 Years
Y Direction = 0.000 Meters ; Z Direction = 0.500 Meters
Concentration (µg/L)
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
1.1
61
120.9
180.8
240.7
300.6
360.5
420.4
480.3
540.2
600.1
Distance X (Meters)
PCE
TCE
DCE
VC
Total Concentration

APPENDIX D

WATER9 Model Calculations and Results

Conservative Modeling of Pollutant Emissions from Excavation

Once the emission flux of pollutants from the excavation was estimated using the WATER9 program, these emissions were applied to dispersion model calculations (zero uptake from the walls of the excavation was assumed). WATER9 was used to estimated emissions from the top of the excavation pit, emissions are provided in units of grams per second.

The objective was to estimate the maximum concentration from the pollutant emissions at ground level at the very edge of the pit. Most of the screening models used by the US EPA (e.g. SCREEN3) are generally valid for downwind distances of greater than 100 m and utilize meteorological inputs more suited for elevated sources than for receptors adjacent to ground level sources such as those emanating from excavation. To generate a conservative estimate for adjacent ground level receptors a special calculation was conducted using approaches and formula found in the modeling literature.

The program for calculating the estimated concentrations (CONC_HOLE) is self documenting and is attached as Appendix 1. The program requires certain input parameters including information about the meteorological conditions.

We have attached the control input file as Appendix 2. The inputs are documented in the lefthand 30 columns plus a "!" delimiter for comments at the end of a line. The program takes inputs in metric units in order to provide a concentration estimate in grams per cubic meter. This concentration can be converted, by the user, to micrograms by multiplying by one million. The settings of the inputs are designed to provide conservative yet realistic worst case conditions for dilution.

The log file produced by the program (Appendix 3) first echoes the inputs (to confirm the input parameters). Each line source strip is modeled and the following parameters are output for each line source;

- Downwind distance to the receptor (m),
- the wind speed at the height input by the user,
- the sigma-z that is estimated using the Hogstrom formula,
- the individual line source average one-hour concentration seen at the downwind receptor at the edge of the excavation.

This output indicates that as expected the line source directly adjacent to the receptor modeled contributes the most and the contributions from the back of the excavation contribute only one twentieth of the closest line source. Sigma-z grows to about 3 m across the length of the excavation. When the individual line source strips are summed, the total concentration at the downwind receptor is approximately 100 micrograms per cubic meter.

