LNAPL RECOVERY ASSESSMENT REPORT
DELPHI AUTOMOTIVE SYSTEMS SITE
1000 LEXINGTON AVENUE
ROCHESTER, NEW YORK

by

Haley & Aldrich of New York
Rochester, New York

for

GM Components Holdings, LLC
Rochester, New York

File No. 70014-102
June 2012

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New York State Department of Environmental Conservation
Division of Environmental Remediation
Region 8 Office
6274 East Avon-Lima Road
Avon, New York 14414

Attention: Kelly Cloyd, PhD.
Environmental Geologist II

Subject: LNAPL Recovery Assessment Report
Delphi Automotive Systems Site
NYSDEC Registry Site #828064
1000 Lexington Avenue
Monroe County, Rochester, New York

Dear Dr. Cloyd:

On behalf of GM Components Holdings, LLC (GMCH), Haley & Aldrich of New York has prepared this *LNAPL Recovery Assessment Report* for the Delphi Automotive Systems Site in Rochester, New York (Site). This document was prepared to establish the process and criteria to satisfy one of the remedial program components identified in the New York Department of Environmental Conservation's Record of Decision (ROD) issued for the Site on March 31, 2011.

Please don't hesitate to call us at 585.321.4245 if you have questions or wish to discuss the findings and recommendations in this report.

Sincerely,
HALEY & ALDRICH OF NEW YORK

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1 INTRODUCTION

On behalf of GM Components Holdings (GMCH), Haley & Aldrich of New York has prepared this *LNAPL Recovery Assessment Report* for the Delphi Automotive Systems Site in Rochester, New York. This document was prepared to address the requirement in the New York State Department of Environmental Conservation (NYSDEC) Record of Decision (ROD) dated March 31, 2011, for "An effectiveness study [to] evaluate NAPL in areas adjacent to the existing NAPL collection points to determine if more aggressive collection techniques are required. Methods to be considered include, but are not limited to: surfactant enhanced recovery, vacuum enhanced recovery, and/or additional recovery wells, etc."

This report presents the historical and current efforts to characterize and recover LNAPL at the Site and sets forth GMCH's approach for an ongoing assessment of LNAPL recovery that will be conducted under the Site Management Plan (SMP), which is another ROD-required remedial program component.

Section 2 of the report presents the site history and summarizes the findings of the Remedial Investigation (RI) and Feasibility Study (FS) activities related to the remediation of LNAPL at the site. This section also identifies the components of the NYSDEC ROD pertinent to the remediation of LNAPL at the site.

Section 3 of the report presents the site subsurface conditions including the geologic and hydrogeologic setting for each area of the Site that have been impacted by LNAPL.

Section 4 presents a conceptual model for the fate and transport of LNAPL in unconsolidated porous media and a conceptual model for the fate and transport of LNAPL in bedrock is discussed in Section 5.

Section 6 describes the nature and extent of the different LNAPL occurrences present in various areas of the Site including historical observations of the impacts to the overburden and bedrock groundwater bearing units.

Section 7 presents the historical and current remedial measures that have been implemented to remediate LNAPL at the Site. Section 8 presents a discussion on the potential for future LNAPL recovery at the site. Section 9 discusses the risks associated with the presence of LNAPL at the site.

Section 10 presents the report conclusions including recommendations for additional LNAPL recovery at the various locations throughout the Site.

2 SITE HISTORY

The Delphi Automotive Systems Site (Site) is located at 1000 Lexington Avenue in the City of Rochester, Monroe County, New York (**Figures 1** and **2**). The Site consists of approximately 87 acres of land located north of Lexington Avenue with a 1.8 million square foot manufacturing building with administrative and engineering offices and numerous smaller buildings used for storage, utility, industrial wastewater pretreatment, and security activities.

General Motors Corporation (GMC) built the original manufacturing building and began manufacturing operations at the Site in 1938. The facility has been used for producing a variety of automotive parts, but automotive fuel systems have been the primary product line since 1945. Manufacturing processes at the Site include machining and forming of metal parts, metal tube manufacturing, metal plating, heat treating, die casting, solvent degreasing, injection molding of plastic parts, and the assembly of finished automotive parts and fuel systems. Fuel systems flow testing and calibration, engine output testing, and related product engineering and testing operations have also been conducted at the facility, as well as wastewater pre-treatment and steam generation for plant heating.

Various GMC divisions operated the facility until ownership of the Site and its operation were transferred to Delphi Automotive Systems LLC ("Delphi") in 1999. In October 2009, GMCH acquired the facility and is currently performing operations at the Site.

2.1 Remedial Investigation

Since 1981, GMC and then Delphi have performed environmental investigations and remediation activities at the Site. An Order on Consent, Index #B8-0531-98-06, between Delphi and the New York State Department of Environmental Conservation (NYSDEC) (effective February 4, 2002) specified the development and implementation of a Remedial Investigation (RI) and a Feasibility Study (FS) to address the areas of environmental contamination or potential contamination that had been identified at the Site. The RI report, dated November 7, 2005, was prepared by Haley & Aldrich of New York and approved by the NYSDEC Division of Environmental Remediation.

Much of the RI activities were devoted to addressing data gaps. The areas where additional data were needed included the delineation of potential on-site sources of contamination that had not been previously investigated and off-site areas to the north and east of the site that were potentially downgradient of the previously-identified source areas of on-site groundwater contamination. The RI was performed from November 2001 through July 2005 resulting in the following summary of the principal findings:

- Site groundwater is impacted with chlorinated volatile organic compounds (cVOCs). Contaminated groundwater extends downgradient from the manufacturing building to the northern and slightly beyond the eastern property boundaries. The vertical extent of the contamination is limited to the overburden groundwater bearing unit and the top 25 feet of underlying bedrock.

- LNAPL is present in areas beneath the manufacturing building and beyond the building footprint to the north and east. The LNAPL consists of machining oils used as lubricants during metal-machining operations, and simulated fuels and calibration fluids used in engineering and product-testing operations. In some areas, the LNAPL contains cVOCs and polychlorinated biphenyls (PCBs). In the eastern portion of the Site, LNAPL is present in the Intermediate

Bedrock Unit at 10 to 25 feet below the top of bedrock and extends slightly beyond the eastern site boundary.

- Soil and soil vapor are impacted by cVOCs beneath the floor slab at the locations of former solvent degreaser systems.

The Site conditions were evaluated for current and future potential risk to human-health and ecological resources in accordance with applicable New York State and USEPA guidance. The findings of the risk assessment indicate that no unacceptable risks to human health or ecological resources exist under current Site use as an industrial manufacturing facility.

For reasonably anticipated future Site activities (continued use as a manufacturing facility), a condition of no risk to human health, public welfare, safety, or the environment exists. However, there is a potential for adverse health effects to temporary utility maintenance and temporary construction workers engaged in extended excavation and remediation activities (or other unrestricted Site activities and uses that would result in similar exposure to the identified Site conditions) unless precautionary measures are taken.

Paragraph III.B of the RI/FS Order noted the following Interim Remedial Measures (IRMs) on the Site:

- Groundwater Migration Control, Collection and Treatment System. This system intercepts, collects, and treats contaminated groundwater from intermediate bedrock moving downgradient from the manufacturing buildings at the Site;

- LNAPL recovery systems that were implemented in a Tank Farm Area (located at the northeast corner of the manufacturing building at the Site) and in the area of Building 22; and

- Soil Vapor Extraction System (Degreaser Investigation Study Area 5). [Note: This IRM was not included in the March 2011 ROD selected remedy and has been shut down.]

These IRMs continued in operation during the RI/FS work and the Order required that they be evaluated as part of the FS and the remedy selection process to determine if they will be part of the selected remedial alternative for the Site.

2.2 Feasibility Study

A Feasibility Study (FS) was performed to identify and recommend a preferred remedial alternative. The FS report, dated July 31, 2008, was prepared by Haley & Aldrich of New York.

The recommended remedial alternative is a combination of the following:

- Institutional controls consisting of a deed restriction that will:
    - Prohibit the use of Site groundwater for any purpose without prior review and approval by NYSDEC;
    - Restrict the use of the Site to industrial or commercial operations; and
    - Require the use of a NYSDEC-approved Site Management Plan (SMP) for any activities that could potentially involve exposure to COCs and provide for periodic monitoring of groundwater quality, the operation of the existing remedial systems, and LNAPL occurrence.

- Continued operation of the groundwater migration-control, collection, and treatment system to capture cVOC impacted groundwater north and east of the manufacturing plant. Primary treatment of the recovered groundwater would be conducted on-site with secondary treatment by Monroe County Pure Waters under existing facility sewer use permits.

- Installation and operation of additional bedrock groundwater recovery wells to enhance the control of dissolved phase groundwater contamination along the eastern property boundary and the occurrence of LNAPL in the East Parking Lot.

- Continued operation of LNAPL recovery systems in the Tank Farm area located east of the manufacturing building. Recovered LNAPL and groundwater would receive primary treatment using the on-site wastewater pre-treatment system. The recovered LNAPL would be sent to a licensed off-site facility for reclamation or fuel blending. The groundwater would be discharged and receive secondary treatment by Monroe County Pure Waters under existing facility sewer use permits.

- Continued operation of the LNAPL-recovery system installed in the Building 22 area. The recovered LNAPL would be containerized and disposed off-site at a Treatment Storage and Disposal Facility (TSDF) permitted to receive, treat, and dispose of waste containing PCBs. Recovered groundwater would be blended with groundwater from the migration control trench for subsequent treatment.

- Additional LNAPL recovery consisting of the manual removal of LNAPL from existing wells installed in the former UST A area east of Building 1, near the Machining Oil Recovery basement adjacent to well R-309, and in the CWTA courtyard area north of Building 2. This additional LNAPL removal would be coordinated with the facility to minimize disruption of manufacturing operations.

- Mitigation methods would be used to limit the potential migration of VOC-impacted soil vapor into the manufacturing plant from the subsurface. These technologies would include the following methods:

    - Floor sealants to restrict diffusion of soil gas through the facility floor and expansion joints;

    - HVAC system operation and management to minimize the potential for soil vapor intrusion. The operation and maintenance of the facility HVAC system will be implemented and monitored by GMCH personnel; and

    - Periodic inspection/air quality monitoring to evaluate HVAC system performance, including periodic inspection and indoor air quality testing.

2.3 Record of Decision

On March 31, 2011, the NYDEC issued a Record of Decision (ROD) for the Site. LNAPL-related components of the selected remedy include:

- Continued LNAPL recovery in the Building 22 and Tank Farm areas, including additional recovery methods in a manner allowing for continued site operations;
- An effectiveness study to evaluate NAPL in areas adjacent to the existing NAPL collection points to determine if more aggressive collection techniques are required.

3 SITE GEOLOGY AND HYDROGEOLOGY

3.1 Geologic Setting

The Site is underlain by unconsolidated fill and native soil (overburden), which varies in total thickness from five to approximately 25 feet. The presence or absence of native or fill overburden is variable across the Site. Bedrock beneath the overburden is the Upper Silurian-aged Rochester Shale which dips to the south at approximately 40 feet per mile. Deep bedrock wells on the northern side of the Site penetrate the Rochester Shale and intersect the underlying Irondequoit Limestone.

Overburden - The overburden generally consists of fill, lacustrine sediments, glacial till, glaciolacustrine sediments, residual soil on weathered bedrock, and weathered bedrock consisting of a dense gray-brown silt to fine sand with the fabric of the original bedrock. Additionally, soft, black swamp deposits have been encountered, primarily north of the manufacturing building within the footprint of a former canal wide-waters basin. In general, the overburden consists of interbedded layers of sand, silt, and clay, or heterogeneous mixtures of various grain sizes.

Bedrock - The Rochester Shale underlies the overburden across the Site and consists of a moderately-hard, fine grained, gray to brown-gray dolomitic mudstone with horizontal bedding planes, occasional pits, vugs, fossils, and secondary gypsum mineralization in available openings and as fossil replacement mineralization. Beneath the Rochester Shale lies the Irondequoit Limestone, a hard, gray to green-gray, fossiliferous limestone with horizontal bedding and occasional vugs.

3.2 Hydrogeologic Setting

The following four (4) hydrogeologic units are recognized at the Site.

Overburden Unit – Saturated unconsolidated overburden deposits. Wells monitoring this unit include wells labeled with ‘OW-’, a number of piezometers (labeled with ‘PZ-’), and Tank Farm area recovery wells RW-101, RW-2, and RW-3.

Shallow Bedrock Unit – This unit consists of the upper seven feet of bedrock. Wells monitoring this unit include wells labeled with an ‘SR’ prefix, piezometers PZ-115, -129, -130, -133 through -144, and Building 22 LNAPL recovery well RW-4.

Intermediate Bedrock Unit – This unit consists of the interval approximately 10 feet to 25 feet below the top of bedrock surface. Monitoring wells labeled with an ‘R’ prefix are installed within this unit with an open interval of approximately 15 feet.

Deep Bedrock Unit - This unit consists of the interval approximately 30 feet to 65 feet below the top of bedrock surface. Wells labeled with a ‘DR’ prefix are installed within this unit with an open interval of approximately 15 feet (about 50 to 65 feet below the top of bedrock surface).

An evaluation of core boring reports for Shallow Bedrock, Intermediate Bedrock, and Deep Bedrock Unit monitoring wells indicate that joints encountered within the Rochester Shale are predominantly horizontal to low angle, with some horizontal clay partings. These horizontal joints are likely related to bedding planes within the Rochester Shale. Thin (generally less than one or two feet thick), discrete zones described as “highly fractured” also exist, with an occasional vertical or high angle fracture described in the core log.

Hydraulic conductivities estimated from single well tests are variable, in particular within the Intermediate Bedrock Unit where hydraulic conductivity is a function of the aperture size and interconnectedness of the fracture network intersected by the monitoring well. Estimated hydraulic conductivities within the Overburden Unit, and Shallow, Intermediate, and Deep Bedrock Units (from single well tests) are provided in **Table 1**.

A groundwater migration control, collection, and treatment system was constructed and began operation in the spring of 1992, consisting of a 1,200-foot long migration control trench located beneath the north parking lot (**Figure 2**). The migration control trench was created using engineered-blasting techniques to enhance bedrock aquifer permeability. Two wells (GR-1 and GR-2) installed in the 50-foot-deep blasted zone are used to pump groundwater. During the RI, the average total groundwater extraction rate was 22 gallons per minute.

Prior to the startup of the groundwater migration control system, lateral groundwater migration at the Site in the Overburden, Shallow Bedrock, and Intermediate Bedrock Units was to the north-northeast. While the overall groundwater migration direction for most of the Site is still to the north-northeast, since the start of the groundwater migration control system, an elongated water level depression in the potentiometric surfaces of the Shallow and Intermediate Bedrock Units has developed (**Figures 3** and **4**), and lateral groundwater migration direction in the Shallow and Intermediate Bedrock Units in the area north of the migration control system has reversed, with an overall flow direction to the south towards the migration control trench.

Based on January 2008 water level data, the overall lateral hydraulic gradient across the Site was approximately 0.017 ft/ft (Shallow Bedrock Unit) and 0.016 ft/ft (Intermediate Bedrock Unit). An evaluation of October 2004 water level data from on-Site monitoring well pairs indicates a consistent downward gradient from the Shallow Bedrock to the Intermediate Bedrock Unit ranging from 0.05 to 4.38 ft/ft[1]. In general, the vertical gradients were relatively steep (greater than 1 ft/ft), suggesting a general lack of hydraulic communication between the Shallow Bedrock and Intermediate Bedrock Units.

During October 2004, vertical gradients were generally downward from the Intermediate Bedrock to Deep Bedrock Unit (except for an upward gradient of 1.15 ft/ft at R-131/DR-315 well pair), ranging from 0.0049 to 2.06 ft/ft. These water level data, along with water quality data at Deep Bedrock Unit monitoring wells, suggest a lack of hydraulic communication between the Intermediate Bedrock and Deep Bedrock Units.

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[1] During January 2008, an upward hydraulic gradient existed at well pair SR-301/R-301 (1.08 ft/ft) along the northwest Site property boundary, and at off-Site well pair SR-304/R-304 (0.14 ft/ft).

4 LNAPL IN UNCONSOLIDATED POROUS MEDIA – CONCEPTUAL MODEL

LNAPL in unconsolidated, porous media occurs as a result of vertical drainage of released LNAPL under gravity and capillary forces. As the LNAPL moves downward in the unsaturated zone, it is subject to volatilization, entrapment of all or part of the LNAPL, and dissolution of LNAPL constituents in pore water. These forces comprise the retention capacity of the soil. If the LNAPL release is either sufficiently large and/or continuous, the retention capacity of the unsaturated soils will be exceeded, and LNAPL will continue moving downward to the capillary fringe above the water table. As LNAPL reaches pore spaces either partially or fully saturated with water, the weight of the LNAPL will displace pore water, with selective entry of LNAPL into larger pore spaces, until hydrostatic equilibrium is reached.

In the past, LNAPL was believed to exist as a thin, continuous layer of hydrocarbons "floating" on top of the water table. More recently, the LNAPL conceptual model has been changed to a multi-phase system, with LNAPL, air, and water coexisting in the subsurface at variable LNAPL saturations, with the highest saturation typically at the capillary fringe. This conceptual model is analogous to an iceberg, with part of the LNAPL at or above the water table, and a significant portion of the LNAPL submerged below the water table, as shown in **Figure 5**.

Once LNAPL is at the water table, a rise in the water table may displace some of the LNAPL out of the pore space, depending on the LNAPL saturation and pore space size; some LNAPL may remain behind and become submerged below the water table, resulting in a vertical "smear zone". This submerged LNAPL is immobile, and will not flow into a well unless the water table declines and LNAPL saturation is sufficient for flow.

Initially, LNAPL occurs at the water table as a continuous network of pores containing interconnected LNAPL. With a significant release, these LNAPL-filled, interconnected pore spaces will continue to drive the lateral and vertical movement of LNAPL, as long as the driving head is sufficient to displace water from the pore spaces. Therefore, LNAPL migration generally occurs during the period of active release. Once the release of LNAPL stops, the LNAPL driving forces decrease with time. Ultimately, LNAPL pore spaces will become disconnected, and the LNAPL mobility will decrease until it ceases altogether at hydrostatic equilibrium. The saturation at which LNAPL is immobile is called the residual saturation. Once immobile, the LNAPL will only constitute a risk via direct contact, dissolution in groundwater, or volatilization to soil gas.

