Coal Tar Detection and Mobility Assessment at Manufactured Gas Plant Sites

Refining the Res-SAT® Tool Protocol

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Technical Update, December 2008

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PRODUCT DESCRIPTION

EPRI has revisited the baseline data used to develop and validate the original Res-SAT® Tool designed in 2004 for determining coal tar mobility using a field screening approach. After reevaluating that data, it was determined that developing a broader data set would further validate the Res-SAT Tool operating protocol and allow it to serve as a complement to other in situ or onsite field assessment tools for use during investigations. This study suggests that a protocol is necessary for performing a second field demonstration. Such a demonstration would refine the tool's performance characteristics in measuring coal tar mobility in saturated soils and identify key opportunities for incorporating tool test results into a conceptual site model and assessment of remedial options to address coal tar in subsurface soils.

One project objective was to identify appropriate Res-SAT Tool operating conditions that can be used to measure the potential for mobility of dense non-aqueous phase liquids (DNAPLs) in fine, medium, and coarse-grained soils. Another objective was to evaluate using the tool in the field without the need for site-specific laboratory calibration. Previous Res-SAT Tool research had only tested a limited range of coal tar and soil characteristics. A review of past work also revealed the majority of testing was completed using relatively low density /viscosity coal tars (specific gravity approximately 1.03) in mainly well-graded medium to coarse sandy soil. As a consequence, additional Res-SAT Tool performance data on samples with a broader range of coal tar and soil property variation were needed (primarily DNAPL density, viscosity, and interfacial surface tension and soil grain-size distribution, porosity, and hydraulic conductivity). These data allow the tool's performance characteristics (for example, critical pressure) to be properly assessed over a range of commonly encountered soil and coal tar types.

Results and Findings

This project has developed a broader data set of Res-SAT Tool performance data on soils and coal tars typically encountered at former manufactured gas plant (MGP) sites. The project also has demonstrated the Res-SAT Tool can be used in the field for coal tar mobility screening without prior site-specific laboratory calibration to identify a site-specific critical pressure. A field demonstration program has been identified that will measure mobility potential of coal-tar-containing soils. In the demonstration, tool configuration and operation will be further refined and the tool operating protocol will be improved to accommodate more widespread use as a field screening tool during site investigations.

Challenges and Objective(s)

This work tested two heavier coal tars from MGP sites on two finer-grained soils. Four coal tar samples were analyzed from which two tars with a specific gravity between 1.05 and 1.07 were selected for evaluation by a third-party laboratory with expertise in the science of residual saturation testing. Having an independent third party use the Res-SAT Tool provided further insight into the tool's performance characteristics, compared performance characteristics to standard laboratory centrifuge tests for NAPL mobility, and allowed for a critical independent review of the previously published operating protocol.

A key project objective was to assess whether changes in soil type and/or tar physical properties (viscosity and specific gravity) affect capillary pressures at residual saturation and, therefore, the pressure to set the Res-SAT tool for a given soil and tar combination. Testing results suggest the

Res-SAT Tool can be operated in the field for screening level coal tar mobility assessments, without prior site-specific laboratory drainage curve development. Results also showed pore fluid interfacial tensions play an important role in fluid saturation and drainage behavior. Characterization of this property is useful in interpreting fluid pressure-saturation relationships.

Applications, Values, and Use

Recently improved field investigation tools to detect coal tar DNAPL, such as the Tar-Specific Green Optical Screening Tool (TarGOST™) by Dakota Technologies, Inc., are now being used routinely to detect and map the extent of coal tar residuals at MGP sites. The Res-SAT Tool can be used alone to evaluate potential mobility of coal-tar-containing soils from a traditional soil-boring investigation. However, the real power of a DNAPL mobility field tool is realized when it is combined with in situ field screening methodologies (for example, TarGOST, cone penetrometer) to generate more detailed real-time site characterization data and mapping. With this combination, the conceptual site model can be developed or modified in real-time as the investigation unfolds. The Res-SAT Tool also can be useful in assessing potential for DNAPL recovery success and for assessing placement of a DNAPL migration barrier technology.

EPRI Perspective

A critical activity in delineating the nature and extent of contamination at MGP sites is adequate characterization of coal tar in soils that may serve as an ongoing source of contamination to groundwater in the form of mobile and/or leachable coal tar. In 2005, EPRI sought to demonstrate at one MGP site that the Res-SAT Tool would provide a rapid and cost-effective alternative to traditional laboratory-based methods of characterizing sources of coal tar in soils that may need to be managed pursuant to certain regulatory programs. During that evaluation, it was determined that more operational experience on a wider range of soil and coal tar properties would benefit deployment of the Res-SAT Tool on a broader scale. Through this study, a protocol has been outlined for the Res-SAT Tool test cell that provides recommendations for using the tool when accompanying other in situ characterization devices.