Appendix 1 – FORTRAN source code listing and program documentation

```
c-----------------------------------------------------------------------
      Program Holeconc
c-----------------------------------------------------------------------
c
c --- CONCLIB      Version 1.00     Level: 041309               HOLECONC
c
c --- Program was written by:
c
c --- Gary Moore
c --- AECOM
c --- 300 Baker Ave
c --- Concord, MA 01742
c
c --- Copyright @2009 Gary Moore - all rights reserved
c
c --- Version-level notes follow
c
c***********************************************************************
c
c --- Program Function:
c
c --- This program was designed to estimate the concentration of pollutant
c --- emissions emanating from a rectangular hole.  The receptor is assumed
c --- to be on the downwind lip of the edge of the hole.  The model assumes
c --- that the wind blows directly across the longest axis of the hole and
c --- the release height is equal to the receptor height (typically Z = 0)
c
c --- Usage:  This program uses the standard CERN control file input format
c --- The program is run using the command line: conc_hole conc_hole.inp.
c --- The program is written in FORTRAN and is compiled using Lahey LF95.
c
c --- Documentation:
c
c --- The near source sigma-Z is parameterized using the Briggs rural
c --- fit of Hogstrom (1964) sigma-Z
c
c --- sigma-Z = A*X**B + C  (x is in meters)
c
c --- A = 0.014 to 0.016
c --- B = 1.00
c --- C = 2.0*Zo
c
c --- The formula for sigma-z represents a best fit to data points provided in Hogstrom, 1964
c
c --- The sigma-z intercept ("C") is estimated as twice the roughness length.  This
c --- assumes that the smallest eddy doing the mixing has a half scale height equal to
c --- the height of the roughness length.
c
c --- The concentration is estimated using a sum over a number of
c --- lines sources tiling the top of the hole across the width of
c --- the hole. Each line source is assumed to be separated by 1 m.
C --- Line sources run parallel to each other and perpendicular to the wind direction.
c --- Lateral dilution is assumed uniform across the hole width.
c
c --- The formula for the concentration is taken from equation 6.28 of
c --- Pasquill and Smith, 1983 (see Ref. below) and assumes neglect of the crosswind spread.
c --- Perfect reflection from the ground is also assumed.
c
c ---  C = sqrt[2/pi]*(Q/U*sigZ)*exp(-H**2/(2.0*sigma-Z**2))
C ---  Where: C is in grams per cubic meter (Concentration)
C ---         Q is in grams/(sec-meter) (release rate)
C ---         U is in meters per second (wind speed)
C ---         Sigma-z is in meters (vertical diffusion coefficient)
C ---         H is in meters (height of release above the ground)
c
c --- The area source is created from the number of lines sources in
c --- 1 m wide strips (crossing the width) that pave the entire area
c --- of the hole. When summed each 1 m line segment within the 1 m
c --- wide strip provides the area emission for the hole.