Once at or below the water table, the more soluble LNAPL constituents will begin to dissolve in groundwater, eventually forming a dissolved-phase groundwater plume in the downgradient direction. However, except for the aromatic hydrocarbons such as benzene, typical LNAPL constituents such as toluene, ethylbenzene, xylenes, and alkyl benzenes have relatively low aqueous solubility, and most LNAPL constituents, including the aromatic hydrocarbons, generally biodegrade over short distances from the LNAPL plume[2]. Therefore, LNAPL at or below the water table rarely results in large scale dissolved-phase hydrocarbon plumes.

The most common LNAPL recovery method is hydraulic removal such as pumping, bailing, or skimming. While these methods may initially be successful at removing LNAPL from the subsurface, it is a self-limiting process, as reducing the LNAPL saturation reduces the potential for further recovery, resulting in asymptotic recovery rates over time. In no case can any hydraulic recovery method reduce

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[2] However, some fuel additives such as MTBE are generally resistant to biological degradation.

the LNAPL to below residual saturation. Therefore, it is only the amount of time until residual saturation is met that differentiates hydraulic recovery methods. In reality, achieving residual saturation is an overly optimistic goal, given geologic uncertainties, inefficiencies of the recovery methods, and access limitations. Therefore, LNAPL saturation at completion of a hydraulic recovery method will likely be higher than residual saturation, even if asymptotic recovery rates are reached.

The conceptual model described above is for conditions where LNAPL is displacing water from the pore space; important differences occur when water is displacing LNAPL from pore spaces, such as during enhanced recovery methods such as water flooding. Once LNAPL is in the pore space, no matter what fluid pressures are applied, and regardless of the period of time for LNAPL recovery, water will not displace all of the LNAPL, resulting in entrapped, residual LNAPL which occurs as the once interconnected LNAPL becomes disconnected in the pore space. Even after enhanced recovery, this entrapped residual often exceeds 50 percent of the initial LNAPL volume (USEPA, 1996).

5 LNAPL IN BEDROCK – CONCEPTUAL MODEL

LNAPL behaves differently in fractured rock as compared to unconsolidated porous media. LNAPL occurrence and movement in bedrock are a function of the geometry, aperture width, and interconnectedness of the fracture network, and properties of the rock matrix such as primary porosity.

LNAPL from a significant release will migrate downwards in the unsaturated zone under the influence of gravity and capillary forces, moving wherever the LNAPL head is sufficient to overcome the entry pressure of a given fracture. LNAPL will preferentially enter fractures with larger apertures due to the lower entry pressures. Vertical and sub-vertical fractures will form the preferred flow paths, as LNAPL heads can build via vertically-connected LNAPL and the effect of gravity is greatest.

Relatively small volumes of interconnected LNAPL in vertical or sub-vertical fractures can produce significant pressure heads which may displace water within the fracture, resulting in LNAPL entry into fractures beneath the water table. LNAPL buoyancy and capillary forces will counteract the LNAPL head, limiting which fractures will be entered and the overall penetration depth. The end result is that LNAPL from a release may penetrate to significant depths below the water table due to buildup of LNAPL head in vertical and sub-vertical fractures, as shown in **Figure 6**[3].

LNAPL will enter a monitoring well that intersects a fracture that contains LNAPL at saturations sufficient for flow. However, the LNAPL thickness in the monitoring well is a function of the pressure head of the LNAPL in the fracture. Therefore, there is no correlation between the LNAPL thickness in a bedrock monitoring well and the LNAPL thickness within the adjacent formation.

As the water table fluctuates, LNAPL in fractures will rise and fall, in particular within vertical fractures with larger apertures. As the water table falls, LNAPL may enter into a newly unsaturated low angle fracture if the driving head can overcome the entry pressure. As the water level begins to rise, LNAPL in vertical, large aperture fractures will be most able to follow. However, some LNAPL will not be able to match the rate of groundwater rise, especially in smaller aperture, low angle fractures, and will become submerged below the water table. Hydraulic LNAPL recovery methods should therefore minimize changes in hydraulic head to prevent remobilizing LNAPL in bedrock fractures. The concepts of the wetting and non-wetting phase are the same in fractured bedrock as compared to porous media. Water (as the wetting phase) will coat the surfaces of the fractures, while LNAPL (as the non-wetting phase) will fill the remaining space within the fracture. LNAPL in small aperture fractures and disconnected LNAPL that is entrapped in fractures is generally immobile. Regardless of the recovery effort, LNAPL will always remain due to residual saturation, immobile LNAPL, the heterogeneous nature of fractured rock systems, access limitations, and inefficiencies of recovery methods.

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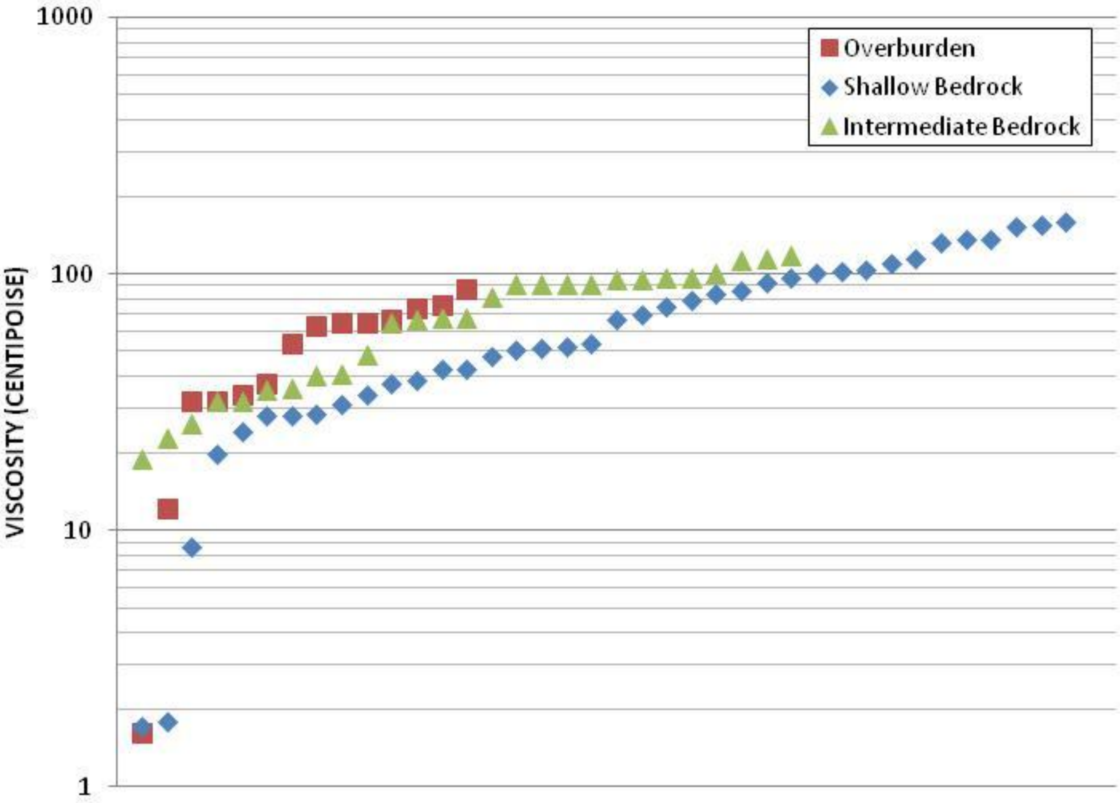
[3] This conceptual model also helps explain why LNAPL is present in Intermediate Bedrock Unit monitoring wells in the East Parking Lot, while LNAPL is absent in the Shallow Bedrock Unit monitoring wells in the same area. In this example, released LNAPL moves vertically through the Shallow Bedrock Unit and into the Intermediate Bedrock Unit, where it then moves laterally in the Intermediate Bedrock Unit due to the pressure head. In the vicinity of the East Parking Lot, the fracture network in the Shallow Bedrock Unit is not connected to the LNAPL release area. The result is a lack of LNAPL in Shallow Bedrock Unit monitoring wells in the East Parking Lot while Intermediate Bedrock Unit monitoring wells in this area contains LNAPL.

6 NATURE AND OCCURRENCE OF LNAPL AT THE SITE

LNAPL at the Site consists primarily of either lubricating oils released during metal machining operations or lighter weight fuel-like products used as calibration fluids and test fuel released during engineering and product testing operations. In most areas, both machining oil and lighter-weight test fluids are present in the LNAPL. **Table 2** provides the viscosity of LNAPL collected from monitoring wells in the Overburden Unit, and the Shallow and Intermediate Bedrock Units. The following graph presents the LNAPL viscosities from select Overburden, Shallow, and Intermediate Bedrock Unit monitoring wells.



As shown on the above graph, the majority of LNAPL viscosities for samples collected at the Site are between 20 and 100 centipoise [cP] and consistent with light motor oil. For comparison, the following table provides the viscosity of different fluids at a temperature of 25°C.

Fluid	Viscosity (cP @ 25ºC)
Water	0.894
Stoddard Solvent	0.95
Ethanol	1.074
Ethylene Glycol	16.1
Motor Oil (SAE10 @ 20ºC)	65
Olive Oil	81
Motor Oil (SAE40 @ 20ºC)	319

LNAPL is present at the water table (in Overburden and/or Shallow Bedrock Units) in five areas of the Site which may, to some degree, be continuous with each other. LNAPL is present in the following areas:

- Building 1 and 2 machining areas and the Tank Farm Area;
- East side of Building 1 (at well SR-236, in the courtyard between the east side of Building 1 and Building 3);
- North Parking lot;
- Building 22 area; and
- East Parking Lot.

In the East Parking Lot area, LNAPL is present in the Intermediate Bedrock Unit although LNAPL is absent in the Overburden and Shallow Bedrock Units in this area (**Figure 2**). Descriptions of LNAPL occurrences are presented below. The approximate extent of LNAPL in the Overburden and Shallow Bedrock Units, and the Intermediate Bedrock Unit, is shown on **Figure 2**. An evaluation of LNAPL thickness versus water level elevations indicates that, in general, LNAPL thicknesses in monitoring wells are relatively constant; for those wells that exhibit some variability in LNAPL thickness, there is no discernable correlation between water levels and LNAPL thickness. More recent LNAPL thickness measurements are provided in **Table 3**.

Based on the historical groundwater data from off-site perimeter wells, dissolved-phase groundwater impacts from LNAPL hydrocarbon constituents (such as ethyl benzene, toluene, xylenes, and alkyl benzenes) are limited to the vicinity of the LNAPL plume footprint. The hydrocarbon dissolved-phase plume is therefore stable, which indicates that the LNAPL plume is stable. As mentioned above, the formation of a limited, stable dissolved-phase hydrocarbon plume is the result of low aqueous solubility and high degradation rates for most LNAPL constituents.

LNAPL constituents that are relatively soluble in groundwater, such as chlorinated VOCs, are captured by the groundwater migration control trench. Two (2) additional groundwater recovery wells (GR-3 and GR-4), were installed in 2011 to provide hydraulic control of VOC-impacted groundwater along the southeast portion of the Site. The operation of these recovery wells in the near future will enhance groundwater migration control along the eastern property boundary.

6.1 LNAPL in Building 1 and 2 Machining Areas and the Tank Farm Area

In the Building 1 and 2 machining areas, the LNAPL occurrences encompass former degreaser areas that were identified during the RI as the source for chlorinated VOCs[4] present in the LNAPL. The Building 1 LNAPL also overlaps former product engineering and fuel-system testing areas which were the sources of aromatic VOCs such as BTEX and substituted benzenes. Underground product lines have been removed from service over time and although some underground gravity lines are still in service, the final pressurized lines were decommissioned in 2007. The former Stoddard Solvent Tank Farm and associated product transfer lines were replaced as part of an approved interim remedial measure (IRM) conducted during the preparation of the FS report in 2006. The former earthen bermed tank farm was replaced with a concrete wall containment structure with double walled underground transfer lines installed to mitigate the potential for release of product to the subsurface.

In the machining areas of both Building 1 and 2, LNAPL is present within the Overburden and the

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[4] The primary chlorinated VOC detected in LNAPL in the Building 1 and Building 2 areas is the TCE breakdown product vinyl chloride.

Shallow Bedrock Units. The Building 2 LNAPL extends north to the Central Waste Treatment Area (CWTA) courtyard. The Building 1 LNAPL extends north beyond the northeast corner of Building 1 out into the Tank Farm Area where LNAPL is present in the Overburden Unit.

6.2 LNAPL at the East Side of Building 1 (SR-236)

LNAPL on the east side of Building 1 at Shallow Bedrock Unit monitoring well SR-236 appears to be a distinct, localized occurrence related to a former underground storage tank (UST) that was used for waste automotive fluids (motor oil, gasoline, etc.) from product engineering activities.

The SR-236 area LNAPL is primarily composed of heavier, lubricating-oil hydrocarbons, consistent with the LNAPL present in the Intermediate Bedrock Unit at companion monitoring well R-236[5]. The four (4) USTs in this area were removed from service in this area in 1987.

6.3 LNAPL at the North Parking Lot

In the center of the North Parking Lot, LNAPL occurs intermittently at some of the Shallow Bedrock Unit monitoring wells located along the Driving Park leg of the municipal sewer (PZ-136, PZ-137, and PZ-138) near migration-control recovery well GR-2. LNAPL has been observed in GR-2 and southeast of GR-2 in migration control trench monitoring well R-240. In the past, LNAPL has been present at sewer tunnel monitoring well PZ-139, located near the southeast end of the migration control trench.

The North Parking Lot LNAPL is dominated by light-weight test fluids, and most closely resembles LNAPL present at OW-327, which is located in the north end of Building 1 just west of the Tank Farm Area. The source of the LNAPL in the center of the North Parking Lot is not known, but the RI data suggest that it may have migrated to this area from the Tank Farm Area in the fill surrounding the Driving Park segment of the sewer tunnel. The segment of the sewer tunnel located beneath the North Parking Lot, northwest of PZ-139, was constructed in a cut-and-fill excavation.

6.4 LNAPL at Building 22 Area

The Building 22 Area LNAPL consists primarily of Stoddard solvent, a lighter-weight petroleum-based solvent similar to mineral spirits that was used as a test fluid in Building 22 carburetor testing operations. The extent of LNAPL in the Building 22 area decreased during the remedial investigation, apparently resulting from the operation of the Building 22 Area LNAPL recovery system. In the past, the Building 22 LNAPL extended from the CWTA courtyard north under Building 22 to Building 14.

6.5 LNAPL at the East Parking Lot

LNAPL at the East Parking Lot area occurs in the Intermediate Bedrock Unit, while LNAPL is absent in the Overburden and Shallow Bedrock Units in this area. This occurrence appears to originate from the eastern portion of Building 1, and extends under the East Parking Lot, slightly beyond the eastern Site boundary. It consists of both machining oil and petroleum test fluids and contains chlorinated VOCs[6]. PCBs have been detected in the LNAPL at monitoring well locations related to the RG&E substation located on the south side of Lexington Avenue, opposite the southeast corner of the Site.

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[5] Three LNAPL samples were collected from both SR-236 and R-236 during the RI. The viscosity of LNAPL at SR-236 ranged from 34 to 135.6 cPs, while the viscosity at R-236 ranged from 40.9 to 113 cPs.

[6] The primary chlorinated VOC detected in LNAPL in the East Parking Lot area is the TCE breakdown product vinyl chloride.

7 LNAPL INTERIM REMEDIAL MEASURES

7.1 Tank Farm Area LNAPL Recovery

Since 1989, a LNAPL recovery system has been in operation in the Tank Farm area located at the northeast corner of the manufacturing building. LNAPL recovery was implemented to collect LNAPL in the Overburden Unit, which consists of a mixture of Stoddard solvent, other gasoline-like test fuels, and machining oils.

The LNAPL recovery system includes three (3) large-diameter recovery wells (RW-101, RW-2, and RW-3) installed along a 400 foot long gravel-filled trench. The locations of the recovery wells and trench are shown on **Figure 2**.

Initial LNAPL recovery operations consisted of passive skimming of LNAPL from the water table at the three (3) recovery wells. In November 1994, the passive skimmers were replaced with a total fluids pumping system installed in RW-2, located in the middle of the LNAPL recovery trench. Oil is removed and groundwater is treated prior to discharge with facility wastewater to the municipal sewer. The municipal sewer flows to the Publicly Owned Treatment Works (POTW) for Monroe County.

Because the oil and groundwater removed from the total fluids system is mixed with other facility process wastewater prior to on-site treatment, LNAPL removal data from the Tank Farm LNAPL recovery system is not available. However, during 2004, the facility performed an oil-water separator trial for the RW-2 discharge. Approximately 475 gallons of LNAPL was recovered during the 5-week trial period. Facility process changes were made in 2010, and groundwater and oil recovered from RW-2 were for a time pumped to an oil/water separator that serviced only two other sources of wastewater with minor oil residue (barrel washer and BE washer); total oil recovery from the oil/water separator was on the order of one gallon/week (Eisenman, personal communication, 2011). Since the oil/water separator serviced RW-2, the barrel washer, and the BE washer, the best case removal rate from RW-2 is about one gallon/week.

Therefore, LNAPL removal from the Tank Farm Recovery System has decreased from about 100 gallons/week in 2004 to about one gallon/week, indicating that LNAPL is at or near residual saturation in the vicinity of this recovery system.

7.2 Building 22 Area LNAPL Recovery

Since 1995, a LNAPL recovery system has been in operation inside Building 22. The system was installed to address LNAPL consisting of Stoddard solvent contaminated with PCBs. Stoddard solvent was used in Building 22 as a calibration fluid for carburetor testing operations, and was released from underground piping during operations. The source of the PCBs has not been identified, but it is suspected that the LNAPL may have leached PCBs from contaminated soil or fill present in the subsurface beneath Building 22 (Haley & Aldrich, 2005).

The LNAPL recovery system originally consisted of a passive LNAPL skimmer and pump installed in well RW-4 (Shallow Bedrock Unit) inside Building 22. In 1999, vacuum-enhanced total fluids pumping was implemented at well RW-4, and a total fluids pumping system was added at Well Z (Shallow Bedrock Unit), located east of Building 22. Collection of LNAPL and groundwater from the foundation drain system for the Additional Waste Treatment Area (AWTA) building (Building 14) located north of Building 22 was also added at that time.

