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September 22, 2017

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RE: Occidental Chemical Corporation, Montague, Michigan – USEPA I.D. No. MID 006 014 906
Three-Year Periodic Technical Review Assessment Report 2017

Dear Ms. Onyszko:

The following is the second Three-Year Periodic Technical Review Assessment Report for the Occidental Chemical Corporation site in Montague, Michigan. This report is submitted pursuant to the United States Environmental Protection Agency's (U.S. EPA's) Administrative Order (Docket No. V-W-009-'93) Section VI.D.2 and the "Amended Final Decision and Response to Comments for Occidental Chemical Corporation, Montague Township, Michigan" (October 2010) (AFDRC). Glenn Springs Holdings, Inc (GSH) is submitting this report on behalf of Occidental Chemical Corporation (OCC).

Sincerely,
Glenn Springs Holdings, Inc.

Joe Branch
Site Manager

Enclosures
cc: Dan Dailey, MDEQ (P.O. Box 30241, Lansing, MI 48909)
Barry Harding, AECOM

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Three-Year Periodic Technical Review Assessment Report

Occidental Chemical Corporation Site
Montague, Michigan

Glenn Springs Holdings, Inc.

Project number: 60553228

September 25, 2017

Prepared for:

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Executive Summary

Glenn Springs Holdings, Inc. (GSH) has prepared a Three-Year Periodic Technical Review Assessment Report as required by the *Amended Final Decision and Response to Comments for Selection of Updated Corrective Measures for the Site* (Amended FDRC), dated October 2010. This periodic technical review was implemented after United States Environmental Protection Agency (U.S. EPA) Region 5 approved technical impracticability as presented in the *Post-Implementation Technical Impracticability Evaluation for Groundwater Restoration at the Occidental Chemical Corporation Site in Montague*, dated September 2009, and accepted in the Amended FDRC.

The Three-Year Periodic Technical Review Assessment Report includes a review of data from the long-term groundwater monitoring program, and a search of available literature related to cleanup technologies potentially applicable to source areas at the site.

The FDRC requires Occidental Chemical Corporation (OCC) to continue to perform long-term groundwater monitoring in accordance with the Groundwater Monitoring Plan (GMP) approved by U.S. EPA in January 2002 and to submit the results and evaluation of the long-term groundwater monitoring program effectiveness as part of this report. The objectives of the approved GMP are to: 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", and to develop information that will be used for future demonstration that the groundwater collection system is reducing the level of contamination in the aquifer.

GSH continues to provide funding to the Muskegon Conservation District to support a full time community Environmental Stewardship Coordinator. GSH has also established a 15 acre conservation easement along their White Lake frontage to preserve the work done under the Great Lakes Restoration Initiative (GLRI) Coastal Restoration. This community-wide partnership was an important step in delisting White Lake as a Great Lakes Area of Concern.

The groundwater collection system inhibits and prevents the flow of impacted groundwater to White Lake. Based on the data evaluation for the 2014-2016 years, it is concluded that the groundwater collection system operated at the site, continues to meet the requirements for the containment by maintaining a 48-hour average inward negative water flow gradient of -0.1 feet or greater from White Lake towards the purge wells.

Based on the analysis of the plume boundary monitoring program, all of the constituents of concern were below applicable groundwater protection standards. This resulted in the conclusion that the plume remained stable in 2014-2016 and stayed within the boundary of impacted groundwater area, delineated during the Resource Conservation and Recovery Act (RCRA) Facility Investigation.

Results of the 2017 review of available literature and patents related to cleanup technologies potentially applicable to source areas at the site indicated that the most promising advances for treatment of C56 and related chemicals are electroreductive remediation technologies. However, no pilot or full-scale implementation of said technology has been performed on C56 or C58 and the technology development is at a lab-scale experimental stage.

1. 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 and caustic soda from 1954 through 1982 and produced hexachlorocyclopentadiene (C56) from 1968 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 C56 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. OCC also installed a groundwater capture system including installation of groundwater purge wells at White Lake, which prevent groundwater contaminants from entering the lake. Currently, in 2017, Glenn Springs Holdings, Inc. (GSH) continues 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 remaining impacts at the site; evaluated the risks from 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 and completed, such as dredging sediment in White Lake and excavation and cover of limited on-site soils. Other requirements are long-term obligations that GSH continues to comply with, such as collection and treatment of impacted groundwater by the purge well system, monitor the plume boundary to determine that impacted groundwater plume remains stable, and demonstrate that the groundwater collection system is reducing the level of contamination in the aquifer.

Residual contamination in the form of dense nonaqueous phase liquids DNAPL is present at the site. The DNAPL is primarily composed of both C56 and octachlorocyclopentene (C58), though the composition of the DNAPL varies, and locally also includes the chlorinated volatile organic compounds (CVOCs) carbon tetrachloride (CT), tetrachloroethene (PCE), and hexachloroethane (C26). 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 (AECOM, 2008). 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) C56 and C58.
- 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 C56 and C58 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.

In September 2009, GSH submitted a Post-Implementation Technical Impracticability Evaluation (TI Evaluation) for Groundwater Restoration at the Occidental Chemical Corporation Site in Montague, Michigan to U.S. EPA Region 5. The TI Evaluation identified a spatially distinct TI Zone corresponding laterally to the well-defined stable contaminant plume boundaries and hydraulic boundary established at White Lake, and a vertical boundary established at the contact between the upper sand aquifer and underlying lower clay unit. The TI Evaluation report demonstrated technical impracticability of groundwater restoration at the Site based on the following factors:

- Residual DNAPL being identified in four geographically wide-spread source areas.
- Multiple technologies were evaluated at the Site through bench or pilot studies, including a variety of *in situ* chemical oxidation (ISCO) reagents, biological Enhanced Reductive Dehalogenation (ERD), and zero-valent iron (ZVI) reductive dechlorination. None of these technologies were effective in treating DNAPL at the Site.
- Predictive groundwater restoration modeling estimates of 4,900 years to reach target groundwater cleanup goals for C56, using excavation of DNAPL at Former Primary Disposal Area (worst case example), and >10,000 years for C56, using in situ stabilization (ISS) of DNAPL at Former Primary Disposal Area (worst case example).
- Inordinately high costs for excavation ($145 Million) and ISS ($88 Million), compared to groundwater 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 (C56 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.

In October 2010, U.S. EPA Region 5 issued an Amended Final Decision and Response to Comments for Selection of Updated Corrective Measures for the Site (Amended FDRC). The TI Zone was designated (accepted by U.S. EPA Region 5) because there were no available practicable technologies found that could enable OCC to meet groundwater cleanup levels derived from the State of Michigan’s Part 201 generic cleanup criteria and screening levels in the approximate 300 acre TI Zone. The Amended FDRC acknowledged the continued operation of the groundwater containment system as being effective for over 25 years.