c
c --- The power law formula for wind speed is of the form
c
c --- U(Z) = U(Zref)(Z/Zref)**p
c
c --- The emissions do not 'feel' the wind at 10 meters ("Zref") until further
c --- downwind.  A more realistic wind is that taken at roughly
c --- 1 m ("Z).  The formula takes a 10 m reference wind and extrapolates
c --- down. The most conservative case is for F stability
```

```
c --- conditions and "p" in the above equation has been set to 0.35 - the average of that used
c --- by CRSTER (EPA, 1977) and SHORTZ (Bjorklund and Bowers, 1982)

c --- References:
c
c --- Pasquill, F. and F.B. Smith, 1983 Atmospheric Diffusion - 3rd Edition
c --- Elliss Horwood Limited/John Wiley and Sons, Ney York, NY 437pages
c
c --- Hogstrom,U., 1964. An experimental study on atmospheric diffusion,
c --- Tellus, Vol 16, p205
c
c --- Briggs, G.A.and K.R. McDonald, 1978. Prarie Grass revisited: Optimum
c --- indicators of vertical spread, Proceedings of the 9th-NATO-CCMS Int.
c --- Tech Symp. Air Pollution Modeling and its.Application, Toronto, CA
c
c --- U.S. Environmental Protection Agency, 1977. Users Manual for single
c --- source (CRSTER) Model, EPA-450/2/77-013 Research Triangle PArk, N.C.
c
c --- Bjorklund, J.R. and J.F. Bowers, 1982. Usrs instructions for the
c --- SHORTZ and LONGZ computer program (Volume 1) EPA-903/9-82-0049, US
c --- EPA Philadelphia PA.
c
c----------------------------------------------------------------------
c
      Character*30 ihead
      Character*80 ipath1,ipath2
c
      Call getcl(ipath1)
      Open(7,file=ipath1,form='formatted')
c
      Read(7,'(a30,a80)')ihead,ipath2
      Open(8,file=ipath2,form='formatted')
c
      Read(7,'(a30,f10.0)')ihead,xlen
      Write(8,'(a30,f10.3)')ihead,xlen
c
      Read(7,'(a30,f10.0)')ihead,xwid
      Write(8,'(a30,f10.3)')ihead,xwid
c
      Read(7,'(a30,f10.0)')ihead,xht
      Write(8,'(a30,f10.3)')ihead,xht
c
      Read(7,'(a30,f10.0)')ihead,zht
      Write(8,'(a30,f10.3)')ihead,zht
c
      Read(7,'(a30,f10.0)')ihead,uref
      Write(8,'(a30,f10.3)')ihead,uref
c
      Read(7,'(a30,f10.0)')ihead,ax
      Write(8,'(a30,f10.3)')ihead,ax
c
      Read(7,'(a30,f10.0)')ihead,xpow
      Write(8,'(a30,f10.3)')ihead,xpow
c
      Read(7,'(a30,f10.0)')ihead,zpow
      Write(8,'(a30,f10.3)')ihead,zpow
c
      Read(7,'(a30,f10.0)')ihead,zo
      Write(8,'(a30,f10.3)')ihead,zo
c
      Read(7,'(a30,e10.0)')ihead,qflx
      Write(8,'(a30,e10.3)')ihead,qflx
c
      nlen = int(xlen)
      us = uref*(zht/10.0)**zpow
      sum = 0.0
      Do k = 1,nlen
         xdown = 1.0*(k - 1) + 0.5
         sigmaz = ax*xdown**xpow + 2.0*zo
         xmult = sqrt(2.0/3.14159)
         coef1 = -(xht*xht)/(2.0*sigmaz**2)
         coef2 = exp(coef1)
         cncrow = qflx*xmult*coef2/(us*sigmaz)
         sum = sum + cncrow
         Write(8,*)xdown,us,sigmaz,cncrow
      Enddo
c
      Print *,'total average concentration: ',sum
      Write(8,*)'total average concentration: ',sum
c
      Stop
      End
```