LNAPL and groundwater collected from these three (3) extraction points are routed through a coalescing filter oil-water separator inside the AWTA building. Collected LNAPL is placed in drums and shipped off-site for disposal, and the separated groundwater from the Building 22 system is passed through particulate filters and co-mingled with groundwater collected from the migration-control system recovery wells prior to discharge to the municipal sewer under the facility sewer use permit.

Between the implementation of upgrades to the system in 1999 and the end of 2000, approximately 2,000 gallons of LNAPL were recovered by the Building 22 area system. Since the beginning of 2001, 500 gallons of product have been recovered, and the subsequent recovery rate has since declined (**Figures 7** and **8**). Less than 15 gallons were recovered during the ten months from September 2004 and July 2005.

In 2011, the pumping system installed within RW-4 was shut down and subsequent monitoring of the well with an oil/water interface probe has not detected LNAPL in this well. In 2012, the pumping system installed within Well Z was shut down for maintenance and this well was also checked for detectable levels of LNAPL using an oil/water interface probe. Detectable levels of LNAPL have not been observed indicating that the recoverable LNAPL within the influence of these wells has been recovered. Recent checks of the Building 14 foundation sump shows only a trace of LNAPL, and the recovery system has accumulated less than one gallon of LNAPL in the past seven months.

These observations indicate that the Building 22 LNAPL Recovery System, which has been operating for more than 10 years, has achieved the practical extent of LNAPL remediation in this area of the Site.

7.3 Multi-Phase Extraction Pilot Test

During 2005, a pilot test was performed using an aboveground vacuum source connected to existing monitoring wells to evaluate the effectiveness of multi-phase extraction (MPE) to remove LNAPL in the Shallow Bedrock Unit (monitoring well SR-102 in the CWTA Courtyard) and the Overburden Unit (monitoring well PZ-123 in the Tank Farm Area). As shown in the following table, the groundwater/LNAPL recovery ratio ranged from 123 to 2,300 and the MPE pilot test primarily produced groundwater. Based on the pilot test results, MPE is not considered an effective recovery method for LNAPL of similar transmissivity at the Site. As discussed in Section 8, LNAPL transmissivity is a function of LNAPL viscosity, LNAPL saturation, pressure head, and the size and interconnectedness of either the pore space or fracture network.

Monitoring Well	Water Removed (gallons)	LNAPL Removed (gallons)	Water/LNAPL Ratio	Groundwater Unit	LNAPL Viscosity Range (cPs)
SR-102	800	6.5	123	Shallow Bedrock	51.4 - 136
PZ-123	1,150	0.5	2,300	Overburden	33.7

8 POTENTIAL FOR LNAPL RECOVERY

The conceptual models for LNAPL in unconsolidated porous media and fractured bedrock provide a framework for evaluating the effectiveness of a LNAPL recovery technology. In both porous media and fractured bedrock, the primary determinant of LNAPL recovery is not LNAPL thickness within a well[7], but rather the LNAPL transmissivity, which is a function of LNAPL viscosity, LNAPL saturation, pressure head, and the size and interconnectedness of either the pore space or fracture network. The most important concept for LNAPL recovery is that LNAPL below the residual saturation in both porous media and fractured bedrock cannot be recovered by hydraulic methods, and residual saturation is the endpoint for any hydraulic recovery method. In addition, LNAPL recovery is self-limiting, as reducing the LNAPL saturation via recovery also reduces the LNAPL mobility, resulting in decreasing recovery rates over time until asymptotic conditions are reached.

In 1996, the United States Environmental Protection Agency (EPA) conducted a thorough literature review and concluded in their peer-reviewed guidance document titled "*How To Effectively Recover Free Product At Leaking Underground Storage Tank Sites: A Guide For State Regulators*", that approximately 20 to 50 percent of the total volume of hydrocarbons released at UST sites can be recovered (EPA, 1996). This range of recoverability represents a wide range of both hydrocarbon types and subsurface geologic conditions. An evaluation of hydraulic recovery case studies by the American Petroleum Institute indicates that total LNAPL recovery for most sites is on the order of 30 percent or less of the original LNAPL volume[8] in place, with an upper range of around 50 percent, while LNAPL removal in fine grained materials is likely in the 15 percent range (API, 2002).

Appendix A presents case studies and an evaluation of enhanced LNAPL recovery methods such as surfactant- and thermal-enhanced recovery. The results of these case studies are used to support the conclusions and recommendations in Section 10.

8.1 Previous Recovery Efforts

The LNAPL recovery efforts at Building 22 and the Tank Farm Area exhibits a common pattern, with initial success at LNAPL recovery followed by decreasing recovery rates over time until asymptotic conditions are reached. Asymptotic recovery rates for the Building 22 and Tank Farm Area systems indicate that residual saturation has been reached in the vicinity of the LNAPL extraction points. Reduction of thickness and/or the disappearance of LNAPL in Building 22 area monitoring wells also indicate that the Building 22 area recovery system has reduced LNAPL saturation to residual saturation in this area.

8.2 MPE Pilot Test

As described above, the 2005 MPE pilot test primarily produced groundwater, and is not considered an effective enhanced LNAPL recovery method under current conditions. The groundwater/LNAPL recovery ratio ranged from 123 to 2,300 for SR-102 (Shallow Bedrock Unit) and PZ-123 (Overburden Unit), respectively. In addition, MPE recovery does not result in a larger percentage of LNAPL recovery compared to traditional hydraulic recovery methods, but rather reduces the time period to reach asymptotic recovery conditions.

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[7] In general, total recovered LNAPL volume does not correlate with initial product thickness in the well.

[8] Estimating the "original LNAPL volume in place", even on an order of magnitude scale, is generally not possible, unless the release was from a single event of known volume.

8.3 Bail Down Tests

LNAPL transmissivity is the primary determinant of LNAPL mobility, and therefore LNAPL recovery. The most common method of estimating LNAPL transmissivity is the bail down test, which involves rapidly removing LNAPL from a well while minimizing the recovery of groundwater, to initiate LNAPL flow towards the well. The change in free product head is measured over time until the level approximately reaches static equilibrium (i.e. the level prior to testing).

During July 2005, a LNAPL bail down test was conducted at Shallow Bedrock monitoring wells SR-310, SR-311, and SR-313, and Intermediate Bedrock monitoring well R-309. The objective of the testing program was to evaluate the feasibility of LNAPL removal from fractured bedrock. LNAPL bail down testing was conducted using the Lundy and Zimmerman approach found in the API Interactive LNAPL Guide.

The bail down data was evaluated using the Cooper et al. (1967) and the Bouwer and Rice (1976, 1989) methods, accounting for specific gravity of the LNAPL. The API Interactive LNAPL Guide Recoverability Screening Charts were then used to determine the initial feasibility of LNAPL recoverability. These charts are based on numerical modeling, and evaluate recoverability based on LNAPL thickness, dynamic viscosities, and hydraulic conductivity.

Corrected LNAPL hydraulic conductivity values ranged from 1.6×10^{-3} cm/sec to 1.8×10^{-6} cm/sec. Laboratory measured dynamic viscosity values ranged between 24 and 43 centipoises (cP). The most recent field measured LNAPL thicknesses were 7.4, 1.17, 5.31, and 5.56 feet for SR-310, SR-311, SR-313, and R-309, respectively. Based on the API Recoverability Screening Charts presented in **Figures 9** and **10**, the LNAPL present at the tested monitoring wells is categorized as “Not Likely Recoverable.”

9 RISK EVALUATION

The results of the Human Health Risk Assessment (HHRA) indicate that, for current and reasonably anticipated future Site use (i.e. as an industrial manufacturing facility), there is no unacceptable risk to human health, public welfare, safety, and the environment[9] (Haley & Aldrich, 2008).

The limited extent of dissolved-phase hydrocarbon constituents in groundwater and the stability of the LNAPL distribution over time (Haley & Aldrich, 2005; Haley & Aldrich, 2008) indicate that LNAPL migration is no longer occurring. Because the LNAPL sources have been removed from service, in some cases decades ago, previously released LNAPL has reached hydrostatic equilibrium, and continued vertical and lateral LNAPL migration (i.e. expansion of the LNAPL plume footprint) in both the Overburden Unit and the Shallow and Intermediate Bedrock Units has not been observed.

The LNAPL hydrocarbon constituents also have relatively low aqueous solubility and/or high rates of degradation (Fetter, 1993), and dissolved-phase hydrocarbon constituents are limited to the immediate vicinity of the LNAPL plumes (Haley & Aldrich, 2005). LNAPL constituents that are relatively soluble in groundwater, such as chlorinated VOCs, are captured by the groundwater migration control systems currently operated on-site. Two (2) additional groundwater recovery wells (GR-3 and GR-4) were installed (and will soon become active) between the East Parking Lot and the North Parking Lot groundwater migration control system to increase hydraulic control of VOC-impacted groundwater along the southeast portion of the Site.

The operation of the additional recovery wells should reduce the risk of off-site exposure to VOC-impacted groundwater, but no additional on-site LNAPL recovery methods are required to protect human health or the environment under the current Site use and conditions.

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[9] However, there is a potential for adverse health effects for temporary utility maintenance/construction workers engaged in extended excavation activities without proper engineering controls or precautions.

10 CONCLUSIONS AND PROPOSED LNAPL RECOVERY METHODS AND ASSESSMENTS

10.1 Conclusions

The primary issue addressed in this report is whether more aggressive collection methods or technologies are required to recover LNAPL at the Site. Based on a review of the LNAPL hydraulic recovery efforts to date, pilot tests, conceptual models of LNAPL in porous media and fractured bedrock, and enhanced recovery case studies in **Appendix A**, efforts such as vacuum-enhanced recovery, and other enhanced recovery methods such as surfactant- and thermal-enhanced recovery would either be ineffective at additional LNAPL removal or are not feasible or practicable given the size and access constraints of the Site, as well as the heterogeneous nature of the Overburden Unit and the fracture network in the Shallow and Intermediate Bedrock Units. This conclusion is based on the following:

- The limited extent of dissolved-phase hydrocarbon constituents in groundwater and the stability of the LNAPL distribution over time indicate that LNAPL migration is no longer occurring;

- Most LNAPL hydrocarbon constituents such as ethylbenzene, toluene, xylene, and alkyl benzenes have low aqueous solubility in groundwater and the LNAPL constituents present at the Site that are relatively soluble, such as chlorinated VOCs, are captured by the groundwater migration control system;

- The groundwater/LNAPL removal ratio for the vacuum-enhanced pilot test in Overburden and Shallow Bedrock Units ranged from 123 to 2,300, indicating that vacuum-enhanced recovery would be an inefficient recovery method for LNAPL of similar transmissivity at the Site;

- The results of bail down tests at Shallow Bedrock and Intermediate Bedrock Unit monitoring wells, along with recoverability screening charts provided in the API Interactive LNAPL Guide, indicates that the LNAPL present in these areas is not likely recoverable in significant quantities;

- The application of surfactant- and thermal-enhanced recovery would be prohibitively expensive given the size and access constraints at the Site. The equipment size and density needed poses significant feasibility issues due to access constraints[10];

- Residual LNAPL will still remain in the subsurface following completion of either conventional or enhanced recovery methods;

- Enhanced recovery methods may mobilize naturally-occurring metals such as arsenic, as well as LNAPL and dissolved-phase hydrocarbon plumes that are currently stable;

- Beneficial natural biodegradation processes may be reduced as a result of enhanced remediation technologies; and

- Enhanced recovery methods, in particular thermal methods, have large energy needs with a correspondingly large carbon footprint.

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[10] Nearly all the LNAPL areas, except the North and East Parking Lots, are under the manufacturing buildings.

10.2 Proposed LNAPL Recovery Methods and Assessments

For the reasons stated above in Section 10.1 and as discussed in Section 1.7 of **Appendix A**, enhanced LNAPL recovery methods such as vacuum-enhanced recovery and other enhanced recovery methods such as surfactant- or thermal-enhanced recovery are not recommended for further evaluation or implementation at the Site.

However, while previous bail down tests in Shallow and Intermediate Bedrock wells suggest that hydraulic recovery would not remove significant amounts of LNAPL, the use of existing monitoring wells for LNAPL recovery would nevertheless remove some LNAPL and therefore remove VOC mass as well. This approach would be relatively easy to implement with minimal risk of unintended LNAPL mobilization. Consideration of a remediation approach with a low environmental footprint is also consistent with NYDEC guidance (DER-31 - Green Remediation).

As such, the following LNAPL recovery methods are proposed to be implemented and then evaluated on an annual basis in connection with GMCH's submission of its Periodic Review Report under a Department-approved Site Management Plan (SMP), which will specify the criteria for suspending LNAPL recovery in the various Site areas at issue pursuant to Section 6.4(b)1 of the NYDEC's DER-10 (Technical Guidance for Site Investigation and Remediation).

10.2.1 LNAPL in Building 1 and 2 Machining Areas and the Tank Farm Area

LNAPL present in the Building 1 and 2 machining areas is confined to the Overburden and the Shallow Bedrock Units. The Building 1 LNAPL extends north beyond the northeast corner of Building 1 to the Tank Farm Area Recovery system. The Building 2 LNAPL extends north to the Central Waste Treatment Area (CWTA) courtyard. LNAPL recovery actions for these areas will include the following elements:

- Continued operation of the Tank Farm LNAPL Recovery system and reporting the quantity of LNAPL recovered as part of the monitoring activities to be conducted under the SMP. The monitoring program will include the measurement of recovered LNAPL from the oil/water separator system and the periodic measurement of LNAPL within monitoring wells PZ-114, PZ-121, PZ-132, RW-2, and RW-101. The SMP will include a schedule for monitoring and reporting and the criteria for the evaluation of system performance, optimization, and shutdown.

- Manual LNAPL recovery or LNAPL recovery using a portable pumping system from existing monitoring wells within the Building 1 and Building 2 that exhibit recoverable amounts of LNAPL. These monitoring well locations include SR-102 and SR-318 in the CWTA Courtyard area and SR-309, SR-310, SR-311, SR-312, SR-313, SR-326, and R-309 within the Building 1 and 2 Machining Areas. The volume of LNAPL recovered from each well will be recorded and tracked versus time until asymptotic conditions are documented. Automated recovery methods will be considered if these procedures are determined to be more cost effective based on the cost of energy, infrastructure, and operation versus the observed labor costs for manual recovery methods. In addition, automated recovery methods will be considered if an appreciable volume of LNAPL is still being recovered even if asymptotic conditions are reached.

10.2.2 LNAPL on the East Side of Building 1

LNAPL is present outside the east wall of Building 1 at monitoring wells SR-236 and R-236. The LNAPL is primarily composed of heavier, lubricating-oil. LNAPL recovery actions for this area will include the following:

- Manual LNAPL recovery or LNAPL recovery using a portable pumping system from these monitoring wells as part of the activities to be conducted under the SMP. The SMP will include a schedule for reporting and the criteria for the evaluation of remedial performance. The volume of LNAPL recovered from each well will be recorded and tracked versus time until asymptotic conditions are documented. Automated recovery methods will be considered if these procedures are determined to be more cost effective based on the cost of energy, infrastructure, and operation versus the observed labor costs for manual recovery methods. In addition, automated recovery methods will be considered if an appreciable volume of LNAPL is still being recovered even if asymptotic conditions are reached.

10.2.3 East Parking Lot LNAPL

Measurable LNAPL is present within monitoring wells R-2, R-235, R-237, R-238, and R-241 in the Intermediate Bedrock Unit extending under the East Parking Lot, and slightly beyond the eastern Site boundary to R-305. LNAPL recovery actions for this area will include the following elements:

- Manual LNAPL recovery or LNAPL recovery using a portable pumping system from monitoring wells R-2, R-235, R-237, R-238, and R-241 as part of the activities to be conducted under the SMP. The SMP will include a schedule for reporting and the criteria for the evaluation of remedial performance. The volume of LNAPL recovered from each well will be recorded and tracked versus time until asymptotic conditions are documented. Automated recovery methods will be considered if these procedures are determined to be more cost effective based on the cost of energy, infrastructure, and operation versus the observed labor costs for manual recovery methods. In addition, automated recovery methods will be considered if an appreciable volume of LNAPL is still being recovered even if asymptotic conditions are reached.

- Operate groundwater extraction wells GR-3 and GR-4 to provide hydraulic control of VOC-impacted groundwater and LNAPL in the northern portion of the East Parking Lot near R-241. Given the presence of chlorinated VOCs, primarily vinyl chloride, LNAPL recovery will remove some of the VOC mass contributing to groundwater impacts. The effluent from the GR-3 and GR-4 will be passed through an oil/water separator for the recovery of LNAPL prior to discharge to the sanitary sewer for treatment by the local POTW under the existing facility sewer use permit. The monitoring program will include the measurement of recovered LNAPL from the oil/water separator system and the periodic monitoring for LNAPL within monitoring wells R-305, R-306, R-401, and R-402. The SMP will include a schedule for monitoring and reporting and the criteria for the evaluation of system performance, optimization, and shutdown.

10.2.4 North Parking Lot LNAPL

Detectable LNAPL has been observed intermittently at a thickness of less than 0.4 feet at some of the monitoring wells (PZ-136, PZ-137, and PZ-138) installed near migration-control recovery well GR-2. LNAPL has also been observed in GR-2 and southeast of GR-2 in monitoring well R-240. LNAPL recovery actions for this area will include the following elements:

- Continue the operation of the groundwater extraction wells GR-1 and GR-2 to provide hydraulic control of VOC-impacted groundwater and LNAPL in the area. The SMP will include a schedule for monitoring and reporting and the criteria for the evaluation of system performance, optimization, and shutdown.

- Continue to monitor for LNAPL within monitoring wells PZ-136, PZ-137, PZ-138, and R-240 as part of the annual groundwater monitoring program through the SMP with recommendations to address any observed changes.

10.2.5 Building 22 Area LNAPL

The Building 22 Area LNAPL consists primarily of Stoddard solvent, a lighter-weight petroleum-based solvent similar to mineral spirits that was used as a test fluid in Building 22 carburetor testing operations. The observed recovery of LNAPL in the Building 22 Recovery System, which consists of pneumatic pumps in two (2) bedrock wells, Well Z and RW-4, and shallow groundwater recovered from the foundation drain sump located at the northeast corner of Building 14, has decreased to asymptotic conditions.