Identified corrective measures in the Amended FDRC included continued operation of the groundwater containment system, OCC completing an energy audit on the existing groundwater containment and treatment system, completion of a soil gas investigation, performing a three-year technology review in 2014 and 2017 (*Section 5* of this report) and voluntary action commitments to be performed by OCC.

This document serves as the second Three-Year Periodic Technical Review Assessment Report as required by the Amended FDRC.

2. Site Chronology

The site has a long regulatory history punctuated with several orders and remedial accomplishments. 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). A Site Chronology is summarized in **Table 1** (*See Attached*). Milestone events are presented below.

2.1 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 C56 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 system 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.

2.2 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. Evaluate the 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. Implement interim and/or long-term corrective measures, if deemed necessary by the U.S. EPA.

2.3 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.

The RFI was performed to determine the nature and extent of releases of hazardous waste or hazardous waste constituents from identified Areas of Concern (AOCs). The RFI was performed in 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, and
- 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 impact, and
- 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 exceeded 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.

2.4 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.

2.5 Technical Impracticability Waiver

In October 2010, U.S. EPA Region 5 granted a Technical Impracticability (TI Waiver) for the Site consistent with criteria set forth in the *Handbook of Groundwater Protection and Cleanup Policies for RCRA Corrective Action for Facilities Subject to Corrective Action Under Subtitle C of the Resource Conservation and Recovery Act,* EPA530-R-04-030, April 2004 at Section 12, and the *Guidance for Evaluating Technical Impracticability of Ground-Water Restoration*, Directive 9234.2-25, September 1993.

2.6 Amended FDRC

In October 2010, U.S. EPA Region 5 issued an Amended Final Decision and Response to Comments for Selection of Updated Corrective Measures for the Site (Amended FDRC). The TI Waiver was accepted under stipulation of periodic (Three-Year) review of the current groundwater containment system efficiency and continued review of available treatment technologies.

Identified corrective measures in the Amended FDRC included continued operation of the groundwater containment system, OCC completing an energy audit on the existing groundwater containment and treatment system, completion of a soil gas investigation, performing a three-year technology review and voluntary action commitments to be performed by OCC.

2.7 2014 Three-Year Periodic Technical Review

On April 1, 2014, GSH submitted a final Three-Year Periodic Technical Review Assessment Report to U.S. EPA Region 5. The report provided the following conclusions:

- GSH continued to provide funding to the Muskegon Conservation District to support a full time community Environmental Stewardship Coordinator. GSH established a 15 acre conservation easement along their White Lake frontage to preserve the work done under the Great Lakes Restoration Initiative (GLRI) Coastal Restoration. This community wide partnership was an important step in delisting White Lake as Great Lakes Area of Concern.
- The groundwater collection system continued to completely halt the flow of impacted groundwater to White Lake. Based on the data evaluation for the 2010-2013 years, it is concluded that the groundwater collection system operated at the site continues to meet the requirements for the containment by maintaining a 48-hour average inward negative water flow gradient of -0.1 feet or greater from White Lake towards the purge wells.
- Based on the analysis of the plume boundary monitoring program, all of the constituents of concern were below applicable groundwater protection standards. This resulted in the conclusion that the plume remained stable in 2010-2013 and stayed within the boundary of impacted groundwater area, delineated during the RCRA Facility Investigation.
- Results of review of available literature related to cleanup technologies potentially applicable to source areas at the site indicated that the most promising advances for treatment of C56 and related chemicals were use of nano-scale zero-valent iron (nZVI), with recent research in the field of using plant-based polyphenols and iron salts for synthesis of zero-valent iron (ZVI), coined “green ZVI” (GnZVI). In 2013, GSH procured Western Michigan University to perform a bench-scale C56 treatability study using GnZVI. While the results of the study were promising in terms of mass reduction of the parent compound (94.1%) compared to a control (7.4%), daughter product production and mass stoichiometry were not confirmed.
- In-situ treatment of DNAPL source zones using GnZVI (and other reactive substrates) are challenged due to inability to precisely deliver reagents to an estimated total DNAPL mass of 568 tons disseminated through a complex sandy aquifer.

3. 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 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 located approximately 1.5 miles west of the Site.

The Site was occupied by the former Hooker Chemical and Plastics Company plant from 1952 to 1983. The facility produced chlorine, caustic soda, C56, muriatic acid, anhydrous hydrochloric acid (HCl), and hydrogen. The chlor-alkali production of chlorine involved passing natural brine recovered from deep underlying bedrock through electrolytic cells. Historical Site features, including AOCs and Solid Waste Management Units (SWMUs) presented in this document are primarily based on the UAO and are summarized in **Table 2** (*See Attached*).

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), and
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 exists vertically near and below the water table disseminated with water within the pore-spaces of sand and finer-grained glacial sediments. The DNAPL architecture model is presented in detail in the *Technical Impracticability Evaluation Report* (AECOM, 2009).

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 C56 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 captures and 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 restrictive covenants are in place on the 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.

4. Remedial Actions

4.1 Historical Remedial Actions

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 2**) have eliminated any unacceptable exposure to impacted environmental media at the site and have also removed the bulk of DNAPL found entrained within vadose zone soils. Many of these remedial actions are discussed briefly below.

Source area excavation and removal actions were completed under the 1979 Consent Judgment 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 bgs 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 C56 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 Judgment, 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 majority of 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.

4.2 Hydraulic Containment System 2014-2017

The groundwater plume from the DNAPL source areas is fully contained. A system of eight purge wells continue to collect approximately 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 2016 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, 2016).

Groundwater monitoring is currently managed by GSH and reported by GHD Inc. (GHD). As part of the Three-Year review, GSH evaluated the hydraulic containment system. The following Groundwater Quality Data Review focuses on three main points, which are: 1) Groundwater Collection Evaluation, 2) Plume Boundary Evaluation, and 3) Concentration of Pollutant Removed Evaluation.

In the years 2014 through 2016, GSH continued operation of the site purge wells for the purpose of containing and capturing any flow of contaminated groundwater into the White Lake. A total of eight purge wells maintain capture of the groundwater plume, which are as follows: Pe, Pd, Pg, Pb, Pi, Ph, Pc, and Pf. One of the main engineering purposes and performance standards for the current purge well system is to create and maintain an inward drawdown from White Lake of -0.1 feet. At a -0.1 feet inward gradient the impacted groundwater is completely captured. 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 and site impacted groundwater cannot discharge to White Lake.

Average pumping rates, total volume and average operating efficiency of extraction wells from 2014-2017 are presented below.