Appendix 2 – Example Control input file for CONC_HOLE program

```
name of the log file         :hole_conc.log
length of the hole (m)       :196.00
width of the hole (m)        :116.00
Height release point (m)     :0.000
Receptor or wind height(m)   :1.000
Wind speed  (m/s) at 10m     :1.000
sigma z multiplier           :0.015
sigma z power law coef       :1.000
wind speed power law         :0.350  !EPA1977 F stability and Bjorklund and Bowers (1982)
roughness length (m)         :0.05   !Calmet barren land roughness
emission flux (g/s)/m2       :0.242E-06
```

Appendix 3 – Example Logfile output

```
length of the hole (m)       :   196.000
width of the hole (m)        :   116.000
Height release point (m)     :     0.000
Wind height/receptor height(m)     1.000
Wind speed  (m/s) at 10m     :     1.000
sigma z multiplier           :     0.015
sigma z power law coef       :     1.000
wind speed power law         :     0.350
roughness length (m)         :     0.050
emission flux (g/s)/m2       : 0.242E-06
Distance (m)  U (m/s)    Sigma Z (m)  Ave Delta Conc (g/m3)
 0.50000000 0.446683615 0.107500002 4.02112073E-06
 1.50000000 0.446683615 0.122500002 3.52873849E-06
 2.50000000 0.446683615 0.137500003 3.14378531E-06
 3.50000000 0.446683615 0.152500004 2.83456052E-06
 4.50000000 0.446683615 0.167500004 2.58071918E-06
 5.50000000 0.446683615 0.182500005 2.36860546E-06
 6.50000000 0.446683615 0.197500005 2.18871128E-06
 7.50000000 0.446683615 0.212500006 2.03421405E-06
 8.50000000 0.446683615 0.227499992 1.90009007E-06
 9.50000000 0.446683615 0.242499992 1.78255868E-06
 10.5000000 0.446683615 0.257499993 1.67872031E-06
 11.5000000 0.446683615 0.272500008 1.58631372E-06
 12.5000000 0.446683615 0.287499994 1.50354947E-06
 13.5000000 0.446683615 0.302500010 1.42899330E-06
 14.5000000 0.446683615 0.317499995 1.36148185E-06
 15.5000000 0.446683615 0.332500011 1.30006163E-06
 16.5000000 0.446683615 0.347499996 1.24394387E-06
 17.5000000 0.446683615 0.362499982 1.19247034E-06
 18.5000000 0.446683615 0.377499998 1.14508737E-06
 19.5000000 0.446683615 0.392499983 1.10132612E-06
 20.5000000 0.446683615 0.407499999 1.06078642E-06
 21.5000000 0.446683615 0.422499985 1.02312538E-06
 22.5000000 0.446683615 0.437500000 9.88046850E-07
 23.5000000 0.446683615 0.452499986 9.55293899E-07
 24.5000000 0.446683615 0.467500001 9.24642734E-07
 25.5000000 0.446683615 0.482499987 8.95897358E-07
 26.5000000 0.446683615 0.497500002 8.68885422E-07
 27.5000000 0.446683615 0.512499988 8.43454586E-07
 28.5000000 0.446683615 0.527499974 8.19470131E-07
 29.5000000 0.446683615 0.542500019 7.96811946E-07
 30.5000000 0.446683615 0.557500005 7.75373053E-07
 31.5000000 0.446683615 0.572499990 7.55057613E-07
 32.5000000 0.446683615 0.587499976 7.35779565E-07
 33.5000000 0.446683615 0.602499962 7.17461376E-07
 34.5000000 0.446683615 0.617500007 7.00033183E-07
 35.5000000 0.446683615 0.632499993 6.83431608E-07
 36.5000000 0.446683615 0.647499979 6.67599181E-07
 37.5000000 0.446683615 0.662499964 6.52483777E-07
 38.5000000 0.446683615 0.677500010 6.38037591E-07
 39.5000000 0.446683615 0.692499995 6.24217307E-07
 40.5000000 0.446683615 0.707499981 6.10983022E-07
 41.5000000 0.446683615 0.722499967 5.98298243E-07
 42.5000000 0.446683615 0.737500012 5.86129488E-07
 43.5000000 0.446683615 0.752499998 5.74445835E-07
 44.5000000 0.446683615 0.767499983 5.63218862E-07
 45.5000000 0.446683615 0.782499969 5.52422364E-07
 46.5000000 0.446683615 0.797500014 5.42031955E-07
 47.5000000 0.446683615 0.812500000 5.32025240E-07
 48.5000000 0.446683615 0.827499986 5.22381242E-07
 49.5000000 0.446683615 0.842499971 5.13080693E-07
 50.5000000 0.446683615 0.857499957 5.04105515E-07
 51.5000000 0.446683615 0.872500002 4.95438940E-07
 52.5000000 0.446683615 0.887499988 4.87065336E-07
 53.5000000 0.446683615 0.902499974 4.78970094E-07
 54.5000000 0.446683615 0.917499959 4.71139487E-07
 55.5000000 0.446683615 0.932500005 4.63560838E-07
 56.5000000 0.446683615 0.947499990 4.56222153E-07
 57.5000000 0.446683615 0.962499976 4.49112207E-07
 58.5000000 0.446683615 0.977499962 4.42220454E-07
 59.5000000 0.446683615 0.992500007 4.35537004E-07
 60.5000000 0.446683615 1.00749993 4.29052591E-07
 61.5000000 0.446683615 1.02250004 4.22758433E-07
```