In 2011, the pumping system installed within RW-4 was shut down and subsequent monitoring of the well with an oil/water interface probe has not detected LNAPL in this well. In 2012, the pumping system installed within Well Z was shut down for maintenance and this well was also checked for detectable levels of LNAPL using an oil/water interface probe. Detectable levels of LNAPL have not been observed indicating that the recoverable LNAPL within the influence of these wells has been recovered. Recent checks of the Building 14 foundation sump shows only a trace of LNAPL, and the recovery system has accumulated less than one gallon of LNAPL since November 2011.

These observations indicate that the Building 22 LNAPL Recovery System, which has been operating for more than 10 years, has achieved the practical extent of LNAPL remediation in this area of the Site and operation of this system should be discontinued at this time. Based on the current status of this system, it would not be productive to incorporate design information, operation and maintenance procedures into the development of the proposed SMP.

LNAPL recovery actions for this area will include the following elements:

- Shut down of the Building 22 LNAPL Recovery system pumping wells with continued operation of the Building 14 Foundation Drain sump as needed for hydraulic control around the building foundation.

- Continue to monitor for the presence of LNAPL within the Well Z and RW-4 as part of the annual groundwater monitoring program with reporting through the SMP with recommendations to address any observed changes.

10.3 Overall Assessment

The LNAPL recovery measures described in Section 10.2 represent technically feasible options available to recover LNAPL detected within the existing remedial systems and monitoring well network at the Delphi Automotive Systems Site. Consideration of a remediation approach with a low environmental footprint is also consistent with NYDEC guidance (DER-31 - Green Remediation).

The operation of these proposed remedial measures at the Site will not appreciably reduce risk associated with the continued use of the Site for industrial or commercial purposes.
Additional efforts to recover LNAPL are also not expected to reduce the anticipated operational time of the VOC-impacted groundwater migration control systems. Nevertheless, the technical issues resulting from the presence of LNAPL at the Site will be assessed as part of the Periodic Review Report process for the Site.

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TABLE 1
HYDRAULIC CONDUCTIVITIES FROM SINGLE WELL TESTS
GMCH Rochester Operations Facility
Rochester, New York

Monitoring Well	Kh (cm/sec)	Groundwater Unit
OW-314	6.6E-02	Overburden
OW-322	1.1E-03	Overburden
OW-323	1.8E-03	Overburden
OW-324	1.4E-03	Overburden
SR-301	3.7E-04	Shallow Bedrock
SR-303	1.5E-03	Shallow Bedrock
SR-308	6.0E-04	Shallow Bedrock
SR-314	4.4E-05	Shallow Bedrock
SR-320	9.2E-04	Shallow Bedrock
SR-325	1.1E-04	Shallow Bedrock
SR-402	3.5E-01	Shallow Bedrock
R-301	3.7E-05	Intermediate Bedrock
R-302	7.6E-04	Intermediate Bedrock
R-303	2.1E-04	Intermediate Bedrock
R-304	6.2E-11	Intermediate Bedrock
R-306	6.7E-11	Intermediate Bedrock
R-307	1.4E-02	Intermediate Bedrock
R-308	8.8E-03	Intermediate Bedrock
R-314	3.3E-11	Intermediate Bedrock
R-401	1.1E-02	Intermediate Bedrock
R-402	3.3E-02	Intermediate Bedrock
DR-132	6.2E-04	Deep Bedrock
DR-315	2.8E-11	Deep Bedrock

NOTES:
1. Estimated hydraulic conductivities from single well tests.
2. cm/sec = centimeters per second.

TABLE 2
LNAPL VISCOSITY AT SELECT MONITORING WELLS
GMCH Rochester Operations Facility
Rochester, New York

Monitoring Well	Viscosity (cPs @ 22 C)	Groundwater Unit	Site Location
OW-102	65	Overburden	CWTA Courtyard
OW-316	38	Overburden	Building 2/2A Machining Area
OW-316	87	Overburden	Building 2/2A Machining Area
OW-327	2	Overburden	Building 1 Fuel Test Area
OW-327	32	Overburden	Building 1 Fuel Test Area
PZ-114	66	Overburden	Tank Farm Recovery Trench
PZ-114	76	Overburden	Tank Farm Recovery Trench
PZ-121	54	Overburden	Tank Farm Recovery Trench
PZ-123	34	Overburden	Tank Farm Recovery Trench
RW-2	12	Overburden	Tank Farm Recovery Trench
RW-2	63	Overburden	Tank Farm Recovery Trench
VM-211	65	Overburden	Building 2/2A Machining Area
VM-211	74	Overburden	Building 2/2A Machining Area
VM-212	32	Overburden	Building 2/2A Machining Area
PZ-129	2	Shallow Bedrock	CWTA Courtyard
PZ-130	155	Shallow Bedrock	CWTA Courtyard
PZ-130	154	Shallow Bedrock	CWTA Courtyard
PZ-136	2	Shallow Bedrock	North Parking Lot
SR-102	51	Shallow Bedrock	CWTA Courtyard
SR-102	136	Shallow Bedrock	CWTA Courtyard
SR-102	97	Shallow Bedrock	CWTA Courtyard
SR-208	102	Shallow Bedrock	Building 2/2A Machining Area
SR-208	92	Shallow Bedrock	Building 2/2A Machining Area
SR-216	20	Shallow Bedrock	Building 2/2A Machining Area
SR-216	69	Shallow Bedrock	Building 2/2A Machining Area
SR-230	54	Shallow Bedrock	Building 2/2A Machining Area
SR-230	52	Shallow Bedrock	Building 2/2A Machining Area
SR-236	34	Shallow Bedrock	East of Building 1
SR-236	136	Shallow Bedrock	East of Building 1
SR-236	110	Shallow Bedrock	East of Building 1
SR-310	43	Shallow Bedrock	Building 1 Fuel Test Area
SR-310	43	Shallow Bedrock	Building 1 Fuel Test Area
SR-310	100	Shallow Bedrock	Building 1 Fuel Test Area
SR-311	24	Shallow Bedrock	Building 1 Fuel Test Area
SR-311	75	Shallow Bedrock	Building 1 Fuel Test Area
SR-312	38	Shallow Bedrock	Building 1 Fuel Test Area
SR-312	105	Shallow Bedrock	Building 1 Fuel Test Area
SR-313	28	Shallow Bedrock	Building 1 Fuel Test Area
SR-313	86	Shallow Bedrock	Building 1 Fuel Test Area
SR-316	29	Shallow Bedrock	Building 2/2A Machining Area
SR-316	83	Shallow Bedrock	Building 2/2A Machining Area
SR-316	79	Shallow Bedrock	Building 2/2A Machining Area
SR-318	31	Shallow Bedrock	CWTA Courtyard
SR-318	38	Shallow Bedrock	CWTA Courtyard
SR-318	115	Shallow Bedrock	CWTA Courtyard
SR-319	51	Shallow Bedrock	Building 2/2A Machining Area
SR-319	132	Shallow Bedrock	Building 2/2A Machining Area
SR-321	66	Shallow Bedrock	Building 2/2A Machining Area
SR-321	161	Shallow Bedrock	Building 2/2A Machining Area
SR-326	9	Shallow Bedrock	Building 1 Fuel Test Area
SR-326	48	Shallow Bedrock	Building 1 Fuel Test Area
SR-503	28	Shallow Bedrock	Building 1 Fuel Test Area

TABLE 2
LNAPL VISCOSITY AT SELECT MONITORING WELLS
GMCH Rochester Operations Facility
Rochester, New York

Monitoring Well	Viscosity (cPs @ 22 C)	Groundwater Unit	Site Location
R-2	91	Intermediate Bedrock	East Parking Lot
R-2	26	Intermediate Bedrock	East Parking Lot
R-2	91	Intermediate Bedrock	East Parking Lot
R-235	115	Intermediate Bedrock	East Parking Lot
R-235	81	Intermediate Bedrock	East Parking Lot
R-235	68	Intermediate Bedrock	East Parking Lot
R-236	41	Intermediate Bedrock	East of Building 1
R-236	48	Intermediate Bedrock	East of Building 1
R-236	113	Intermediate Bedrock	East of Building 1
R-237	118	Intermediate Bedrock	East Parking Lot
R-238	67	Intermediate Bedrock	East Parking Lot
R-238	67	Intermediate Bedrock	East Parking Lot
R-240	32	Intermediate Bedrock	North Parking Lot
R-240	32	Intermediate Bedrock	North Parking Lot
R-241	19	Intermediate Bedrock	East Parking Lot
R-241	64	Intermediate Bedrock	East Parking Lot
R-305	95	Intermediate Bedrock	East Parking Lot
R-305	36	Intermediate Bedrock	East Parking Lot
R-305	35	Intermediate Bedrock	East Parking Lot
R-305	91	Intermediate Bedrock	East Parking Lot
R-305	97	Intermediate Bedrock	East Parking Lot
R-305	97	Intermediate Bedrock	East Parking Lot
R-305	91	Intermediate Bedrock	East Parking Lot
R-305	96	Intermediate Bedrock	East Parking Lot
R-309	23	Intermediate Bedrock	Building 1 Fuel Test Area
R-309	40	Intermediate Bedrock	Building 1 Fuel Test Area
R-309	101	Intermediate Bedrock	Building 1 Fuel Test Area

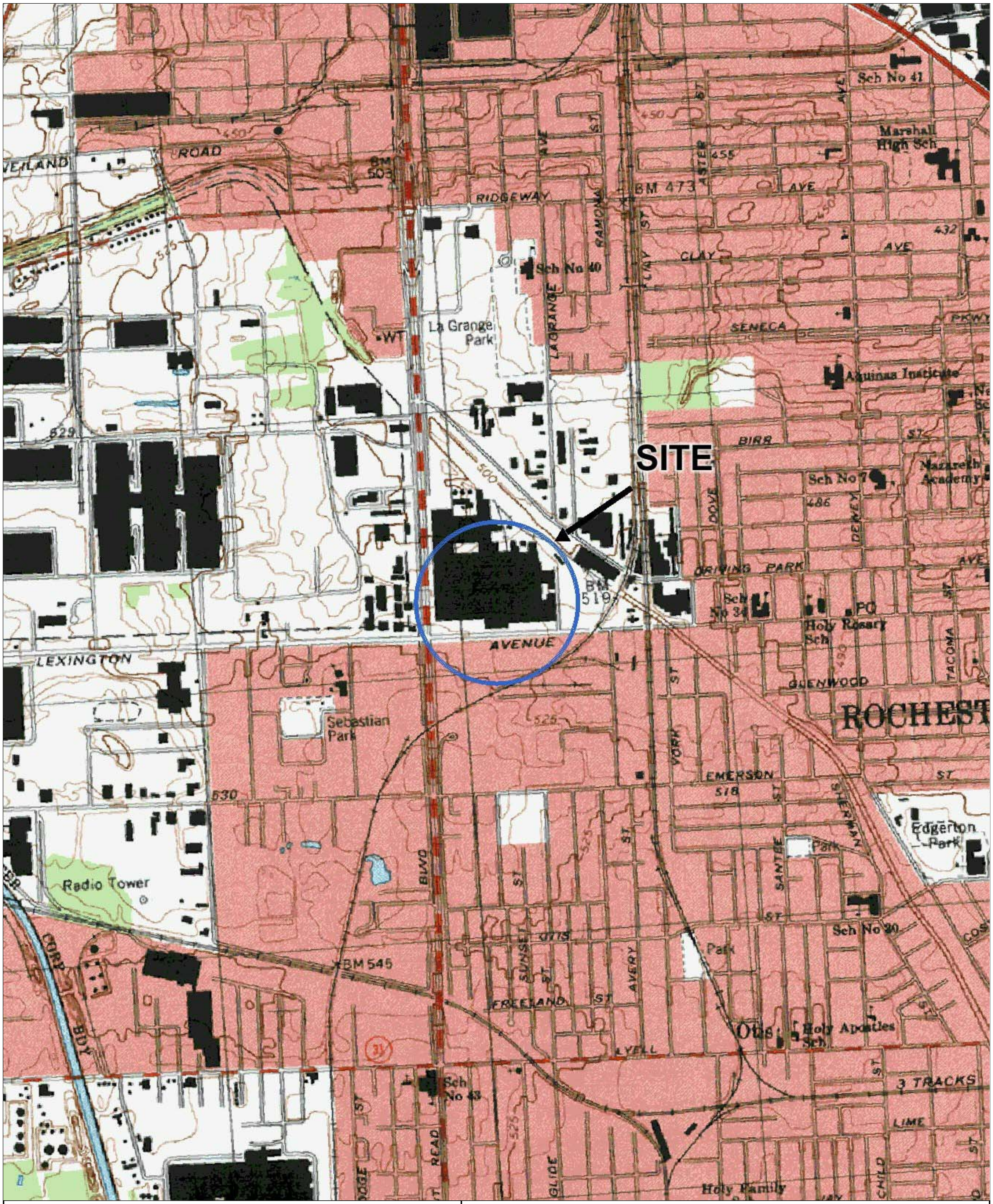
NOTES:
1. cPs = centipoise.

TABLE 3
RECENT LNAPL THICKNESS IN SELECT MONITORING WELLS

GMCH Rochester Operations Facility
Rochester, New York

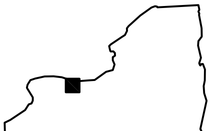
		LNAPL THICKNESS (FEET)					
WELL ID	LOCATION	3/19/2008	2/2/2010	4/15/2010	8/11/2010	11/11/2011	5/23/2012
OVERBURDEN WELLS							
OW-317	Bldg 2 MA	---	0.26	---	---	---	---
PZ-114	TFT	---	1.16	---	---	0.42	0.42
PZ-121	TFT	---	1.07	---	---	0.70	0.82
PZ-132	TFT	---	0.03	---	---	5.00	0.00
SHALLOW BEDROCK UNIT WELLS							
PZ-129	CWTA Ctyd	1.15	---	---	---	---	---
PZ-130	CWTA Ctyd	---	0.47	---	---	5.74	---
PZ-137	NP MCT	0.44	0.03	---	---	---	---
SR-102	CWTA Ctyd	---	8.07	---	---	---	---
SR-236	East Bldg 1	3.72	3.21	3.07	---	1.47	2.95
SR-309	Bldg 1 FTA	10.89	11.44	11.31	---	---	10.33
SR-310	Bldg 1 FTA	---	7.78	---	---	---	7.4
SR-311	Bldg 1 FTA	---	7.96	---	---	---	1.17
SR-312	Bldg 1 FTA	5.80	4.58	---	---	---	0.00
SR-313	Bldg 1 FTA	---	5.63	---	---	---	5.31
SR-317	Bldg 2 MA	1.19	0.26	---	---	---	---
SR-318	CWTA Ctyd	---	9.26	9.23	---	6.72	8.80
SR-320	Bldg 2 MA	7.74	2.77	---	---	---	---
SR-321	Bldg 2 MA	11.42	11.85	---	---	---	---
SR-326	East Bldg 1	4.36	4.02	---	---	---	1.22
SR-503	Bldg 1 FTA	---	8.09	6.12	---	---	4.62
INTERMEDIATE BEDROCK UNIT WELLS							
R-2	EPL	1.89	0.64	---	1.6	0.49	1.25
R-235	EPL	8.1	1.6	---	---	---	1.33
R-236	East Bldg 1	8.91	6.77	7.83	6.22	7.93	6.19
R-237	EPL	5.16	4.35	---	4.32	4.82	4.30
R-238	EPL	4.94	0.59	---	0.28	---	---
R-240	NP MCT	0.36	0.01	---	---	0.02	
R-241	EPL	2.39	2.37	---	2.37	---	2.40
R-305	EPL	---	0.32	---	0.96	---	1.09
R-309	Bldg 1 FTA	8.67	7.11	5.68	---	---	5.56

NOTES:
1. "---" = LNAPL not measured.
2. Bldg 2 MA - Building 2/2a Former Machining Area
3. TFT - Former Tank Farm Trench
4. Bldg 1 FTA - Building 1 Former Test Area
5. CWTA Ctyd - Central Waste Treatment Area Courtyard
6. East Bldg 1 - Former UST Area East of Building 1
7. EPL - East Parking Lot
8. NP MCT - North Parking Lot Groundwater Migration Control Trench



SITE COORDINATES: 43°10'56"N 77°39'22"W

N
W E
S



U.S.G.S. QUADRANGLE: ROCHESTER WEST, NY

HALEY & ALDRICH

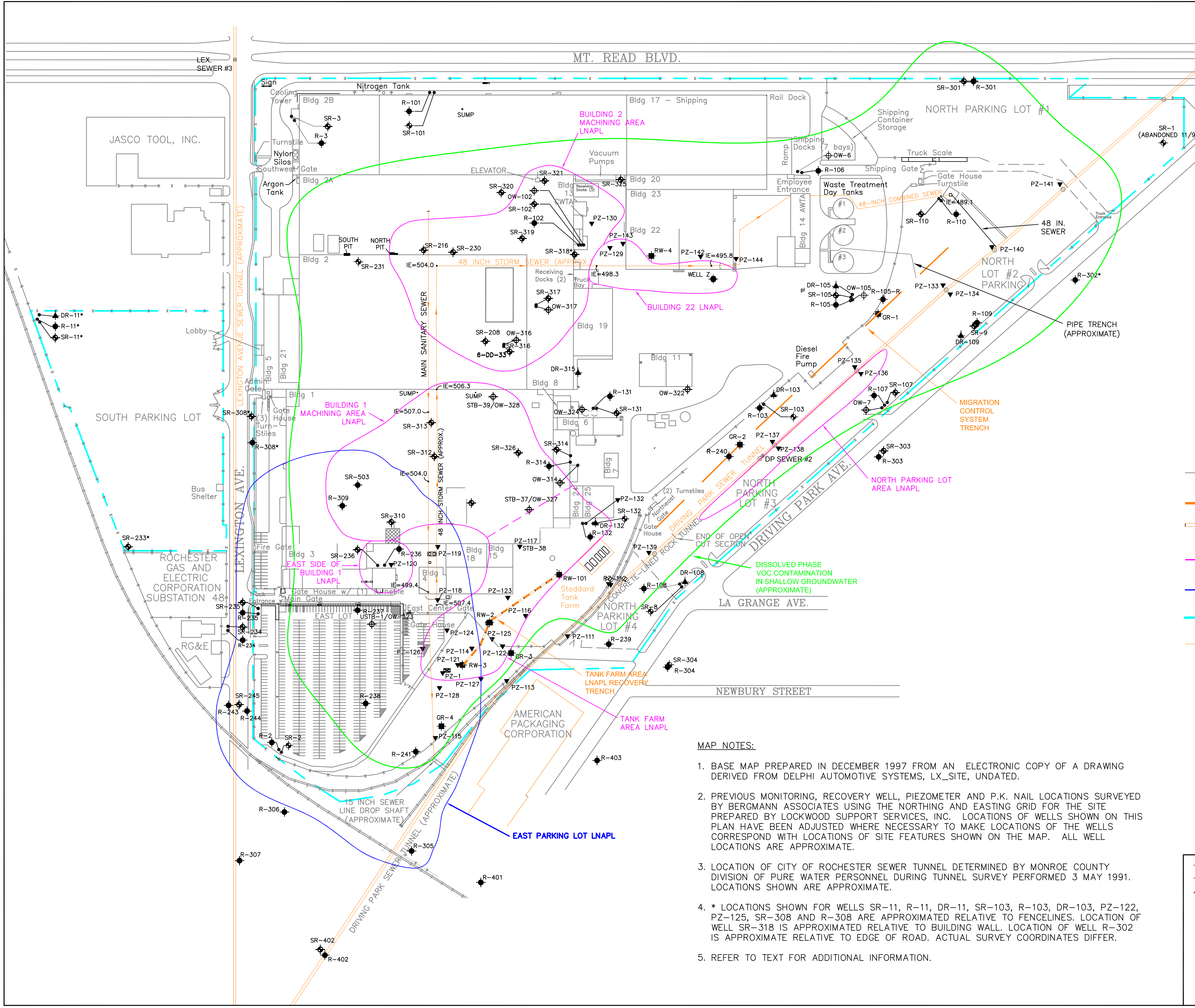
LEXINGTON AVENUE FACILITY
ROCHESTER, NEW YORK