Year	Average Pumping Rate (GPM)	Annual Total Volume (Millions Gallons)	Average Operating Efficiency (Percent)
2014	692	364	98
2015	705	370	99
2016	701	368	95

Performance of the current hydraulic containment system is accomplished using six performance monitoring wells (MW-1 through MW-6) located closer to White Lake and east of the purge well system along with a well in White Lake (stilling well). To compare the water level of White Lake to the level of water in the monitoring wells, data are collected a minimum of two times per week. For White Lake elevations, approximately 19,000 measurements are done for calculating the average water levels (192 per event) every 12 months. The performance results from 2014-2016 are summarized in *Section 4.2.1* below.

For the years 2014 through 2016, GSH sampled and analyzed for Target Analytes on a semi-annual basis from 12 plume boundary monitoring wells, designated as B, C, MW-03-01, MW-97-02, MW-97-03, MW-97-04, MW-97-05, T, WW-2, WW-6, WW-13, and WW-24. Two wells which were used for the plume boundary evaluation were MW-05-01 (added to the plume boundary program in 2005) and MW-05-01, were added voluntarily by GSH to the southwest side of the plume to provide additional plume boundary information. The performance results from 2014-2016 are summarized in *Section 4.2.2* below.

4.2.1 Groundwater Collection Evaluation

For the years 2014-2016, the measured water level difference showed that the purge well system was able to exceed the required 0.1 feet difference all year in all six monitoring wells with only three exceptions from 2014-2016. In July 2014, well MW-5 had a head difference of -0.08 feet. In May 2015, wells MW-1 and MW-3 had head difference of -0.07 feet. However, these events did not compromise the current purge well system and average head differences at the monitoring wells were maintained greater than 0.1 feet. An assessment of the results shows that, in the years 2014-2016 the purge well system was able to completely halt the discharge of groundwater contaminated with chlorinated organic compounds to White Lake by achieving an inward gradient from White Lake more than the required -0.1 feet.

4.2.2 Plume Boundary Evaluation

In the years 2014-2016, the analytical results showed that all of the constituents of concern were below applicable groundwater protection standards in the entire plume boundary monitoring well system. This resulted in the conclusion that the plume was stable in the years 2014-2016 and stayed within the boundary of impacted groundwater delineated area during the RCRA Facility Investigation.

4.2.3 Concentration of Pollutant Removed Summary

An estimated 364, 370, and 368 million gallons of groundwater were pumped in 2014, 2015, and 2016, respectively. For all the years 2014-2016, the analytical results were consistent with historical data.

In 2011, 2012 and 2013, the following pounds of VOCs and SVOCs were removed, respectively: 4,369, 4,835 and 4,418 or three year average of 4,541 pounds of mass. The three year average for 2014-2016 was estimated to be 4,466 pounds of mass.

Historical Rate of Mass Removal is presented below.

Year	Annual Total Mass Removed (Pounds)	Mass Removal Rate (Pounds/Day)
2011	4,369	12
2012	4,835	13
2013	4,418	12
2014	4,423	12
2015	4,830	13
2016	4,145	11

4.2.4 Conclusions

Based on the data evaluation for years 2014-2016, it is concluded that removal system implemented by GSH has met the requirements for the containment and decontamination by maintaining an inward negative water flow gradient of -0.1 feet from White Lake towards the contaminated groundwater plume. The purge well system was also able to capture all of the contamination flowing towards White Lake.

Based on the analysis of the plume boundary monitoring well system, results showed that all of the constituents of concern were below applicable groundwater protection standards at the plume boundary monitoring well system. This resulted in the conclusion that the plume remained stable in 2014-2016 and stayed within the boundary of impacted groundwater delineated area during the RCRA Facility Investigation. Since 1990, the annual average daily contaminant removal rate has steadily decreased from 27 lbs/day to 11 lb/day in 2016.

4.3 Technical Impracticability Waiver

The TI Evaluation focused on an estimated mass of 568 tons of residual contaminants residing primarily as DNAPL in the upper sand aquifer at the Site. Several remedial options were evaluated in the TI Evaluation. Innovative chemical and biological methods to address DNAPL that were evaluated through bench and pilot studies were shown to be ineffective at treating the DNAPL. Physical methods to address the DNAPL (excavation and solidification) were also evaluated further in the report. From a human exposure perspective, residual contaminant removal/isolation or treatment was shown to potentially increase risks compared to leaving the residual material in place due to 1) increased exposure scenarios (excavation) and 2) contaminant mobilization (excavation, isolation and solidification).

Because it was deemed technically infeasible to treat the DNAPL at the site, the document also evaluated restoring the down gradient aqueous contaminant plume outside of the DNAPL zone to required cleanup levels. However, predictive groundwater restoration modeling estimates were impracticable for cleanup of 4,900 years to reach target groundwater cleanup goals for C56, using excavation of DNAPL at Former Primary Disposal Area (worst case example), and >10,000 years for C56, using ISS of DNAPL at Former Primary Disposal Area (worst case example).

4.4 Current Status

GSH has completed all of the corrective measures requirements of the Amended FDRC, including completion of soil gas investigation at the OCC resort area and the residential area; performance of an energy audit of the existing groundwater capture and treatment system; establishment of a conservation easement adjacent to White Lake; and Three-Year Technology Review. As a result of the site’s energy audit that was completed in 2011, the groundwater collection system’s controls and telemetry underwent a significant upgrade in 2012 to optimize the treatment efficiency. In addition to the required actions from the FDRC GSH also completed the following voluntary actions: established and financially supports an Environmental Outreach Coordinator position with the Muskegon Conservation District; included 15 acres of property in the GLRI White Lake shoreline restoration; in collaboration with the White Lake Public Advisory Council held two public tours at the GLRI restoration area and continues site wildlife habitat restoration activities. In 2016 Occidental was able to purchase the last remaining residential groundwater well in Blueberry Ridge subdivision. This well was abandoned by Raymer Company Inc. a registered Michigan water well drilling contractor # 70-2055 on 11/22/2016. MDEQ Well Abandonment form is attached in **Appendix A**.

5. Three-Year Technology Review

The Amended FDRC refers to OCC performing a “periodic technical review” as an assessment report every three years. A literature review was done in order to assess if any new potentially applicable technologies for treatment of C56 and related chemicals have become available in the past three years, or if any improvements to previously screened technologies have been identified.

OCC currently has an active groundwater collection system consisting of eight purge wells that completely captures all contaminated groundwater before reaching White Lake. As a result, all potential complete exposure pathways have been eliminated and the constructed remedy remains protective of human health and the environment. The goal of the literature search is to assess the availability of technologies that may treat on-site DNAPL source areas and expedite groundwater cleanup.

5.1 Literature Review

The following on-line sources were used in the literature review:

- Google,
- Google Scholar,
- Google Patents,
- Environmental Science & Technology,
- IEEEXplore,
- American Chemical Society (ACS) Publications,
- Wiley Online Library, and
- Springer Online Journals.