Approach

The project team has reconfirmed the Res-SAT Tool is a useful field screening tool for detecting potentially mobile coal tar in soils. Prior testing of the tool also has demonstrated its utility in assessing the relative degree of leachability risk posed by a coal-tar-impacted soil sample. Given the time required for DNAPL saturation/mobility tests and leaching tests, the Res-SAT Tool, when used according to the protocols in this report, is a useful complimentary field tool for characterizing and delineating potentially mobile coal tar at MGP sites.

Keywords

MGP
Coal tar
Residual saturation
DNAPL
Field screening

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1 INTRODUCTION

Coal tar byproducts are often encountered in the subsurface at former manufactured gas plants (MGPs) due to spills, discharges, or historic or ongoing releases from remnant process structures that may remain buried at these sites. Coal tar in the form of a dense non-aqueous phase liquid (DNAPL) is routinely encountered during MGP site investigations. The presence and mobility of DNAPL are often key regulatory drivers for the prioritization of MGP sites as well as the determination of the nature and extent of remedial actions required. Identifying areas of a site where the DNAPL is mobile is also beneficial in determining where DNAPL recovery wells have a higher probability of successfully recovering product.

The physical and chemical properties of coal tar often result in its downward movement through the subsurface into the saturated zone (i.e., below the water table) until it encounters lower permeability strata. In addition to downward migration, the coal tar can also move laterally, controlled by the slope of the low permeability strata, the driving head of DNAPL, and the relative saturation of DNAPL in the soil pore spaces. Collectively, gravity, capillary pressure and hydrodynamic forces, as well as DNAPL density and viscosity influence its migration and retention characteristics (EPRI, 2004a).

When soil capillary forces are greater than gravity and hydraulic forces acting on a DNAPL, the DNAPL is defined as being immobile and is often termed “residual” (Cohen and Mercer, 1993). The point at which the gravity, hydraulic, and capillary forces are in equilibrium is termed the “residual saturation point”. The residual saturation point, or the DNAPL retention capacity of soils, is a function of soil porosity, soil bulk density, DNAPL density and viscosity (Hoag and Marley, 1986, Zytner et al., 1993), and the interfacial tensions between the fluid phases. Prior research has identified coal tar residual saturation values ranging from 7.7 percent to 22.6 percent of the pore space volume (EPRI, 2004a). At concentrations at or below the residual saturation, DNAPL is immobile. At concentrations above the residual saturation, DNAPL is considered potentially mobile.

Understanding the presence and movement of DNAPL in the subsurface is a key issue that has to be addressed at MGP sites. Early characterization of a site relative to DNAPL presence and mobility allows utility managers to prioritize their sites in terms of relative risk, and also allows a determination of how the site fits into various regulatory classifications that may affect the remedial approach for the site. Regulatory terms such as “free product”, “residual product”, “separate phase product”, “DNAPL”, and “source material” are often used as regulatory drivers for coal tar management (EPRI, 2006), with an inherent assumption regarding mobility and leachability. Determining the mobility of DNAPL at an MGP allows more informed decision-making regarding potential site risks and can also be used to assess the potential for successful DNAPL recovery from specific areas of a site.

1.1 The EPRI Res-SAT® Tool

EPRI and its researchers developed a field screening investigative tool, the Res-SAT® Tool in 2004, to measure the mobility potential of coal tar DNAPL at former MGP sites (EPRI, 2004b).

The tool consists of a control panel for monitoring and controlling fluid and air flow application to the cell, and a pressurized chamber or test cell to hold a coal tar-containing soil sample as shown in Figure 1-1. The Res-SAT® Tool and its control panel enable the development of site-specific coal tar imbibition and drainage curves, comparing the fluid pressure applied to the measured relative saturation of coal tar. The pressure/saturation relationship for a typical water-coal tar system is depicted on Figure 1-2.