PROJECT LOCUS

SCALE: 1:24000
JUNE 2012

FIGURE 1

C:\FILES\70014-102\FIG 1_LOCUS.DWG

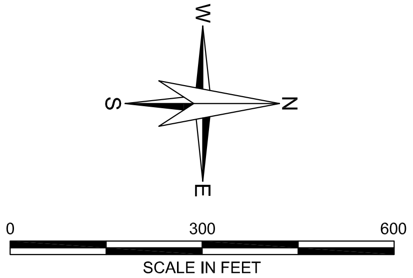


LEGEND:

OW-7	OVERBURDEN WELL
SR-1	SHALLOW BEDROCK WELL
R-107	INTERMEDIATE BEDROCK WELL
DR-109	DEEP BEDROCK WELL
●	WELL Z
RW-3 GR-1	RECOVERY WELL (FLOATING PRODUCT) RECOVERY WELL (GROUNDWATER)
▼ PZ-111	PIEZOMETER
─○─	CITY OF ROCHESTER SEWER TUNNEL LOCATION P.K. NAIL AT SURFACE ABOVE SEWER CENTERLINE
━ ━	LOCATION OF BLASTED BEDROCK TRENCH
━ ━	LOCATION OF FLOATING PRODUCT RECOVERY TRENCH
─	SHALLOW LNAPL OUTLINE
─	INTERMEDIATE BEDROCK LNAPL OUTLINE
─	SITE BOUNDARY
─	AOI LOCATION

MAP NOTES:

1. BASE MAP PREPARED IN DECEMBER 1997 FROM AN ELECTRONIC COPY OF A DRAWING DERIVED FROM DELPHI AUTOMOTIVE SYSTEMS, LX_SITE, UNDATED.
2. PREVIOUS MONITORING, RECOVERY WELL, PIEZOMETER AND P.K. NAIL LOCATIONS SURVEYED BY BERGMANN ASSOCIATES USING THE NORTHING AND EASTING GRID FOR THE SITE PREPARED BY LOCKWOOD SUPPORT SERVICES, INC. LOCATIONS OF WELLS SHOWN ON THIS PLAN HAVE BEEN ADJUSTED WHERE NECESSARY TO MATCH LOCATIONS OF THE WELLS CORRESPOND WITH LOCATIONS OF SITE FEATURES SHOWN ON THE MAP. ALL WELL LOCATIONS ARE APPROXIMATE.
3. LOCATION OF CITY OF ROCHESTER SEWER TUNNEL DETERMINED BY MONROE COUNTY DIVISION OF PURE WATER PERSONNEL DURING TUNNEL SURVEY PERFORMED 3 MAY 1991. LOCATIONS SHOWN ARE APPROXIMATE.
4. * LOCATIONS SHOWN FOR WELLS SR-11, R-11, DR-11, SR-103, R-103, DR-103, PZ-122, PZ-125, SR-308 AND R-308 ARE APPROXIMATED RELATIVE TO FENCELINES. LOCATION OF WELL SR-318 IS APPROXIMATED RELATIVE TO BUILDING WALL. LOCATION OF WELL R-302 IS APPROXIMATE RELATIVE TO EDGE OF ROAD. ACTUAL SURVEY COORDINATES DIFFER.
5. REFER TO TEXT FOR ADDITIONAL INFORMATION.



HALEY & ALDRICH

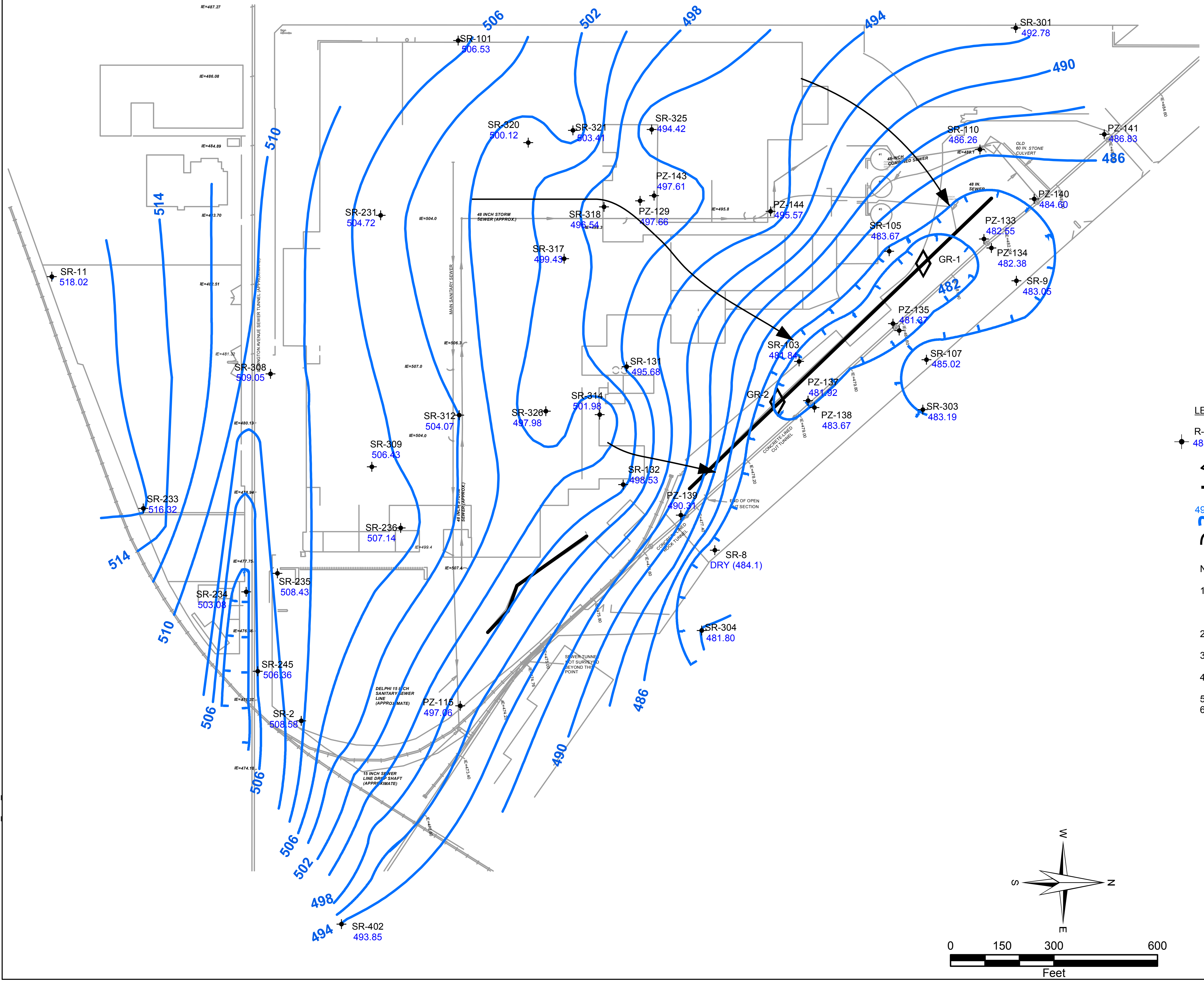
LNAPL RECOVERY ASSESSMENT REPORT
DELPHI AUTOMOTIVE SYSTEMS SITE
1000 LEXINGTON AVENUE
ROCHESTER, NEW YORK

SITE PLAN

SCALE: AS SHOWN
JUNE 2012

FIGURE 2

C:\FILES\70014-102\FIG 2_SITE PLAN-R2.DWG



LEGEND:

R-305 485.60	SHALLOW BEDROCK WELL LOCATION ID GROUNDWATER ELEVATION
◇	BLASTED BEDROCK TRENCH RECOVERY WELL
▬	GROUNDWATER RECOVERY TRENCH
492	GROUNDWATER CONTOURS 2-FT INTERVAL (DASHED WHERE INFERRED)
↷	INFERRED GROUNDWATER FLOW DIRECTION

NOTES:

1. Depth to groundwater measured by Haley & Aldrich of New York on 8-9 January 2008. Migration control trench recovery well GR-1 was in operation during the January 2008 measurement period. Recovery wells within the Tank Farm Area gravel-filled trench were not in operation during the water level measurement event.
2. Contours created with Surver 7.0. Contours adjusted as necessary by H&A of New York to account for other known site features and conditions.
3. Contours reflect values interpolated between data points. Actual values between data points will vary.
4. Datum is Mean Sea Level (MSL). Contour interval is two feet. Elevations expressed in feet.
5. Arrows indicate interpreted groundwater flow direction.
6. Refer to text for additional information.

HALEY & ALDRICH

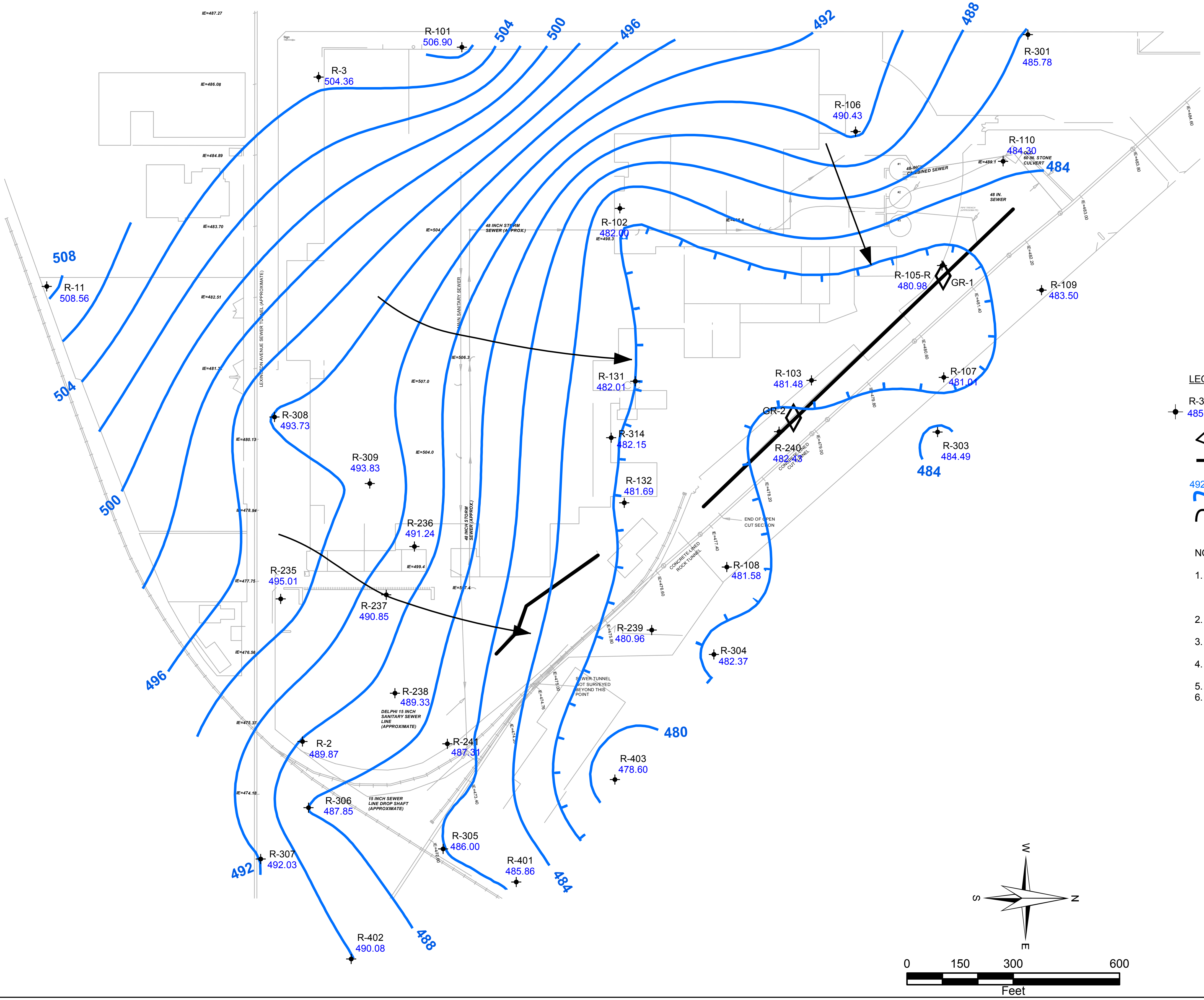
1000 LEXINGTON AVENUE
ROCHESTER, NEW YORK

SHALLOW BEDROCK
GROUNDWATER CONTOUR PLAN
JANUARY 2008

SCALE: AS SHOWN
JUNE 2012

FIGURE 3

G:\PROJECTS\70014\066\ARCGIS\2008_JAN_S.MXD



G:\PROJECTS\70014\066\ARCGIS\2008_JAN_I.MXD

LEGEND:

R-305 485.60	INTERMEDIATE BEDROCK WELL LOCATION ID GROUNDWATER ELEVATION
◇	BLASTED BEDROCK TRENCH RECOVERY WELL
—	GROUNDWATER RECOVERY TRENCH
492	GROUNDWATER CONTOURS 2-FT INTERVAL (DASHED WHERE INFERRED)
↘	INFERRED GROUNDWATER FLOW DIRECTION

NOTES:

1. Depth to groundwater measured by Haley & Aldrich of New York on 8-9 January 2008. Migration control trench recovery well GR-1 was in operation during the January 2008 measurement period. Recovery wells within the Tank Farm Area gravel-filled trench were not in operation during the water level measurement event.
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3. Contours reflect values interpolated between data points. Actual values between data points will vary.
4. Datum is Mean Sea Level (MSL). Contour interval is two feet. Elevations expressed in feet.
5. Arrows indicate interpreted groundwater flow direction.
6. Refer to text for additional information

HALEY & ALDRICH

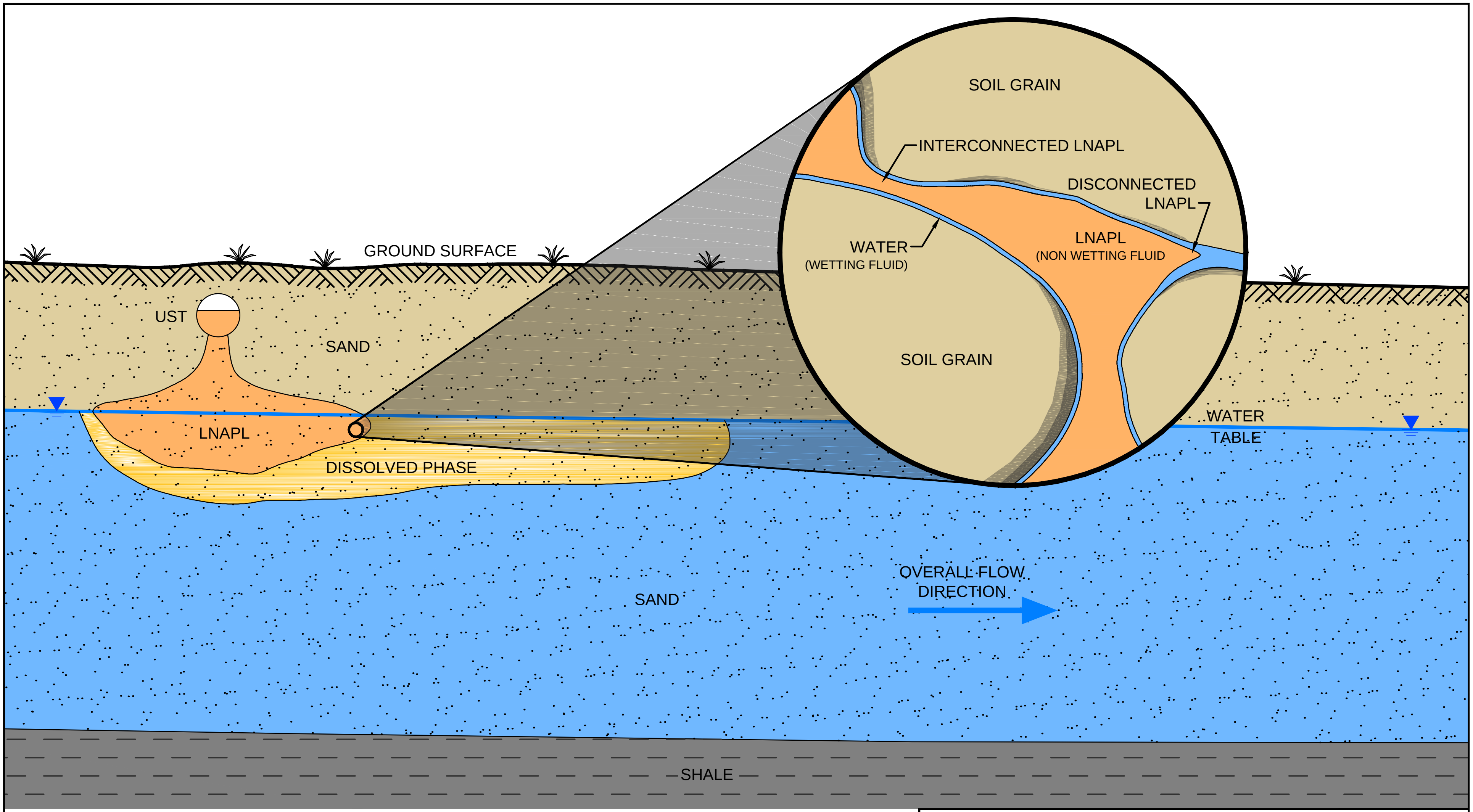
1000 LEXINGTON AVENUE
ROCHESTER, NEW YORK