The literature search was performed using JabREF software (http://www.jabref.org/), an open source bibliography reference manager which can accumulate and sort BibTeX native file formats. JabREF is a user-friendly and efficient software that allows rapid entry searches in external databases. BibTeX entries were fetched through various on-line search engines noted above. Google Patents was searched for specific and relevant chemical and mechanical treatment patents for C56 and C58. Results of the literature and patent search are included in Appendix B (key papers and references are denoted with a ★).

The literature review focused primarily on the problematic COCs present at the OCC site, which are C56 and C58. The total estimated mass of the DNAPL is 568 tons with an estimated DNAPL volume of 82,500 gallons (AECOM, 2009). However, the majority of this mass is composed of C56 and C58 with an approximate percentage of 37.78% and 46.92%, respectively. The remaining major COCs percentages are 4.78%, 0.74%, and 0.54% for PCE, C26, and carbon tetrachloride (CT), respectively. Because C56 and C58 comprise approximately 85% of the total mass of the COCs, any technology that would be used for remediation of the Site has to first address these two chemicals (AECOM, 2009).

In-Situ Chemical Reduction technologies were revisited during the literature review (**Table 3**). One additional technology Electroreductive Remediation (Martin, et al., 2016) was identified (not previously discussed in the 2009 TI Waiver Report or the 2014 technical review) and is further discussed in *Section 5.3.*

Table 3. Evaluated Treatment Technologies, Occidental Chemical Corporation, Montague Township Site

In-Situ Chemical Reduction
Nano-scale ZVI
Green ZVI
★New Identified Technology
Electroreductive Remediation (Martin, et al., 2016)

At this time, no new technologies have been found to address the specific removal of C56 and C58 present at the Site. However, electroreductive remediation has shown promise for treatment of emerging compounds and various halogenated environmental pollutants (Radjenovic, et al., 2012; Martin, et al., 2016). No new papers have been found from the past three years regarding improvements in treatability approaches for the two primary COCs, C56 and C58.

Nano-scale ZVI, Green ZVI and Electroreductive Remediation have been retained for further discussion below.

5.2 Nano-scale ZVI

The first documented use of the degradation potential of metals for treating recalcitrant organic compounds (halogenated pesticides) was by Sweeney and Fisher (1972), who acquired a United States patent for treatment of pesticides using granulated zinc under acidic conditions. Since 1972, treatment of contaminant plumes using elemental metal has become a reliable applied remedial technology (Gavaskar, et al., 1998; Carroll *et al.*, 2013). The exact mechanism of degradation of chlorinated compounds by iron or other metal catalysts is not fully understood (Gavaskar, et al., 1998). In the natural environment iron typically exists only as Fe^{2+} and Fe^{3+} states, and as a result elemental iron (e.g., ZVI) must be manufactured or synthesized (Geiger, et al., 2001).

Use of ZVI is a technology that can be effective in treating some chlorinated organic compounds, especially chlorinated ethenes such as trichloroethene (TCE). The technology has also been applied to DNAPL and pesticides (Geiger, et al., 2001; Sweeney and Fischer, 1972). The National Aeronautics and Space Administration (NASA) developed a technology using an emulsified form of ZVI (EZVI). EZVI consists of an emulsion of vegetable oil in water, with nano-scale iron particles contained within the emulsion droplets. The degradation of chlorinated organics by ZVI is a surface mediated reaction. Particles with a high surface area to volume ratio, such as nanoscale particles, therefore typically exhibit faster reaction rates. The vegetable oil membrane of EZVI allows the DNAPL to diffuse through to the ZVI surface where it is degraded. The vegetable oil also acts as an electron donor source to bio-stimulate indigenous microorganisms to reductively dechlorinate aqueous phase solvent contamination (Earth Tech, 2005a).

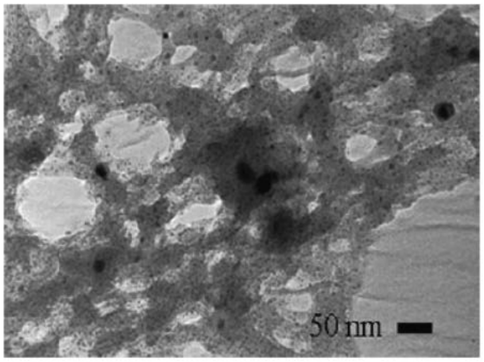
In 2004, a bench study was performed at the site to evaluate the treatment of the DNAPL with EZVI. Studies on the behavior of C56 and C58 in the presence of EZVI were not available prior to the investigations related to this Site. TEA was the licensed contractor that implemented the pilot study on samples from the Site. The study showed reductions in the concentrations of C56 and C58 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 C56 and C58, 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 C56 and C58 degraded. Incomplete reaction byproducts are documented in ZVI systems on smaller molecules such as carbon tetrachloride (CT), and this incomplete mineralization of C56 and C58 suggested that other chlorinated byproducts remained in the samples (Earth Tech, 2005a).

Results from the 2013 bench-scale testing strongly suggested that C56 and C58 were not completely mineralized by EZVI, and were instead converted to intermediate degradation products. A significant concern in attempting to implement this technology was 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 fully dechlorinate site-specific DNAPL compounds, ZVI was not retained as an effective treatment technology (AECOM, 2009). A focused literature review from 2014-2016 indicated no milestone advancements in ZVI treatment.

5.3 Green ZVI

Use of Green ZVI (GnZVI) was previously discussed in the 2014 technical review. GnZVI synthesizes ZVI from iron salts in the presence of plant-derived polyphenols and was developed primarily by VeruTEK (U.S. EPA, 2014). The exact mechanisms for GnZVI formation are not known, but it is known that polyphenols promote H-atom transfer (Di Meo et al., 2013). It has also been shown that quinones, oxidized intermediates of hydroquinone constituents of polyphenols, serve as electron shuttles that reduce iron salts (Chen and Pignatello, 1997). When normal ZVI reduces contaminants it becomes oxidized to Fe2+ which is no longer effective as a chemical reductant. However, the polyphenols in this technology recycle Fe^{2+} back to ZVI, maintaining its ability to act as a direct reductant. Polyphenol extracts serve as both a reductant and dispersing agent (Hoag et al., 2009).



Transmission electron micrograph showing nano-scale iron particles synthesized in tea polyphenols (Hoag, *et al*. 2009).

In 2013, OCC's consultant AECOM Technical Services, Inc. (AECOM) solicited input from professors Daniel Cassidy, P.E., PhD at Western Michigan University (WMU), Kalamazoo, Michigan and Eric Seagren, PhD at Michigan Technical University (Michigan Tech), Houghton, Michigan regarding treatability approaches for chemical reduction and biological oxidation, respectively, of C56. Professors Cassidy and Seagren are both well-published specialists in the treatment of non-aqueous phase liquids (NAPLs). Both professors acknowledged that limited research has historically been performed on the treatability of C56, and concurred that contemporary bench-scale studies should expand from previous work and lessons learned from bench-scale work performed on C56 and related compounds at the Site.