62.5000000 0.446683615 1.03750002 4.16646259E-07
63.5000000 0.446683615 1.05250001 4.10708310E-07
64.5000000 0.446683615 1.06750000 4.04937225E-07
65.5000000 0.446683615 1.08249998 3.99326098E-07
66.5000000 0.446683615 1.09749997 3.93868334E-07
67.5000000 0.446683615 1.11249995 3.88557737E-07
68.5000000 0.446683615 1.12749994 3.83388453E-07
69.5000000 0.446683615 1.14249992 3.78354912E-07
70.5000000 0.446683615 1.15750003 3.73451826E-07
71.5000000 0.446683615 1.17250001 3.68674193E-07
72.5000000 0.446683615 1.18750000 3.64017239E-07
73.5000000 0.446683615 1.20249999 3.59476502E-07
74.5000000 0.446683615 1.21749997 3.55047632E-07
75.5000000 0.446683615 1.23249996 3.50726566E-07
76.5000000 0.446683615 1.24749994 3.46509410E-07
77.5000000 0.446683615 1.26249993 3.42392468E-07
78.5000000 0.446683615 1.27750003 3.38372189E-07
79.5000000 0.446683615 1.29250002 3.34445247E-07
80.5000000 0.446683615 1.30750000 3.30608401E-07
81.5000000 0.446683615 1.32249999 3.26858583E-07
82.5000000 0.446683615 1.33749998 3.23192893E-07
83.5000000 0.446683615 1.35249996 3.19608489E-07
84.5000000 0.446683615 1.36749995 3.16102728E-07
85.5000000 0.446683615 1.38249993 3.12673052E-07
86.5000000 0.446683615 1.39749992 3.09316988E-07
87.5000000 0.446683615 1.41250002 3.06032206E-07
88.5000000 0.446683615 1.42750001 3.02816460E-07
89.5000000 0.446683615 1.44250000 2.99667590E-07
90.5000000 0.446683615 1.45749998 2.96583522E-07
91.5000000 0.446683615 1.47249997 2.93562294E-07
92.5000000 0.446683615 1.48749995 2.90602003E-07
93.5000000 0.446683615 1.50249994 2.87700828E-07
94.5000000 0.446683615 1.51749992 2.84856981E-07
95.5000000 0.446683615 1.53250003 2.82068839E-07
96.5000000 0.446683615 1.54750001 2.79334728E-07
97.5000000 0.446683615 1.56250000 2.76653111E-07
98.5000000 0.446683615 1.57749999 2.74022483E-07
99.5000000 0.446683615 1.59249997 2.71441422E-07
100.500000 0.446683615 1.60749996 2.68908536E-07
101.500000 0.446683615 1.62249994 2.66422489E-07
102.500000 0.446683615 1.63749993 2.63981974E-07
103.500000 0.446683615 1.65249991 2.61585768E-07
104.500000 0.446683615 1.66750002 2.59232678E-07
105.500000 0.446683615 1.68250000 2.56921538E-07
106.500000 0.446683615 1.69749999 2.54651241E-07
107.500000 0.446683615 1.71249998 2.52420733E-07
108.500000 0.446683615 1.72749996 2.50228936E-07
109.500000 0.446683615 1.74249995 2.48074883E-07
110.500000 0.446683615 1.75749993 2.45957608E-07
111.500000 0.446683615 1.77249992 2.43876144E-07
112.500000 0.446683615 1.78749990 2.41829639E-07
113.500000 0.446683615 1.80250001 2.39817183E-07
114.500000 0.446683615 1.81750000 2.37837952E-07
115.500000 0.446683615 1.83249998 2.35891122E-07
116.500000 0.446683615 1.84749997 2.33975911E-07
117.500000 0.446683615 1.86249995 2.32091537E-07
118.500000 0.446683615 1.87749994 2.30237276E-07
119.500000 0.446683615 1.89249992 2.28412418E-07
120.500000 0.446683615 1.90749991 2.26616251E-07
121.500000 0.446683615 1.92250001 2.24848108E-07
122.500000 0.446683615 1.93750000 2.23107349E-07
123.500000 0.446683615 1.95249999 2.21393336E-07
124.500000 0.446683615 1.96749997 2.19705456E-07
125.500000 0.446683615 1.98249996 2.18043127E-07
126.500000 0.446683615 1.99749994 2.16405752E-07
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128.500000 0.446683615 2.02749991 2.13203691E-07
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132.500000 0.446683615 2.08749986 2.07075686E-07
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138.500000 0.446683615 2.17750001 1.98516872E-07
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141.500000 0.446683615 2.22249985 1.94497403E-07
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144.500000 0.446683615 2.26749992 1.90637479E-07
145.500000 0.446683615 2.28250003 1.89384664E-07
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