INTERMEDIATE BEDROCK
GROUNDWATER CONTOUR PLAN
JANUARY 2008

SCALE: AS SHOWN
JUNE 2012

FIGURE 4

C:\FILES\70014-102\70014-LNAPL-CONCEPTUAL_MODELS.DWG



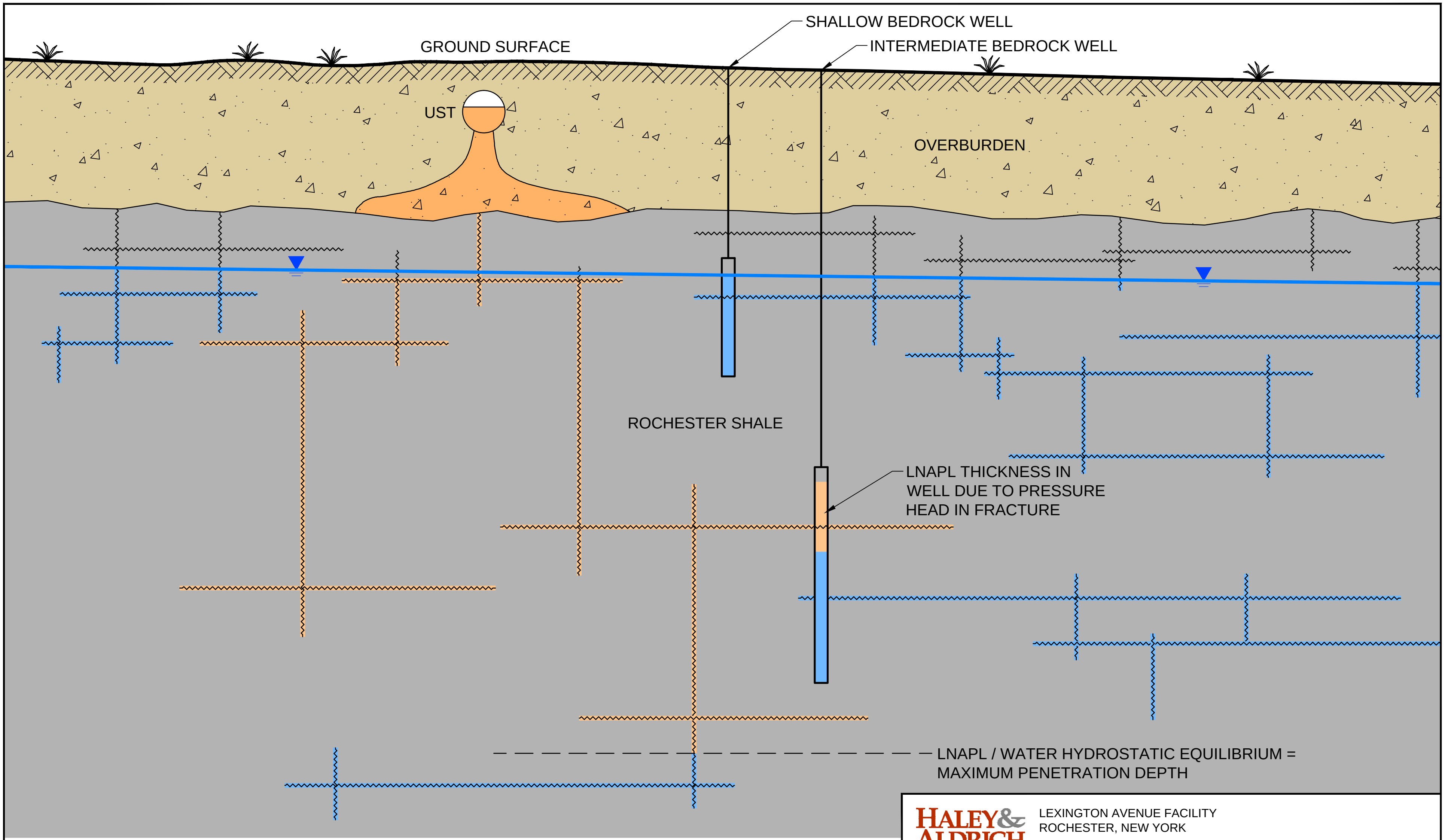
HALEY & ALDRICH

LEXINGTON AVENUE FACILITY
ROCHESTER, NEW YORK

CONCEPTUAL SCHEMATIC OF LNAPL IN POROUS MEDIA

SCALE: AS SHOWN
JUNE 2012

FIGURE 5



HALEY & ALDRICH

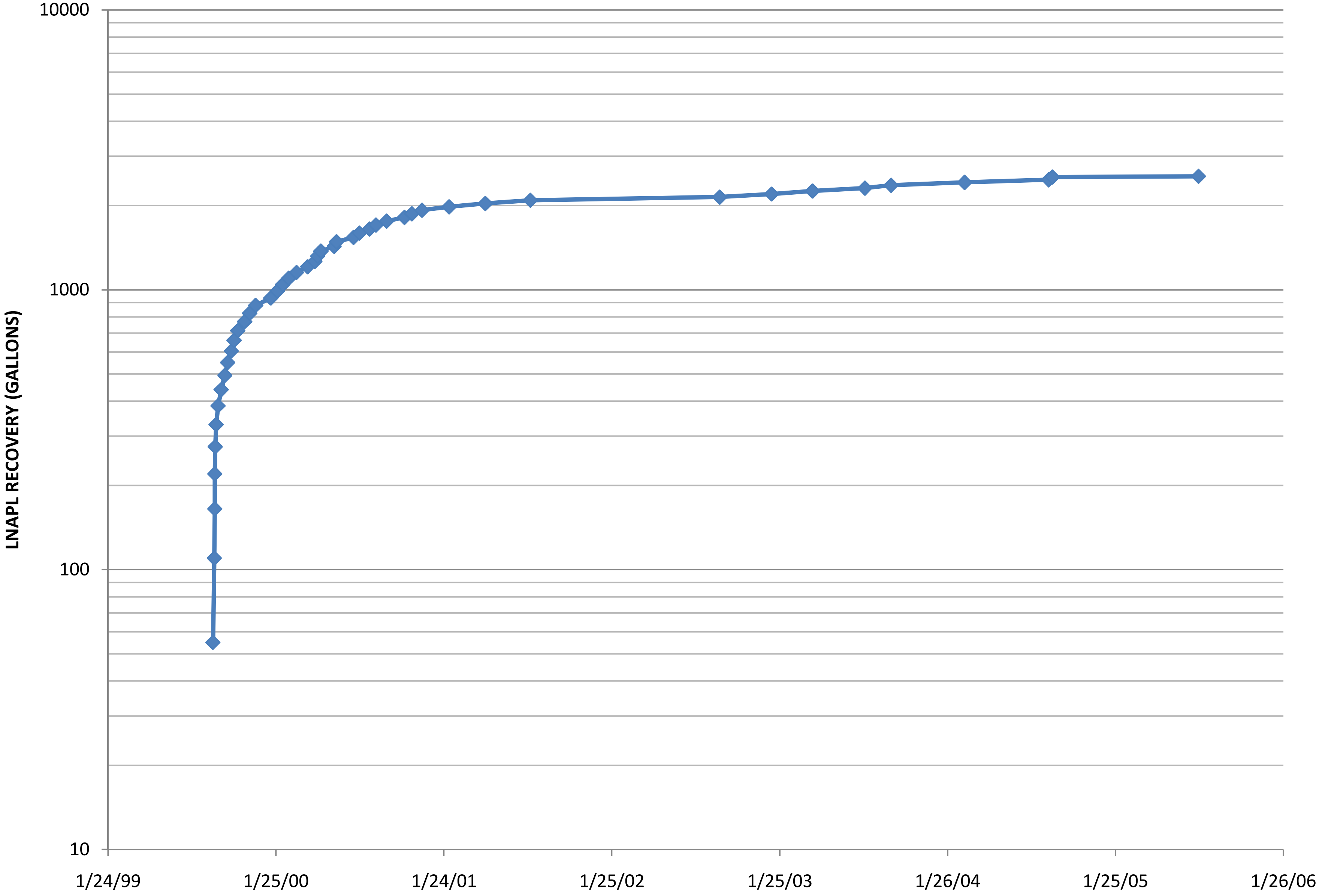
LEXINGTON AVENUE FACILITY
ROCHESTER, NEW YORK

CONCEPTUAL SCHEMATIC OF LNAPL IN FRACTURED ROCK

SCALE: AS SHOWN
JUNE 2012

FIGURE 6

FIGURE 7 - Building 22 LNAPL Recovery



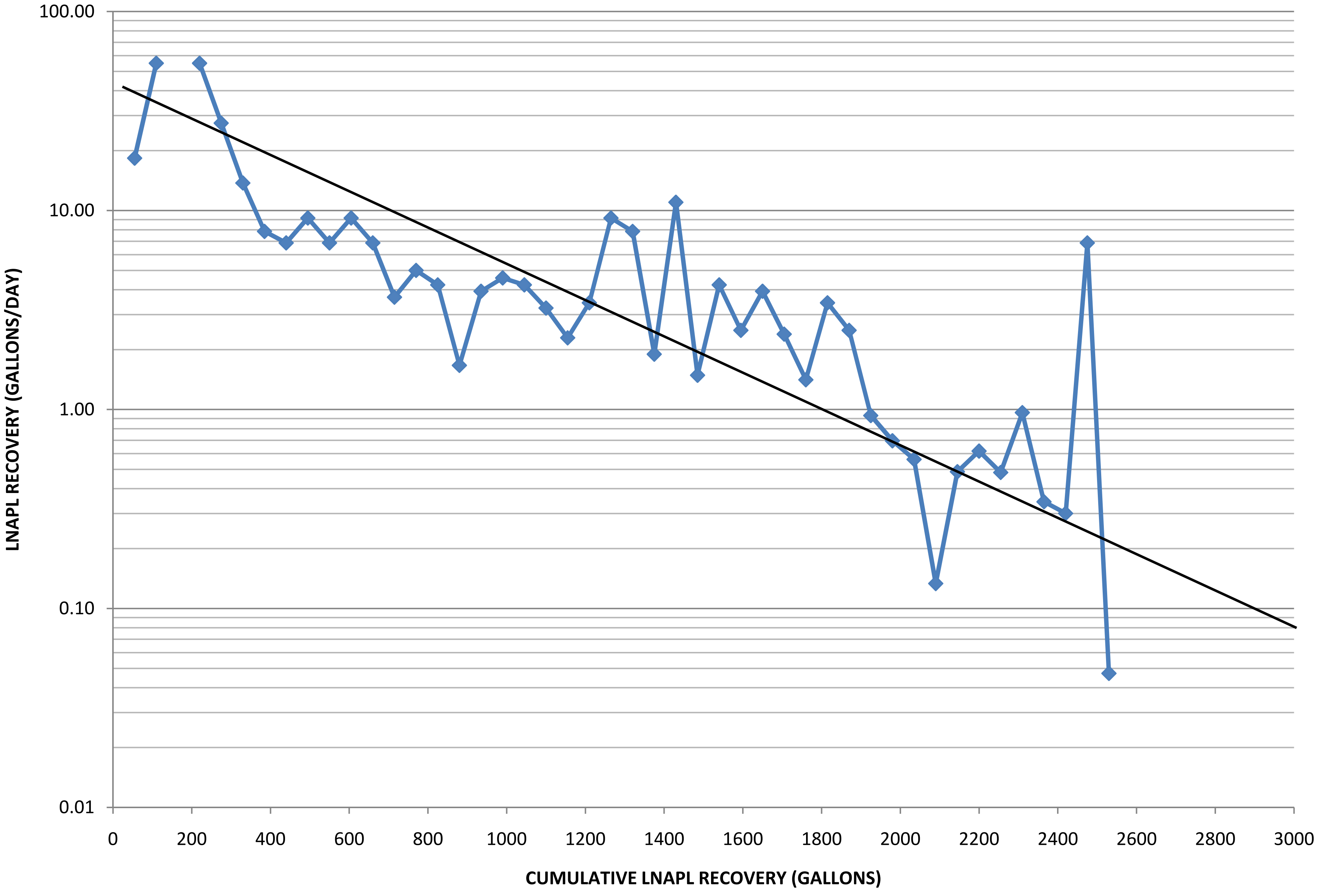


FIGURE 8 - Building 22 LNAPL Recovery

FIGURE 9 - Potential LNAPL Recoverability - Max. Well Oil Thickness = 2.5 feet

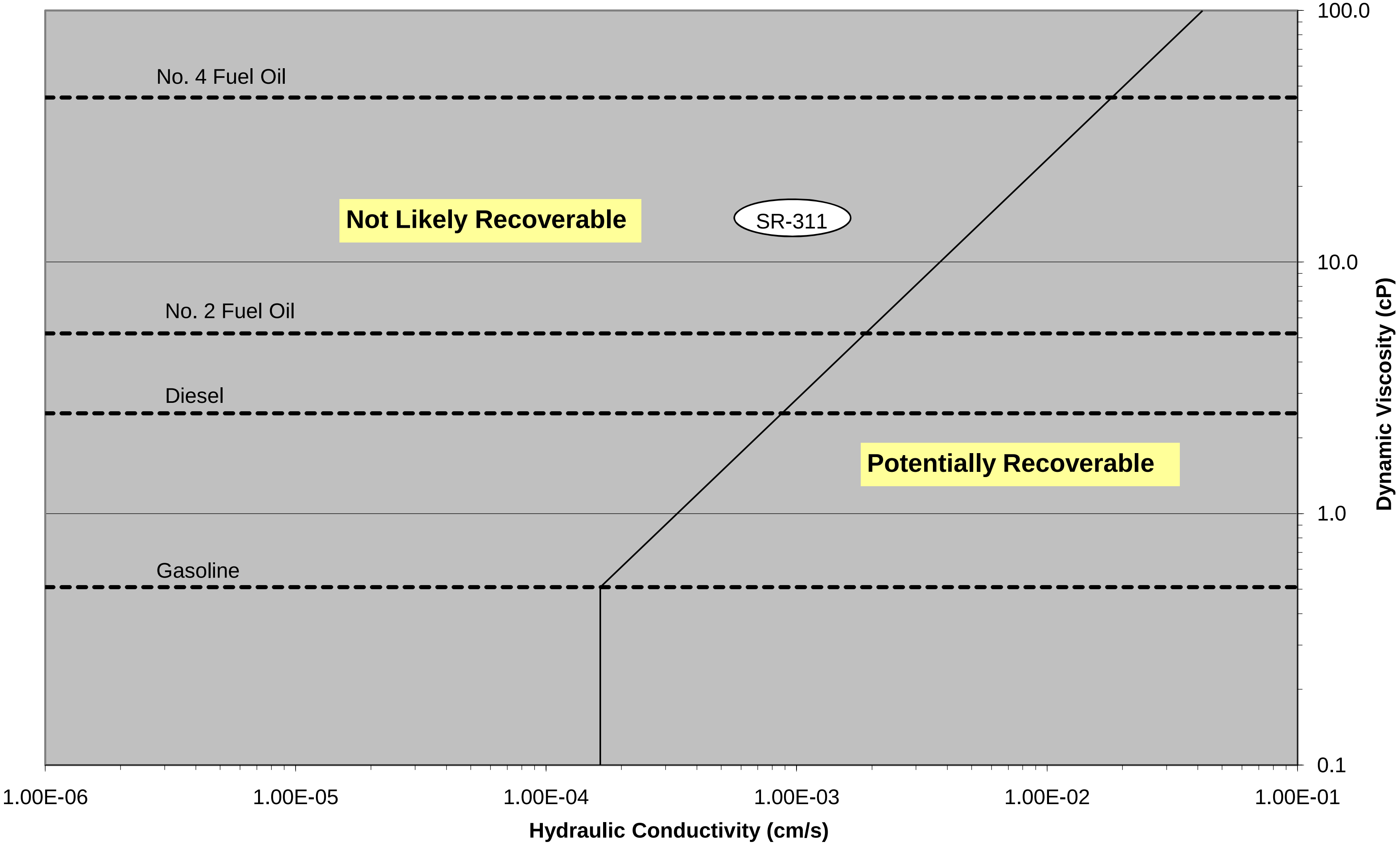
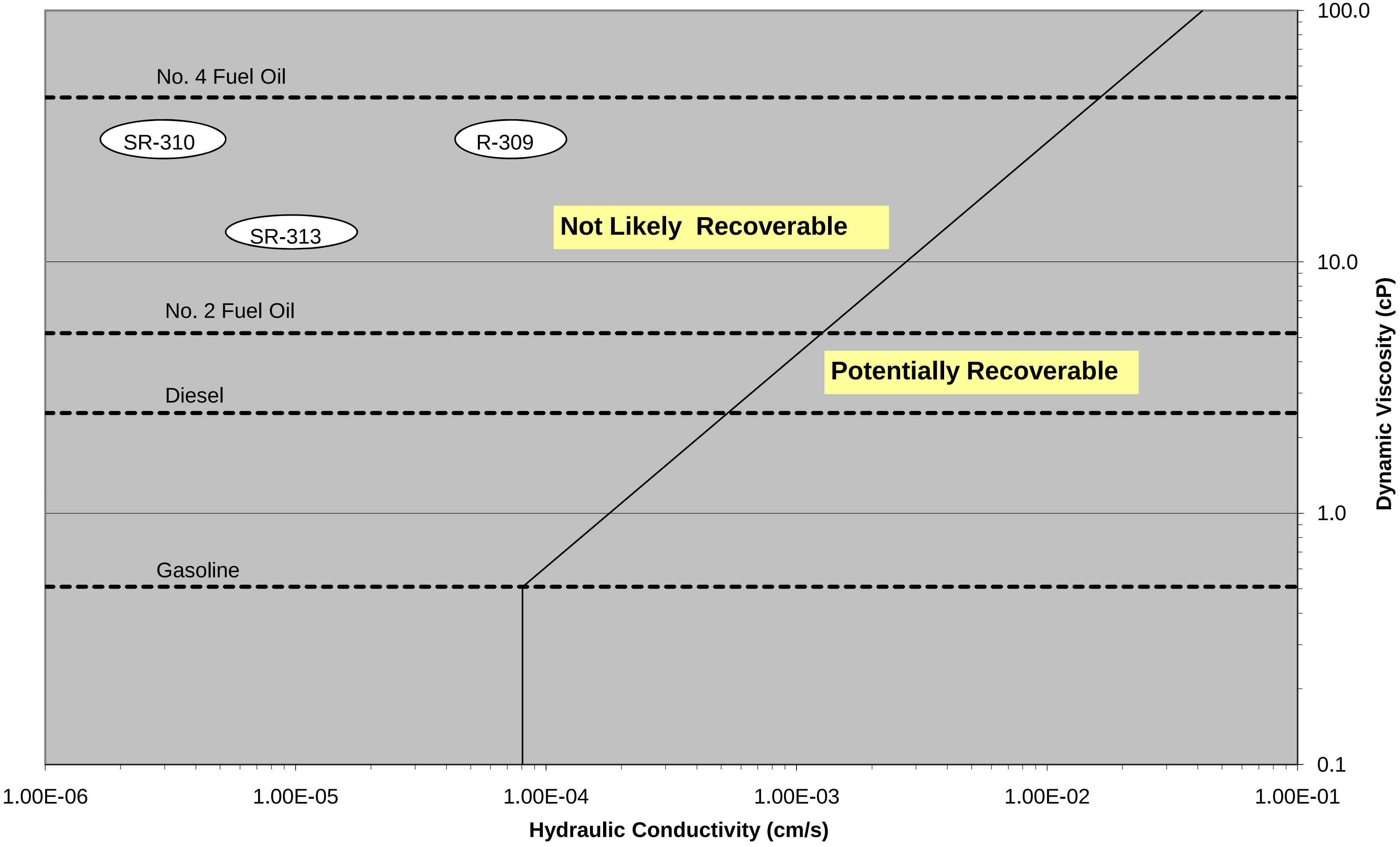