Previous bench and pilot-scale studies are summarized in the Technical Impracticability Evaluation Report and the Evaluation of DNAPL Treatment at the Occidental Chemical Corporation Site (AECOM, 2009; Earth Tech, 2006). Based upon efficacy of previous chemical reduction studies using zero-valent iron (Fe^0 or ZVI) showing 25% to 40% reduction of C56 and C58 (TEA, 2004), additional bench-scale testing using the GnZVI form of ZVI was selected in 2013 for the voluntary bench-scale research for treatment of C56. WMU was selected to perform the study, using plant-based polyphenolic compounds as a catalyst for formation of GnZVI.

Results of the 2013 bench-scale study indicated that C56 was degraded 94.1% in the test reactor by the GnZVI, and that very little removal of polyphenol took place. However, it is not known how much actual mineralization of the C56 occurred. Based on a previous study of C56 treatment with ZVI at the Montague site it is possible that very little, if any, complete dechlorination of the C56 took place in these studies.

A focused literature review from 2014-2016 indicated no milestone advancements in the subsurface delivery of Gn ZVI, remedial approach and treatment efficacy.

5.4 Electroreductive Remediation

Electroreductive remediation is identified as a technology not previously evaluated at the OCC Chemical Site. Beginning in the 1980's, electrochemical reduction of organic compounds has been extensively studied and reviewed by remediation practitioners (Martin, et al., 2016; Jütter, et al., 2000). However, recent advances in electrochemical remediation have focused on the electroreduction of recalcitrant and emerging compounds (Rodrigo, et al., 2014).

5.4.1 Technology Overview

Applied to halogenated organic pollutants, the approach entails inducing a natural (galvanic) or generated electrical current across a chemically-impacted media field, which results in release of free halide ions into the surrounding media, or essentially stripping of Cl^- or other ions from the parent molecule (Hammerich & Speiser, 2016). An example is the electrochemical reduction of dibromochloromethane ($CHBr_2Cl$) using a silver cathode in an electrolyte, where methane, chlorine and bromine are liberated (Martin, et al., 2016):

$$CHBr_2Cl + 3H^+ + 6e^- \rightarrow CH_4 + 2Br^- + Cl^-$$

The reductive cleavage of the carbon-halogen bond is a complex process that is affected by four distinct parameters. The four parameters include the structural features of the molecule of interest, the composition and construction of the cathode material, the particular solvent/electrolyte combination that is employed, and the electrical potential of the cathode itself (Martin, et al., 2016). Documented lab-scale testing has been performed on the following compounds (Rodrigo, et al., 2014): Atrazine, Bentazone, Chlorobenzene, Hexachlorobenzene, DDT, Pentachlorophenol, Trichlorobenzene isomers, 2,4-DCP and Molinate (Ordram).

Photograph of a laboratory electro-reduction cell for measuring electrical potentials or cyclic voltammetry of electro-reduction reaction (Martin, et al., 2016)

Lab-scale electrodes are varied ranging from inexpensive materials to exotic and precious metals, including, for anodic processes, carbon, gold, platinum, boron-doped diamond, iron, lead, steel and titanium. For cathodic reactions, carbon, mercury, copper, steel, tin and several noble metal electrodes have been utilized (Martin, et al., 2016). It should be noted that several of these metals and metalloids are not environmentally-friendly elements.

5.4.2 Technology Applicability to OCC Site

The use of electroreduction to remediate halogenated environmental pollutants has its advantages and disadvantages. Advantages could potentially include a relatively lower consumption of energy and time for focused efforts in identified DNAPL source areas, and the pollutant reduction could be more attainable due to the selectivity of different potential electrodes (Martin, et al., 2016). Also, chemical reduction efficiencies greater than 75% have been reported on various pesticides such as pentachlorophenol (Rodrigo, et al., 2014). However, most reported reduction efficiencies are less than 50%.

There are many challenges faced with application of electroreductive technology full-scale at the site. To date, no pilot or full-scale implementation has been completed. No bench-scale work using electroreduction has been performed on C56 or C58. The majority of the studies that have been conducted were done at lab level using aqueous-phase solutions (Rodrigo, et al., 2014). The scaling-up of laboratory experiments to a level of field-scale evaluation has not been explored. Work implemented so far is largely experimental.

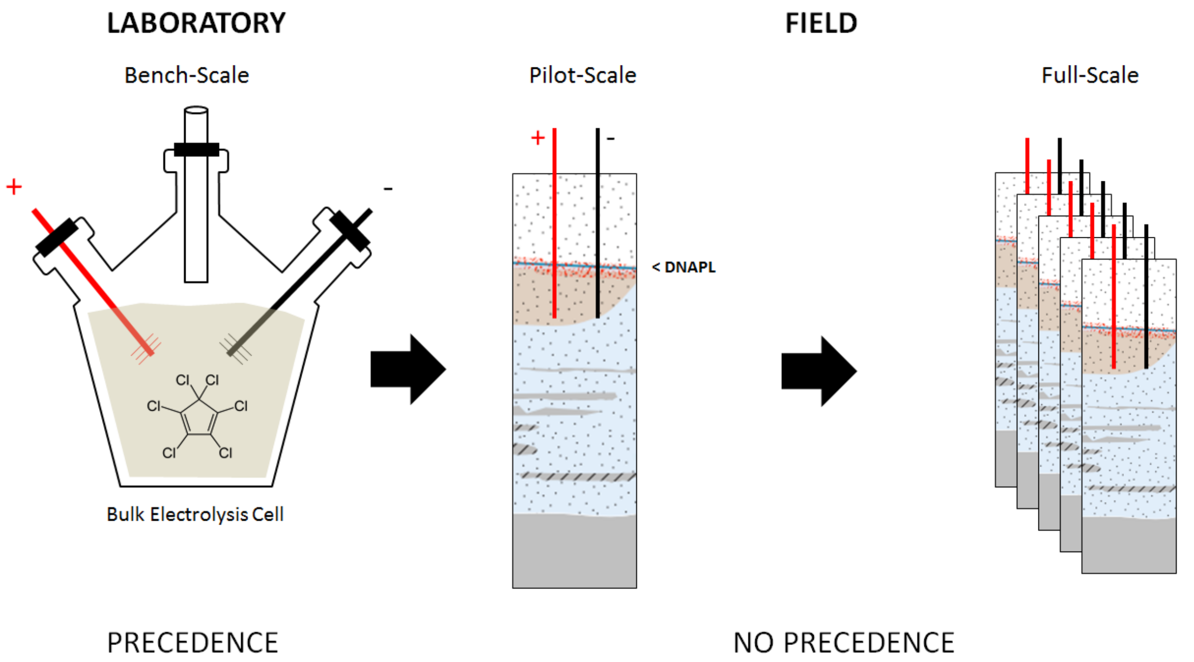


Illustration depicting the conceptual proof-of-concept for electroreduction of C56 DNAPL at the OCC Site. Precedence has been established for bench-scale treatment of pesticides, but no laboratory work has been performed specific to C56 or to bulk DNAPL. Field scale-up is potentially impracticable due to the voltage requirements to target over 500 tons of contaminant mass. Other challenges include selection of environmentally conscious electrodes and potential liberation of deleterious daughter products (e.g. methane, metals, and halogens).

5.5 Technology Screening

Based on the literature search, it is concluded that no available remedial technology is available to be used to expedite the cleanup of the Site and address the source zones. Both nano-scale and green ZVI chemical reduction are promising technologies applied in the industry for the reduction of some chlorinated organic compounds. However, their application for the full treatment of C56 and C58 is likely to affect only partial dechlorination leaving intermediate degradation products. Remediation of residual C56 and C58 DNAPL source areas using electroreductive technology is technically impracticable at this time. While a promising experimental technology, electroreductive remediation appears to be more suited for focused ex-situ “soil pile” treatment or ex-situ treatment of impacted water. Currently a well-documented pump and treat system is in place which prevents migration of the contaminant plume to White Lake. The system also contributes to mass depletion as evidenced in annual monitoring.

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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
2009	Post-Implementation Technical Impracticability Evaluation for Groundwater Restoration at the Occidental Chemical Corporation Site in Montague, Michigan completed and submitted to EPA Region V.
2010	Amended Final Decision and Response to Comments issued by EPA Region V. TI Waiver is granted. Other stipulations are specified: 1. Continued operation of the groundwater containment system. 2. Energy audit and assessment of waste management practices to ptimize purge well system and minimize its long-term energy use and carbon emissions. 3. Perform soil gas study of VOCs and hexachloroethane potential resding in vapor phase above the groundwater contaminant plume. 4. Perform literature review to assess whether potentially applicable technologies have become available to clean up the four identified DNAPL source areas. 5. Perform "voluntary action commitments" including bench-scale research for treatment of site contaminants, and establishment of conservation easement along White Lake.
2011	Energy audit of existing groundwater containment system is performed and submitted to EPA Region V.
2011	Work plan for Soil Gas Investigation South of Old Channel Trail near Montague, Michigan submitted to EPA Region V.
2012	Indoor Air & Sub-Slab Sampling Work Plan for Residential Area is submitted to EPA Region V.
2012	Soil Gas Investigation Investigation Report submitted to EPA Region V. Soil gas investigations were performed in the Occidental Resort Area and the Residential Area. GSH completed three rounds of soil gas sampling in the resort area. No unacceptable risks were detected in any samples in the resort and residential areas, including at residential homes sampled.
2013	GSH retained Western Michigan University to perform a bench-scale treatability using green zero-valent iron (polyphenol synthesized ZVI) for treatment of C56. The bench-scale study was completed in January 2013.

TABLE 2. 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-vegetation of Site
On-Going		White Lake	Un-related to AOCs	Conservation Easement Established

Appendix A

DEQ

Abandoned Well Plugging Record

Completion is required under authority of Part 127 Act 368 PA 1978.
Failure to comply is a misdemeanor.

Wellogic

Import ID:

Tax No:
Permit No:
County: Muskegon
Township: Montague
Town/Range: 12N 17W
Section: 31
WSSN:
Source ID/Well No:

Well ID: 61000015652

Elevation:
Latitude: 43.390967
Longitude: -86.380582
Measurement Method: GPS Std Positioning Svc SA Off

Distance and Direction from Road Intersection:
1/4 MILE SOUTH OF OLD CHANNEL TRAIL & 200 FT. EAST OF McFALL RD.

Well Owner: GEORGE CARROL

Well Address:
7250 McFALL RD.
MONTAGUE, MI 49437

Owner Address:
7250 McFALL RD.
MONTAGUE, MI 49437

Date of Well Plugging: 11/22/2016
Well Use: Household
Well Construction Type: Sand/Gravel Well
Date Well Constructed:
Casing Status after Plugging: 3.00 ft. below grade
Reason for Abandoning Well: Well no longer needed
Abandonment Method: Poured from surface
Drilling Record:
Casing Type: Steel - galvanized
Diameter: 2.00 in. to 78.00 ft. depth
Pumping Equipment Removed: Yes
Equipment Removed: Pitless adapter spool, Drop pipe, Check valve, Bremer check valve
Measured Well Depth: 78 ft.
Well Diameter: 2 in.

Note: Cutting casing off 4 feet below grade is recommended.

Plugging Material	From (ft)	To (ft)	Quantity	Quantity Unit
Bentonite chips/pellets	0.00	78.00	3.00	Bags

Plugging Remarks:

Note: Plugging from well bottom up to ground surface is required.

Certification: Water Well Drilling Contractor
Registration No: 70-2055
Registered Contractor: Gerald F Neubecker III

Business Name: Raymer Company Inc
Address: 1357 Comstock St
Marne, MI 49435

Remarks:

Water Well Contractor's Certification

This well plugging was performed under my registration.