FIGURE 10 - Potential LNAPL Recoverability for Max. Apparent Well Oil Thickness = 5.0 feet



APPENDIX A

Enhanced LNAPL Recovery Case Studies

APPENDIX A

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Page

1. ENHANCED RECOVERY TECHNIQUES

Enhanced recovery methods such as surfactant-enhanced or thermal-enhanced recovery are theoretically capable of recovering greater percentages of free phase hydrocarbons as compared to standard hydraulic recovery methods. However on larger-scale projects, enhanced recovery technologies still leave a significant volume of hydrocarbon in the subsurface and therefore provide little incremental benefit towards meeting regulatory water quality objectives, and do not generally change the risk to human health or the environment.

1.1 Surfactant-Enhanced Recovery

Surfactant-enhanced remediation was first considered in the late 1970's as a way to increase the solubilization or mobilization of NAPL contaminants in porous media. Depending on the type of surfactant used, they can increase NAPL solubility through the formation of micelles or enhance mobility by decreasing interfacial tension at the NAPL/water interface. Increases in the solubility and/or mobility of NAPL can increase removal efficiency and shorten treatment times while at the same time pose challenges regarding unstable or "runaway" NAPL and dissolve-phase plumes.

This technology, although widely discussed and pilot and/or laboratory tested, has rarely been applied to full-scale projects except as a demonstration project (often with federal funding). The primary reasons for its very limited use include cost, concerns with residual surfactants in the subsurface, significant post-treatment mass left in place, and lower cost/availability of lower risk alternatives (Simpkin et al, 1999). There are also significant concerns regarding unintended migration of free-phase and/or dissolved-phase contaminants.

Current surfactant enhancement techniques are known as surfactant flushing, surfactant enhanced aquifer remediation (SEAR), and surfactant enhanced subsurface remediation (SESR). Of the field-scale tests that have been performed, the majority focused on remediation of DNAPL, particularly when containing chlorinated hydrocarbons, because DNAPL typically sits atop low permeability layers which serves as an aquitard during surfactant flushing (Abdul, 1994; Brown, 1999; Fountain, 1992; Knox, 1999; Shiau, 2002). Small-scale projects targeting LNAPL have also been performed (Jawitz, 1998).

In addition to water and anionic or nonionic surfactants, a typical surfactant solution may contain cosolvents (e.g. alcohols) to enhance solubilization or components that enhance the viscosity of the delivered solution (e.g. polymers or Guar Gum). A cosolvent, such as isopropanol, can be used to improve the surfactant solubility in solution and provide the surfactant/contaminant solution with an acceptable viscosity. A negative side effect of adding chemicals to the surfactant solution is the need to treat the additives along with the contaminant at the recovery end of the process (NFESC, 2002) and the treatment and management of the produced fluids of these additives is one of the biggest challenges of surfactant-cosolvent flushing applications.

Accurate characterization of the subsurface geology is critical to ensure the effective implementation of SEAR, which requires a fairly high level of homogeneity within the aquifer to facilitate relatively uniform distribution of surfactant, moderate-to-high permeability within the treatment zone (greater than 10^{-3} cm/sec) to facilitate fluid injection/recovery, and the ability to predict and monitor groundwater flow to maintain hydraulic control. In addition, regulatory constraints may have to be satisfied, including permits and meeting discharge limits. Treatment zone heterogeneities can cause significant channeling of the injected fluids and bypassing of impacted zones, causing poor surfactant sweep of the targeted area (NFESC, 2002). Rigorous hydraulic control and understanding is necessary to reduce the risk of increasing the size of the contaminant plume when increasing NAPL mobility. The

GM Lexington site poses significant challenges for all these items, including:

- A heterogeneous Overburden Unit, and the complex heterogeneity of fracture systems within the Shallow and Intermediate Bedrock Units;
- Relatively low hydraulic conductivities for the Overburden Unit and the Shallow and Intermediate Bedrock Units;
- Complex fracture networks within the Shallow and Intermediate Units which would pose a challenge to monitor at the level required to assure hydraulic control during the remedial activities; and
- Various LNAPL compositions at the Site, such as lubricating oils, lighter weight fuel-like products, test fuel, and Stoddard solvent, in some cases intermixed at the same location.

Studies of surfactants have been conducted that provide information on 37 applications (NRC, 2005; Simpkin et al, 1999). The vast majority of these applications were in sand and/or gravels which allowed for delivery and recovery of fluids within the treatment zone. Another study performed on surfactant applications showed that the average reported percent removal was 55 percent and the average endpoint (remaining concentrations after a surfactant application) was 7,000 mg/kg (Simpkin et al, 1999). Post-treatment concentrations of this magnitude indicate that substantial fractions of the pore space remained filled with NAPL. While an appreciable percent removal has been achieved in past surfactant projects, significant contaminant mass will persist in the subsurface resulting in concentrations above drinking water standards in the vicinity of the LNAPL, even for the best, most favorable applications. Performance would be much lower for less favorable applications. In addition, residual flushing solution chemicals (e.g., surfactant, salts, and polymer) are likely to persist in the subsurface and make the water unsuitable for potable use for an extended period.

Field implementation typically involves sequential delivery of chemical solutions. This includes:

1. Pre-flushing with water from one to tens of pore volumes. This is known as a pre-flush and is performed to precondition the aquifer for subsequent flushing;
2. Flush surfactant solution through the target area with one to four pore volumes. Surfactant maybe a mixture of surfactant, alcohols, polymers, and/or salts; and
3. Post-flushing with water to continue flushing mobilized NAPL and contaminants. This can involve anywhere from a few to tens of pore volumes of water.

This sequence of delivery can be difficult to achieve in certain geologic settings. For example, past applications have shown that it can be difficult to focus the flushing solutions on the desired treatment zone because of preferential flow in heterogeneous zones. Additionally, after a surfactant application is completed, large amounts of the chemicals and mobilized NAPL have been shown to remain in the soil. This was the case at a large-scale demonstration conducted in Laramie, Wyoming, where data showed that thousands of pounds of surfactant remained per acre-foot of target treatment area, even after reconditioning (CH2M Hill, 1990). Recognizing that much of surfactant solution is readily biodegradable, post-treatment subsurface conditions are likely to be highly reduced. This can create two general concerns:

1. Depletion of available electron acceptors may diminish the degree to which natural attenuation is limiting migration of dissolved-phase contaminants; and
2. Mobilization of naturally-occurring metals can occur under the reduced conditions.

Implementation costs for surfactant-enhanced remediation techniques include design, capital, and operating costs. These costs are lower for homogenous, highly permeable sites with relatively constrained NAPL plumes. Capital costs are highly dependent on the amount of surfactant used, the type and amount of cosolvents, the amount and type of waste stream treatment, and whether or not the surfactant is recycled. Cost summaries provided in Simpkin et al 1999, show that costs can range from $65 to $750 per cubic yard with an average of $314 per cubic yard. Additionally, the estimated cost for SEAR application at a high-permeability site recovering tetrachloroethene was calculated at nearly $4.5 million dollars per acre, with surfactant recycling reducing the cost by about $150,000 per acre (ESTCP, 2001, NEFSC, 2002). Recent advances have advocated low-concentration surfactant flushes and breaking treatment sites into small sections and treating them sequentially (Sabatini, 2010) in an attempt to make these applications more cost effective.

1.2 Surfactant Flushing Challenges

Surfactant applications are a multi-step remediation technology that has only been implemented for small remediation areas. There are benefits of applying surfactants which primarily involves an increase in LNAPL mobilization and a resulting increase in LNAPL recovery. However, there are also challenges and uncertainties. Based on past lessons learned, a few of the primary challenges include:

Aboveground Process Equipment: For surfactant projects, the recovered fluids and surfactant solution have to be separated and treated. A second mixing, filtration, and metering system is needed to inject the surfactant. These systems require substantially more equipment than standard pump-and-treat processes due to the challenges of separating surfactant from the water solution.

Surfactant Injection Challenges: The introduction of surfactant introduces a number of challenges, including injection of surfactant at desired rates, at the correct depth in the aquifer, and in sufficient quantities to contact the NAPL in the target treatment zone, avoiding channeling of surfactants and unintended mobilization of contaminants both laterally and vertically, and challenges for treatment of extracted fluids and reuse of surfactants.

Increased Solubility and Mobility: Surfactants were developed to reduce interfacial tension with NAPL. This decreased tension allows for increased mobility of NAPLs both laterally and vertically. Surfactants also increase the effective solubility of NAPL components. An increase in effective solubility increases the source concentration and may result in the formation and/or expansion of a dissolved-phase groundwater plume.

Residual Surfactants: For surfactant projects, it has been shown that a large volume of the surfactant solution and mobilized NAPL will be left in the subsurface. This remaining solution, also biodegradable, can lead to reducing conditions which can deplete available electron acceptors and diminish the degree to which natural attenuation is limiting migration of dissolved phase contaminants. This condition can also mobilize naturally-occurring metals such as arsenic into groundwater.

Design, Installation, and Access: Surfactant applications typically require an injection spacing density of 10 to 15 feet and an extraction spacing density of 15 to 20 feet. Additional monitoring wells are also needed to monitor vertical and horizontal migration outside the treatment zone. Given the high density of wells, piping, and treatment equipment, large, utility-free areas are typically required for reasonable implementation.

1.3 Surfactant-Enhanced Recovery Case Studies

1.3.1 Former Gasoline Station, Golden, Oklahoma

SEAR was used for LNAPL recovery at former gasoline station in Golden, Oklahoma. The treatment volume was 44,000 cubic yards of gasoline fuel treated using in-situ surfactant flushing followed by chemical oxidation at a depth of 5 to 25 feet bgs. The footprint of this application was approximately 200 feet x 200 feet. Cleanup levels involved free-phase hydrocarbon removal and benzene reduction to 9 ug/L in groundwater. The site was treated in 2001 to 2002 at a cost of $700,000. The site geology included shallow silt, sandy silt and silty clay with sand and gravel at depths greater than 15 feet (Surbec, 2006).

1.3.2 Hill Air Force Base

A surfactant field demonstration project was conducted at Hill Air Force Base (AFB) in 1996 to evaluate potential applications and demonstrate potential drawbacks.

Key findings from this field demonstration include the following:

- A surfactant mixture could be effectively delivered to the Hill AFB Site;
- Greater than 9.5 pore volumes would be needed to reduce LNAPL saturation to below detection limits;
- Application had significant separation/treatment challenges for recovered surfactant and water solutions while also leaving significant surfactant behind in the subsurface; and
- Concerns about potential migration of LNAPL resulted in the pilot test being conducted in a contained sheet-piling cell. Options for applications elsewhere would either require a similar sheet-piling cell around the target treatment area or accept risks of significant migration that might occur from target treatment areas.

Approximately 6.5 pore volumes of surfactant were pumped through a small, 10 foot x 16.4 foot sheet-piling cell to recover 90 percent of a mixture of jet fuel and other components. The treatment zone sediments were sands and gravels (Mulligan, 2001; NRC, 1999). Sabatini (Sabatini, 2010) reported that 9.5 pore volumes of surfactant were swept through the 5.9-cubic yard zone. Results indicated that 86 percent of LNAPL consisting of jet fuel and other components was recovered. However, data indicated that LNAPL in excess of residual saturation remained after treatment.

1.3.3 Chevron Cincinnati

In 2001, SEAR was evaluated in collaboration with EPA to treat LNAPL contamination at the Chevron Cincinnati Facility in Hooven, Ohio (U.S. EPA, 2005). Note that this application was never implemented and is only described in concept below.

Key conclusions from this conceptual evaluation include the following:

- The application of SEAR would have required approximately 8 to 12 years to conduct and would not meet the desired cleanup goals of reaching MCLs;
- This would be the largest surfactant application on record at two orders of magnitude larger than published work for surfactant applications (200 acres versus largest to-date of around

2 acres); and

- Substantial technology development would be required to bridge this experience gap to ensure that this approach could be successful.

Field characterization identified residual LNAPL saturation within the smear zone ranging from 1 percent to 8 percent of soil pore volume (equating to 1,000 to 8,500 mg/kg). An estimated 8 million gallons of LNAPL were obtained based on a 10-foot smear zone thickness, an area of 200 acres, LNAPL saturation of 4 percent, and soil porosity of 0.3. The specific goal for the SEAR system was to reduce the LNAPL to levels where SEAR can no longer mobilize the LNAPL, determined to be between 0.5 percent and 1 percent saturation. The preliminary cleanup goal used as a basis to select the final remedy was a benzene concentration in groundwater below the drinking water MCL of 5 ug/L. The 2004 draft Corrective Measures Study (CMS) produced for this project estimated that SEAR operations, in conjunction with SVE, would take from 8 to 12 years. However, application of these technologies would not achieve final cleanup goals and would need to be followed by hydraulic containment and monitored natural attenuation for decades to reach cleanup goals. Uncertainty in the volume of LNAPL at the site precluded more refined estimates.

As a remedial alternative in the groundwater CMS, SEAR would be incorporated with ongoing groundwater containment through pump-and-treat for hydraulic control, institutional controls, and SVE. SEAR and SVE would be used together during periods when the groundwater table was seasonally low. SEAR would be used to flush most of the LNAPL from the saturated zone and remove the free-phase LNAPL, while SVE would be used to remediate the residual soil contamination in the vadose zone. SEAR would be implemented in consecutive panels (500 feet long x 100 feet wide; each having between 30 and 50 central injection wells spaced 10 to 15 feet on center, and a similar number of extraction wells), each treated for a few weeks, after which time the operation would move to the next downgradient panel. This process would extend over several low groundwater seasons, progressing downgradient until the entire site was treated. SVE would be installed and operated immediately after SEAR was completed in a particular panel until it became ineffective (estimated in the CMS to be approximately eight years). Present value cost for this system was estimated to be $150 million.

It was assumed that the extracted LNAPL and groundwater emulsion could be treated using aboveground technologies to recover LNAPL and reduce contaminants prior to reinjection. However, the feasibility of the aboveground treatment has not been proven. Based on the size of the LNAPL plume at this site (8 million gallons), the SEAR system was estimated to be two orders of magnitude larger than the largest SEAR operation conducted through October 2001, which was when the technology evaluation was completed. The CMS stated that substantial technology development would be required to bridge this experience gap.

The CMS noted that the implementation of SEAR in a piecemeal manner (working its way downgradient) described in the conceptual design could delay redevelopment of the site because of the dense network of wells required. SEAR would have to be completed in any given area before site redevelopment could begin. In the case of the Chevron site, the most downgradient impacted area, which would have to be treated last under the sequential panel treatment method, would benefit most from the earliest development. In addition, site contacts stated that when SEAR is used to remove LNAPL from large sites such as refineries and tank farms, it is generally applied only to the “hot zone”. Planned applications at other sites are designed to use SEAR to remove LNAPL “hot zones” and create an “attenuation zone” where benzene concentrations will be reduced (U.S. EPA, 2005) but other contaminants will remain, sometimes above residual saturation.

1.4 Thermal-Enhanced Recovery

In-situ thermal heating has drawn increasing interest over the past 10 years as a method to potentially enhance cleanup of impacted sites. The basic technologies were originally developed by the petroleum industry to enhance crude oil recovery in deep underground reservoirs. There are several similar thermal technologies which, in general, heat the subsurface to enhance the recovery of organic compounds, the main differences being the method of heat distribution. The most widely tested and reasonably available among these techniques are thermal conductive heating, electrical resistive heating (ERH), and steam-enhanced remediation. By heating the impacted zone, organic compound vapor pressures, volatilization rates, solubilities, and diffusion rates increase, while organic compound viscosity decreases. Initially, as the subsurface is heated slightly (up to 40°C), biodegradation will increase. However, as heating continues and temperatures increase above 40°C, biodegradation rates have been shown to decrease or cease, as beneficial bacteria are killed by the high temperatures. Additional research shows that after thermal heating, biodegradation rates at some sites may rebound, but this is not a certainty.

ERH and steam injection are the two thermal remediation technologies most often considered and applied for enhancing free-phase hydrocarbon removal. Other thermal technologies such as thermal conduction heating and radio frequency heating have been tested at various sites, but to a significantly smaller degree and/or with less success.