Signature of Registered Contractor **Date**

Contractor 11/30/2016 10:59 AM

Appendix B

Appendix A
2017 Literature and Patent Search
Former OCC Site, Montague, Michigan

Key Ref	Year	Author	Title	Journal	Volume	Number	Notes
★	2016	Martin E. T.; McGuire C. M., Mohammad S. M.; Peters D. G.	Electroreductive Remediation of Halogenated Environmental Pollutants	Chem. Rev.	116	24	Recent paper focuses on bench-scale treatment of recalcitrant POPs. Good overview on theory.
	2014	Zhang, H. Y.; Wang, Y. W.; Sun, C.; Yu, M.; Gao, Y.; Wang, T.; Liu, J. Y. & Jiang, G. B.	Levels and distributions of hexachlorobutadiene and three chlorobenzenes in biosolids from wastewater treatment plants and in soils within and surrounding a chemical plant in China	Environ. Sci. Technol.	48		
★	2014	Rodrigo, M. A.; Oturan, N.; Oturan, M. A.	Electrochemically Assisted Remediation of Pesticides in Soils and Water: A Review	Chem. Rev.	114		An overview of electrochemical (EC) remediation of pesticides. Summarizes different catagories of EC.
	2012	Gharagheizi, F.; Eslamimanesh, A.; Ilani-Kashkouli, P.; Mohammadi, A. H. & Richon, D.	Determination of Vapor Pressure of Chemical Compounds: A Group Contribution Model for an Extremely Large Database	Ind. Eng. Chem. Res.	51		
	2010	Hegg, V.R.	Microwave Ground, Road, Water, and Waste Treatment Systems. US Patent 2010/0322713 A1	US Patent Office			Unusual patent for directed microwave emitter. For shallow, near-surface soil treatment and not saturated deeply-entrained DNAPL.
★	2009	Brillas, E.; Sires, I.; Oturan, M. A.	Electro-Fenton Process and Related Electrochemical Technologies Based on Fenton's Reaction Chemistry	Chem. Rev.	109		Fenton's reactions previously tested as Pilot Study at Site. Field testing raised aquifer temperature 10°C warranting concern of DNAPL mobilization. No significant mass reduction was observed during the pilot.
★	2006	Geisel, D.J.	Device, System, and Method for Remediation if Contaminated Soil. US Patent 2006/0112627 A1	US Patent Office			Patent for hot-fluid recirculation generates stream. Soil flushing technology. Direct-thermal warming. Not practicable for site application due to presence of DNAPL.
★	2000	Juttner, K.; Galla, U.; Schmieder, H.	Electrochemically Approaches to Environmental Problems in the Process Industry	Electrochim. Acta	45		Overview on electrochemical treatment technologies focuses on water wastestream treatment.
	1999	Watts, Richard J.; Bottenberg, Brett C.; Hess, Thomas F.; Jensen, Mark D. & Teel, Amy L.	Role of Reductants in the Enhanced Desorption and Transformation of Chloroaliphatic Compounds by Modified Fenton's Reactions	Environmental Science & Technology	33	19	
★	1999	Shaw, E.A.	Remediation of Pesticide-Contaminated Soil. US Patent 5908774	US Patent Office			Use of methanotrophic and denitrifying bacteria and methane sparging. Lab-scale bioremediation evaluation using various bacteria consortiums was previous implemented unsuccessfully on site soils.
	1997	Haller, Jan; Niwayama, Satomi; Duh, How-Yunn & Houk, K. N.	Stereoselective Diels- Alder Reactions of Hexachlorocyclopentadiene with Chiral Alkenes: New Insights Into the Inside-Alkoxyl Model of Stereoselectivity	The Journal of Organic Chemistry	62	17	
	1995	Nubbe, Mary E.; Adams, V. Dean & Moore, William M.	The direct and sensitized photo-oxidation of hexachlorocyclopentadiene	Water Research	29	5	
★	1995	Aislabie, J. & Lloyd-Jones, G.	A review of bacterial-degradation of pesticides	Soil Research	33	6	A 20-year old overview on known bacteria degradation of select pesticides. C56 and C58 are not presented in paper.
	1994	Abraham, M. H.; Andonian-Haftvan, J.; Whiting, S.; Leo, A. & Taft, S.	Hydrogen bonding. Part 34. The factors that influence the solubility of gases and vapors in water at 398 K, and a new method for its determination	J. Chem. Soc., Perkin. Trans.	2		

	1993	Chou, C.	Soil Decontamination. US Patent 5209604	US Patent Office			Patent using direct heat via a mobile track-mounted system. Shallow soil treatment technology.
	1987	Suntio, L. R.; Shiu, W. Y.; Mackay, D.; Seiber, J. N. & Glotfelty, D. E.	Critical review of Henrys law constants for pesticides	Rev. Environ. Contam. Toxicol.	103		
	1982	Wolfe, N. L.; Zepp, R. G.; Schlotzhauer, P. & Sink, M.	Transformation pathways of hexachlorocyclopentadiene in the aquatic environment	Chemosphere	11	2	Previously reviewed toxicology article.
	1980	DeLeon, Ildefonso R.; Brown, N. Jean; Cocchiara, Joy P.; Miles, Sarah K.; Laseter, John L.; Kremer III, Eugene H. & Makk, Laszlo	Determination of Trace Levels of Hexachlorocyclopentadiene and Octachlorocyclopentene in Body Fluids	Journal of analytical toxicology	4	6	Previously reviewed toxicology article.
	1980	Mazzocchi, Paul H.; Stahly, Barbara; Dodd, John; Rondan, Nelson G.; Domelsmith, L. N.; Rozeboom, Melvin D.; Caramella, Pierluigi & Houk, K. N.	pi.-Facial stereoselectivity: rates and stereoselectivities of cycloadditions of hexachlorocyclopentadiene to 7-substituted norbornadienes and photoelectron spectral and molecular orbital computation investigations of norbornadienes	Journal of the American Chemical Society	102	21	
	1979	Spehar, R. L.; Veith, G. D.; DeFoe, D. L. & Bergstedt, B. V.	Toxicity and bioaccumulation of hexachlorocyclopentadiene, hexachloronorbornadiene and heptachloronorbornene in larval and early juvenile fathead minnows, Pimephales promelas	Bulletin of environmental contamination and toxicology	21	1	Previously reviewed toxicology article.
	1975	Hine, J. & Mookerjee, P. K.	The intrinsic hydrophilic character of organic compounds, correlations in terms of structural contribution	J. Org. Chem.	40		
	1972	Sweeney, K.H.; Fischer, J.R.	Reductive Degradation of Halogenated Pesticides. US Patent 3640821	US Patent Office			
	1970	Mod, Robert R.; Magne, Frank C.; Skau, Evald L. & Sumrell, Gene.	Hexachlorocyclopentadiene adducts of unsaturated amides	Journal of Medicinal Chemistry	13	2	
	1969	Lyon, C. K. & Fuller, Glenn	Flame-Resistant Urethane Foams from Adducts of Hexachlorocyclopentadiene and Castor Oil	Product R\&D	8	1	
	1966	others	Process for the treatment of metallic compounds with octachlorocyclopentene				
	1966	Feoktistov, L. G.	Unusual dependence of the polarographic behavior of halogensubstituted octachlorocyclopentene and hexachlorocyclopentadiene on pH of the solution	Elektrokhimiya	2		
	1966	Little, L.S.; Isroe, B.A.	Treatment of Hexachlorocyclopentadiene. US Patent 3258499	US Patent Office			Patent for synthesis and production of C56. Not a treatment technology.
	1965	Liva, M. & Hriv, k, J.	The analysis of technical hexachlorocyclopentadiene by infrared spectrophotometric and gas-liquid chromatographic methods	Analyst	90	1072	
	1964	Brooks, G. T. & Harrison, A.	The effect of pyrethrin synergists, especially sesamex, on the insecticidal potency of hexachlorocyclopentadiene derivatives (cyclodiene insecticides) in the adult housefly, Musca domestica L	Biochemical pharmacology	13	6	
	1964	McBee, E.; Dilling, Wendell & Braendlin, H.	Additions and Corrections - The Pyrolysis of Hexachlorocyclopentadiene.	The Journal of Organic Chemistry	29	12	Liquid phase pyrolysis of C56 yields C58 and others compounds including hexachlorobezene. Not a treatment technology paper.
	1963	McBee, E. T.; Dilling, Wendell L. & Braendlin, H. P.	The Pyrolysis of Hexachlorocyclopentadiene	The Journal of Organic Chemistry	28	9	Liquid phase pyrolysis of C56 yields C58 and others compounds including hexachlorobezene. Not a treatment technology paper.