Oil recovery using thermal recovery methods has been used by the petroleum industry for over 70 years. The first thermal method used in 1933 was steam injection for tertiary petroleum recovery (White and Moss, 1983). It enhanced the recovery of viscous oils, primarily by reducing oil viscosity and allowing more effective displacement of oil towards recovery wells. As early as 1969, ERH was deployed in petroleum reservoir formations by applying alternating current to reduce oil viscosity (Pizarro and Trevisan, 1990). As thermally-enhanced technologies were developed further, steam was most often used as the principal enhanced oil recovery method, using a steam flooding approach with cyclic steam injection (Ali and Meldau, 1979).

As thermally-enhanced oil recovery methods were considered for soil and groundwater applications starting in the 1980s, additional research and technology development were required to allow appropriate adaptation of the technologies for environmental remediation purposes. During the use of thermal recovery methods in the petroleum field, unintended migration of oil often occurred due to a general lack of monitoring. The primary concern for thermally-enhanced oil recovery was that increased production exceeded the cost of the enhancements. The use of thermal recovery methods for oil recovery also did not require aboveground water treatment equipment.

To date there have been on the order of 200 applications, pilot tests, or full-scale implementations of various thermal recovery methods. Based on a comprehensive technology review completed by Kingston et al (2010), this relatively large number of thermal applications has provided significant insight regarding favorable applications/conditions for thermal remediation and less favorable applications/conditions.

1.5 Thermal Treatment Challenges

Thermal applications are complex and dynamic treatment approaches that can increase mass recovery and benefit sites, but at the same time have a number of challenges and uncertainties associated with their implementation. The literature identifying the benefits of thermal is prevalent and includes reduced long-term monitoring and source zone treatment; however the challenges and uncertainties are rarely addressed. Based on past lessons learned, the following captures a few of the possible thermal treatment challenges.

Aboveground Treatment Equipment: For steam injection projects, the recovered fluids can have properties that are quite different from the LNAPL free-phase product existing at ambient temperatures. For example, at the Guadalupe steam injection pilot test described below (PTP Report, 2005), the recovered product was difficult to separate in a normal oil/water separator because it kept foaming over the top (a common problem for steam injection projects). Additionally, if chlorinated solvents are being extracted and treated using a thermal oxidizer, they can produce significant amounts of hydrochloric acid that must be neutralized.

Design, Installation, and Access: Thermal applications typically design systems with the following density of heating locations:

- Steam injection spacings of 20 to 50 feet (depending upon site permeability and depth to water);
- ERH spacings of 15 to 23 feet; and
- Conductive spacings of 12 to 20 feet.

Additional installation of extraction wells, temperature monitoring points, and pressure monitoring points will also need to be installed and typically account for approximately 50 percent of the installed points. The installation of typical thermal application (an acre or less) takes on the order of 3 to 4 months with 10 hour work days and two operating rigs to install, with significantly more time needed if the installed heating locations, extraction wells, and monitoring points need to be operated below ground surface. To date, only vertical extraction wells for water and product recovery have been installed at depth. Horizontal trench wells installed with excavator equipment for vapor recovery have been used at high groundwater table sites.

Steam Injection Challenges: The introduction of steam at high pressures and temperatures, particularly at significant depths (greater than 50 feet bgs) introduces a number of challenges. These challenges include steam injection at desired rates and locations, balancing different injection points, and tracking of the steam front or zone of elevated temperature. To mitigate these challenges, steam injection projects include considerable amounts of thermocouples to define the steam zone. This aids in avoiding unintended mobilization of contaminants both vertically and horizontally, chemical condensation at the periphery of the steam zone, and challenges for treatment of extracted fluids.

Increased Solubility and Mobility: Thermal enhanced recovery methods results in increased mobility of LNAPLs both laterally and vertically, which could result in unintended mobilization of LNAPL and/or dissolved-phase constituents. Rigorous hydraulic control and understanding is necessary to reduce the risk of increasing the size of the contaminant plume when increasing LNAPL mobility. Thermal methods can also significantly suppress or destroy beneficial microorganisms responsible for the natural attenuation of residual hydrocarbon and maintaining plume stability.

Operational Risks: All thermal treatment systems have inherent risks associated with implementation. These risks include vapor intrusion, physical hazards, and heat escape through the surface. Physical hazards associated with thermal projects also include aboveground piping, steam leaks, and high voltage power lines. These operational risks can be managed but require an added level of caution and safety processes to ensure a safe working environment, and should be considered during the decision process.

Other thermal remediation challenges are specified below. These challenges relate to remediation endpoints and impacts of the system operation.

Remediation Endpoints: Thermal treatment technologies have evolved significantly over the past few years. A major change is recognition that the remedial endpoint affects the operation of the system. It is critical that the required remediation endpoints be defined prior to initiating the feasibility analysis of thermal because of the aggressive nature of the technologies. This is due in part that while thermal techniques can substantially reduce concentrations, in the case of free-phase product, significant mass is still left behind and acts as a continuing source for years to come. Review of similar thermal applications indicates that thermal remediation will not reduce mass levels sufficient to meet typical groundwater cleanup criteria such as maximum contaminant levels (MCLs).

Energy Consumption: Thermal applications require a significant amount of energy to heat the subsurface and to power the aboveground treatment system. For example, a cubic yard of saturated soil will typically require on the order of 120 kilowatt hours per cubic card to reach boil temperatures. This assumes negligible heat losses. As heat losses increase, the energy input per cubic yard is increased to accommodate the loss. Thermal systems have been shown to use up to 320 kilowatt hours per cubic yard in low permeability formations or formations with significant groundwater velocities.

Carbon Footprint: Thermal technologies have a large carbon footprint. The carbon footprint associated with the production of electricity required to treat one cubic yard of soil (assumed to need 120 kilowatt hours per cubic yard) is approximately 87 pounds of carbon dioxide.

Access: Thermal systems require significantly more oversight and access to the remediation area than conventional remediation projects. Thermal projects typically require approximately 2 to 4 months of drilling for installation of a full-scale treatment system and possibly more if subgrade installation of well heads, piping, etc. is required. Given the high density of wells, piping, and treatment equipment, large, utility-free areas are typically required for reasonable implementation. They also include daily (8 to 10 hours per day) on-site equipment checks to ensure the system is functioning properly.

1.6 Thermal-Enhanced Recovery Case Studies

Thermal recovery methods employed at four sites are described below. These applications include the Guadalupe Oil Field Hot Water/Steam Injection Pilot Test, the Lemoore Naval Air Station project, the TOTAL Petrochemicals former Bulk Fuel Terminal, and steam enhanced recovery of PCE in fractured bedrock at the Loring Air Force Base in Limestone, Maine. Note that three of these applications address LNAPL in unconsolidated deposits only, in some cases relatively homogeneous sands, as compared to LNAPL in heterogeneous, unconsolidated fill and native deposits, and LNAPL in fractured bedrock at the GM Lexington site. Despite these differences, a review of these four sites still provide valuable insight into thermal recovery methods.

1.6.1 Former Guadalupe Oil Field Pilot Test

The Guadalupe Oil Field (GOF) consisted of a pilot test of hot water flooding followed by steam injection conducted over nine months in 2003 and 2004. A summary and the key findings of the pilot test and data analysis include the following:

- Even for highly homogeneous sand, steam delivery to the target treatment zone was incomplete; the upper 7 feet of the target treatment zone received the majority of steam, with significantly less steam in the lower 5 feet of the water-bearing zone due primarily to heat loss;

- The pilot test data demonstrated that a relatively-close well injection/extraction well spacing of about 20 feet would be needed to treat the entire source area;

- The upward extent of the steam zone was well-controlled using soil vapor extraction from shallow wells screened above the steam injection wells. Control of vertical steam migration required close monitoring of the subsurface temperature in the vadose zone and adjustment of steam injection rates at individual wells if the steam zone expanded above designated levels. This type of monitoring and adjustments would be necessary throughout the target footprint to minimize heat losses and nonbeneficial steam venting in the vadose zone;

- Near the steam injection wells, diluent concentrations in the zones were significantly reduced in upper parts of the target zone. Concentrations of diluents in groundwater increased at the bottom of the steam zone due to the draining of mobile diluents and condensation of vapor-laden steam;

- Although diluent was recovered throughout the target treatment zone, most of the diluent recovery, about 85 percent, occurred within 15 feet of each injection well. At distances greater than 20 feet from the well, recovery rates fell sharply, ranging from 24 percent to 67 percent. Soil analysis showed from 2 percent to 50 percent of diluent mass remained after steam treatment, even after the injection of 18.8 pore volumes of steam;

- Post-treatment dissolved total petroleum hydrocarbon (TPH) concentrations in groundwater were observed to be about one-third of pre-treatment values;

- The expert panel concluded that injection of a larger number of pore volumes would not lead to complete removal of hydrocarbons due to the low volatility of a large fraction of the diluent constituents, and would lead to an order of magnitude increase in the duration of operation. In addition, it was estimated that achieving the best-case scenario (residual free phase hydrocarbons and 1,000 to 5,000 milligrams/kilogram [mg/kg] residual TPH) would require that the remediation be designed such that steam is able to reach the entire vertical zone of diluent-impacted soils throughout the area of treatment, a goal achieved during the pilot test only within 16 feet of the injection wells; and

- Calculation performed for the best-case scenario thermal system (1,000 – 5,000 mg/kg TPH remaining) showed that the remaining mass would continue to act as a source of groundwater impacts for decades despite the considerable effort and cost expended.

Haley & Aldrich served as technical consultants throughout the pilot test and assumed operational responsibility for the majority of the test. Professor David Huntley (San Diego State University) was also one of three members of the expert panel assembled by the Los Angeles Regional Water Quality Control Board (LARWQCB) to provide review and recommendations to the LARWQCB regarding all aspects of the pilot test. Based on the expert panel review and recommendation, LARWQCB determined that steam injection alone would not provide cleanup results that would achieve water quality objectives. LARWQCB decided it was not appropriate to proceed with full-scale application of thermal treatment at the former GOF (PTP, 2005).

1.6.2 Naval Air Station Lemoore Pilot Test

A pilot scale demonstration project was carried out at Naval Air Station Lemoore in Port Hueneme, California in 1994 to recover JP-5 Jet Fuel using steam-enhanced extraction (Udell et al., 1995). The project involved 6,296 cubic yards of product located in an area covering 48,125 square feet (~1 acre) to a depth of 20 feet bgs. The geology of the site consisted of shallow silt and clay and deeper sand with a groundwater table at approximately 16 feet bgs. The project ran from July through September 1994. Published accounts of total recovered volume vary, but estimates ranged from 78,500 to 200,000 gallons. The concentration of TPH inside the treatment area at and below the water table remained about the same (~20,000 parts per million) after treatment, indicating that potential to impact groundwater also remained about the same. Soil samples taken after 35 days of steam injection showed continued high TPH concentrations at the interface of the surface clay layer and the underlying silty sand that previously appeared to be unimpacted. Continued steam injection reduced these concentrations.

Some of the key conclusions from this pilot test included:

- Significant hydrocarbons can be recovered using steam-enhanced recovery, but the added product recovery may not provide much additional benefit in groundwater quality;
- Control of the groundwater elevation is important to avoid mounding and unintended product migration. It can be problematic to control groundwater elevations with heterogeneous sites;
- The aboveground treatment system must be over-designed to handle higher than expected extraction rates in both the liquid and vapor phases. Although this extra capacity may never be needed, requiring shutdown of thermal operation to supplement/repair/modify treatment equipments will decrease the proportion of free phase hydrocarbons that can be recovered; and
- Energy input must be sufficient to overcome heat losses and condensation in low permeability confining layers around the treatment zone. These heat losses can be difficult to predict.

1.6.3 Total Petrochemicals Former Bulk Fuel Terminal, Greensboro, NC

The Former Fina Bulk Fuel Terminal in Greensboro, North Carolina, now owned by Total Petrochemicals, consists of a pilot and full-scale application of ERH heating for the recovery of diesel fuel at a 6.5 acre site.

Key findings from this pilot test include the following:

- Equipment sizing, energy demands, and project sequencing make it challenging and cost prohibitive to treat a footprint as large as 6.5 acres at one time. It is much more cost effective to break treatment into 1.5 acre sections, although treating the area in sections causes some migration of product into previously-heated areas;
- Close heater well spacings of about 20 feet were needed to meet the remedial objectives in the target treatment areas;
- Significant hydrocarbon mass was being removed via thermally-enhanced extraction, although free-phase hydrocarbon remained. The focus was on reducing free-product to the point that product is no longer migrating;
- Significant hydrocarbon mass will still remain in the subsurface and will provide a long term impact to groundwater; and
- Massive infrastructure and intrusive work was needed to implement a thermal treatment in each zone.

Because of its size, the treatment area was divided into four 1.5-acre zones, each treated consecutively. Treatment of the Zone 1 (62,500 square feet/51,400 cubic yards) yielded about 214,000 pounds (32,000 gallons) of petroleum hydrocarbons. This included approximately 2,000 pounds of petroleum hydrocarbons in the groundwater phase, 14,000 pounds as liquid petroleum product, and 198,000 pounds in the vapor phase. Despite these substantial efforts, significant mass of diesel fuel remained in the subsurface providing a long-term source for groundwater impacts.

1.6.4 Loring Air Force Base, Steam-Enhanced Remediation, Limestone, MA

From 2001 to 2002, a steam-enhanced recovery research project was conducted in an abandoned limestone quarry at the Loring Air Force Base in Limestone, Maine. The quarry was historically used for waste disposal at the base, resulting in chlorinated VOCs and fuel-related compounds in groundwater within the fractured limestone, in particular PCE (during April 2002, PCE concentrations in the treatment area ranged from 7.4 ug/L to 6,300 ug/L). The U.S. Air Force, Maine Department of Environmental Protection, and U.S. EPA agreed to perform this research project to further develop remedial technologies in fractured rock.

The overall size of the treatment zone was relatively small, on the order of 150 feet by 60 feet, with good access within the quarry (i.e. no buildings, other infrastructure, or underground utilities). Extensive characterization of the site was completed in 2001, including detailed surface mapping, borehole logging and coring, methanol extracted rock chip sampling, borehole geophysics and acoustic televiewer logging, discrete interval groundwater sampling and transmissivity testing, and interconnectivity testing between boreholes.

The remedial system consisted of approximately six steam injection wells and six extraction wells and was started on September 1, 2002. However, steam injection ceased on November 19, 2002 as the funding ran out, while extraction continued until November 26, 2002. Despite extensive site characterization within the relatively small treatment area, the steam injection rates were lower than anticipated due to low transmissivity in the injection intervals. Heating was mostly local, restricted to regions near the steam injection wells and adjacent to high transmissivity fractures.

While vapor effluent samples showed that VOC mass was removed during the test period, some groundwater concentrations in monitoring wells within the treatment area increased based on one round of post-treatment groundwater samples. Within the treatment area, post-treatment PCE concentrations in the steam injection wells were reduced, while the extraction wells either declined or increased, in some cases significantly (i.e. 23.5 to 2,100 ug/L; 24 to 770 ug/L). However, this evaluation was based on one set of pre- and post-treatment sampling data; the pre- and post-steam injection PCE concentrations could be the result of normal temporal variability at the site, as the report states that "order of magnitude variation of PCE and TCE concentrations has been observed in wells within the test site in the period prior to the test."

Some of the report's conclusions and challenges included:

- Despite considerable effort, the bedrock fracture system could not be fully characterized;
- Highly variable fracture properties make prediction of flow direction of injected fluids difficult;
- The lateral and vertical distribution of DNAPL is extremely difficult to characterize and cannot be fully understood;
- Some contaminant mass resides in closed, dead end fractures which cannot be remediated via steam, air, or hot water injections;
- Matrix diffusion will limit the mass available for removal via steam injection;

- Small fracture apertures, clay lining of fractures, and sparse fracture networks may severely limit steam injection and the subsequent heating rate; and
- Hydraulic and pneumatic control is much more challenging in fractured rock, as well as very difficult to document.

No definitive conclusions were offered due to the relatively short duration of the project, but the report stated that steam injection may not be a feasible technology for highly complex, low permeability fractured bedrock systems with low interconnectivity.

1.7 Enhanced LNAPL Recovery Challenges at Delphi Automotive Systems Site

Nearly all of the surfactant-enhanced and thermal-enhanced recovery challenges discussed in Section 1.2 and 1.5 above are applicable to the Delphi Automotive Systems Site, in particular the heterogeneous nature of both the overburden and bedrock units, the size and access constraints of the Site, and the potential for inadvertently re-mobilizing both LNAPL and dissolved-phase hydrocarbon plumes that are currently stable. These challenges include:

- A heterogeneous Overburden Unit, the complex heterogeneity of fracture systems within the Shallow and Intermediate Bedrock Units, and the relatively low hydraulic conductivities in these units, would pose significant surfactant- and thermal-enhanced recovery challenges; monitoring at the level required to assure hydraulic control during surfactant-enhanced recovery, as well as monitoring the steam front for steam-enhanced recovery, would also be extremely difficult;

- Various LNAPL compositions are present at the Site, such as lubricating oils, lighter weight fuel-like products, test fuel, and Stoddard solvent, in some cases intermixed at the same location. Since the design of enhanced-recovery methods are based on viscosities and chemical properties such as solubility, boiling point, vapor pressure, volatilization rate, and diffusion rate, variable and/or intermixed LNAPL compositions would complicate both surfactant- and thermal-enhanced recovery methods.

- The application of surfactant- and thermal-enhanced recovery would be prohibitively expensive given the size and access constraints at the Site. The high density of wells, piping, and treatment equipment required poses significant feasibility issues due to access constraints as nearly all the LNAPL areas, except the North and East Parking Lots, are under the manufacturing buildings;

- For surfactant projects, it has been shown that a large volume of the surfactant solution and mobilized NAPL will be left in the subsurface. This remaining solution, also biodegradable, can lead to reducing conditions which can deplete available electron acceptors and diminish the degree to which natural attenuation is limiting migration of dissolved-phase contaminants. This condition can also mobilize naturally-occurring metals such as arsenic into groundwater;

- Both surfactant- and thermal-enhanced recovery methods may inadvertently re-mobilize LNAPL and dissolved-phase hydrocarbon plumes that are currently stable; and

- Thermal applications require a significant amount of energy to heat the subsurface and to power the aboveground treatment system and have a large carbon footprint.

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