	1963	McBee, E.; Dilling, Wendell & Braendlin, H.	Additions and Corrections-The Pyrolysis of Hexachlorocyclopentadiene	The Journal of Organic Chemistry	28	12	Liquid phase pyrolysis of C56 yields C58 and others compounds including hexachlorobezene. Not a treatment technology paper.
	1961	Society, American Chemical	BRIEFS - C-56 (hexachlorocyclopentadiene) benzyl chloride Nialk Trichlorethylene	Chemical \& Engineering News Archive	39	50	
	1960	Roberts, Carleton & Haigh, Daniel	Notes- Diels-Alder Adducts of Hexachlorocyclopentadiene with Allyloxyalkanols	The Journal of Organic Chemistry	25	7	
	1960	Morrison, D.	Notes- An Adduct of Hexachlorocyclopentadiene with Acenaphthylene	The Journal of Organic Chemistry	25	9	
	1960	McKinney, R. M. & Pearce, G. W.	Isotope-Labeled Insecticides, Synthesis of Carbon-14-Labeled Aldrin and Dieldrin	Journal of Agricultural and Food Chemistry	8	6	
	1960	Fields, Ellis K.	Novel Derivative of Hexachlorocyclopentadiene. US Patent 2952710	US Patent Office			Patent previously not identfied during 2014 search.
	1956	Fields, Ellis K.	Thiophosphoryl Derivatives of the Adducts from Hexachlorocyclopentadiene and Unsaturated Alcohols	Journal of the American Chemical Society	78	22	
	1956	McBee, E. T.; Roberts, C. W. & Idol Jr, J. D.	Ring Opening by Chlorinolysis in a Highly Chlorinated Dicyclopentadiene	Journal of the American Chemical Society	78	5	
	1956	Maude, Aylmer H. & Rosenberg, David S.	Dechlorination of octachlorocyclopentene to hexachlorocyclopentadiene. US Patent 2742506	US Patent Office			Patent for production of C56 using nickel catalyst. Patent previously not identified in 2014.
	1955	Idol Jr, James D.; Roberts, C. W. & McBee, E. T.	The Ultraviolet Spectra of Chlorine-containing Cyclopentenes and Cyclopentadienes	The Journal of Organic Chemistry	20	12	
	1955	Treon, J. F.; Cleveland, F. P.; Cappel, J. & others	The toxicity of hexachlorocyclopentadiene.	Arch. Indust. Health	11	6	
	1955	McBee, E. T. & Smith, D. K.	The Reduction of Hexachlorocyclopentadiene. 1,2,3,4,5-Pentachlorocyclopentadiene1	Journal of the American Chemical Society	77	2	
	1955	McBee, E. T.; Smith, D. K. & Ungnade, H. E.	The Absorption Spectra of Halogenated Cyclopentenones	Journal of the American Chemical Society	77	3	
	1955	McBee, E. T.; Idol, J. D. & Roberts, C. W.	Chemistry of Hexachlorocyclopentadiene. VI. Diels-Alder Adducts with Alkynes1	Journal of the American Chemical Society	77	24	
	1955	McBee, E. T.; Rakoff, H. & Meyers, R. K.	Chemistry of Hexachlorocyclopentadiene. V. 1 The Diels-Alder Reactions with Allylic and Halogen-containing Dienophiles	Journal of the American Chemical Society	77	16	
	1955	McBee, E. T.; Idol Jr, J. D. & Roberts, C.-W_	Chemistry of Hexachlorocyclopentadiene. III. Synthesis of Bis-(pentachlorocyclopentadienyl) and Related Compounds1, 2	Journal of the American Chemical Society	77	16	
	1955	Johnson, A.N.	Condensation of Hexachlorocyclopentadiene. US Patent 2724730	US Patent Office			Patent previously not identfied during 2014 search.
	1954	Fields, Ellis K.	Reactions of Monoalefins and Hexachlorocyclopentadiene	Journal of the American Chemical Society	76	10	
	1954	Robitschek, P. & Bean, C. Thomas	Flame-Resistant Polyesters from Hexachlorocyclopentadiene	Industrial & Engineering Chemistry	46	8	
	1953	McBee, Earl T. & Newcomer, Jack S.	Hexachlorocyclopentenone Preparation. US Patent 2650939	US Patent Office			Patent previously not identfied during 2014 search.
	1952	Herzfeld, S.; Lidov, E., Bluestone, H.	Diels-Aldter Adducts of Hexachlorocyclopentadiene. US Patent 2606910	US Patent Office			Patent previously not identfied during 2014 search.
	1951	McBee, E.T.; Newcomer, J.S.	Fluorosulfonic Acid treatment of Hexachlorocyclopentadiene. US Patent 2552568	US Patent Office			Patent previously not identfied during 2014 search.

Appendix A

2017 Literature and Patent Search

Former OCC Site, Montague, Michigan

	1951	Yowell, Howard L.	Fungicidal compositions containing hexachlorocyclopentadiene. US Patent 2548509	US Patent Office			Patent previously not identfied during 2014 search.
	1950	McBee, E; Branauchas, C.	Making Hexachlorocyclopentadiene. US Patent 2509160	US Patent Office			Original patent for production of C56, Purdue University.
	1950	Hyman, J.	Polyhalogenated polycyclic hydrocarbons and insecticides thereof. US Patent 2519190	US Patent Office			
	1949	Newcomer, J. S. & McBee, E. T.	The Chemical Behavior of Hexachlorocyclopentadiene. II. Condensation with Trichloroethylene	Journal of the American Chemical Society	71	3	
	1949	Newcomer, J. S. & McBee, E. T.	The chemical behavior of hexachlorocyclopentadiene. I. Transformation to octachloro-3a, 4, 7, 7a-tetrahydro-4, 7-methanoindene-1, 8-dione	Journal of the American Chemical Society	71	3	
	1949	Krynitsky, J. A. & Carhart, H. W.	Pyrolysis and Chlorinolysis of Some Perchlorinated Unsaturated Hydrocarbons	Journal of the American Chemical Society	71	3	
	1949	McBee, E. T. & Baranauckas, C. F.	Production of Hexachlorocyclopentadiene.	Industrial & Engineering Chemistry	41	4	
	1948	Krynitsky, J. & Bost, R.	Additions and Corrections - The Preparation of Hexachlorocyclopentadiene and Certain Derivatives	Journal of the American Chemical Society	70	12	
	1947	Krynitsky, J. A. & Bost, R. W.	The Preparation of Hexachlorocyclopentadiene and Certain Derivatives	Journal of the American Chemical Society	69	8	
	1947	Prill, Edward A.	Diels-Alder Syntheses with Hexachlorocyclopentadiene	Journal of the American Chemical Society	69	1	
	1941	Huggins, M. L.	Solutions of long chain compounds	J. Chem. Phys.	9		

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