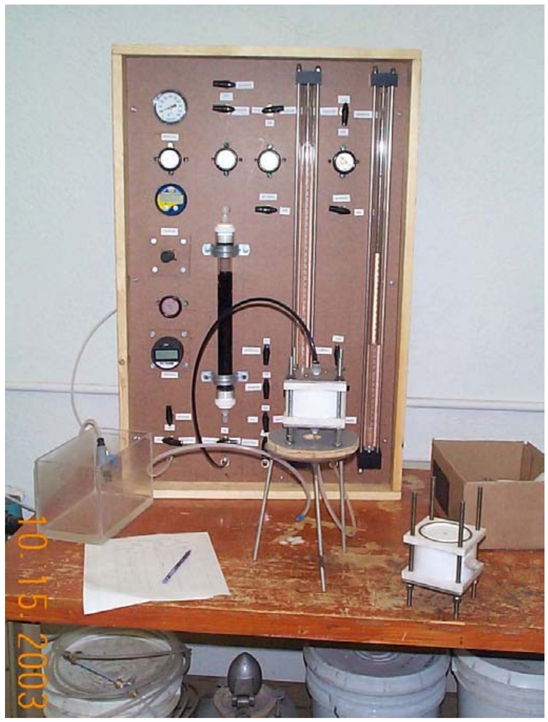

Figure 1-1
Res-SAT® Tool Control Panel and Cell

For site-specific tool calibration, a soil sample is first saturated with DNAPL, air pressure is then applied incrementally to drain the DNAPL to its residual saturation point. From this DNAPL drainage step, a site-specific pressure-coal tar saturation curve is developed. An example of a DNAPL pressure-saturation curve for DNAPL drainage is shown in Figure 1-3. From this curve, the coal tar residual saturation point is identified as the volumetric coal tar content at which increased pressure application does not result in additional coal tar drainage from the sample. The minimum applied pressure at which residual saturation is achieved is considered the “critical pressure” for the soil-DNAPL specimen. This calibrated critical pressure can then be used in the field to screen soil samples with coal tar for the presence of mobile DNAPL. That is, a soil sample is packed into the Res-SAT® cell in the field and air pressure (or vacuum) is applied incrementally up to the laboratory determined critical pressure. If DNAPL does not drain from the sample, the sample is considered to be below the residual saturation point and the DNAPL is immobile. If DNAPL drains from the sample, the sample is considered to be above its residual saturation point, and the DNAPL is potentially mobile. The theory behind the Res-SAT® Tool and its development research is described in EPRI, 2004b. A limited field trial at an MGP site was performed in 2004 (EPRI, 2005).

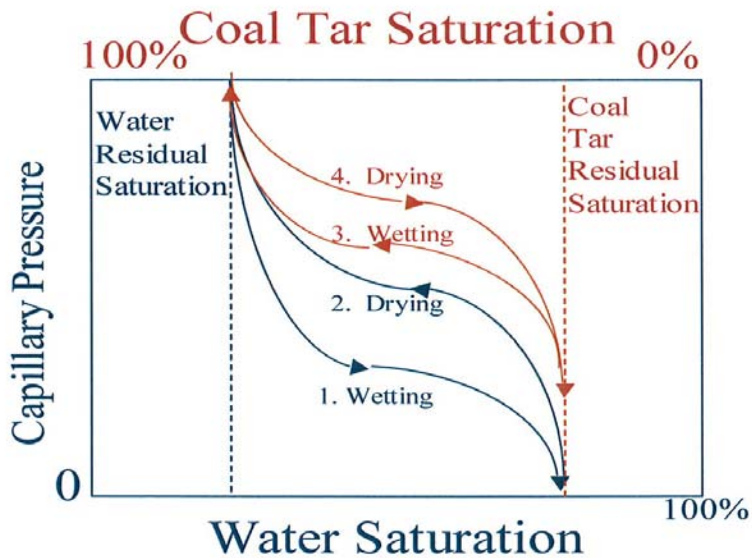

Figure 1-2
Capillary Pressure-Saturation Relationships for a Water-Coal Tar System

1.2 Integration of DNAPL Mobility Field Screening into a Site Characterization Program

The investigation and remediation of MGP sites has been the subject of significant and on-going research. The United States Environmental Protection Agency (USEPA) recognized that former MGPs can be difficult to characterize, but that site characterization and remediation can be expedited through the application of innovative tools and technologies (USEPA, 2000). Consistent with this approach described by the USEPA, there has been significant effort in the site characterization field to develop rapid site assessment approaches to detect and track contaminants on sites in real time. Coal tar is often present in the subsurface at MGP sites. Recent advancement of field tools to detect the presence of coal tar DNAPL, such as the Tar-Specific Green Optical Screening Tool (TarGOST™) by Dakota Technologies, Inc., are now being used routinely to detect and map the extent of coal tar residuals at MGP sites. The Res-SAT® Tool can be used alone to evaluate potential mobility of coal tar-containing soils from a traditional soil boring investigation program. However, the real power of a DNAPL mobility field tool is realized when it is combined with other field screening methodologies (e.g., TarGOST™, cone penetrometer) to generate more detailed real-time site characterization data

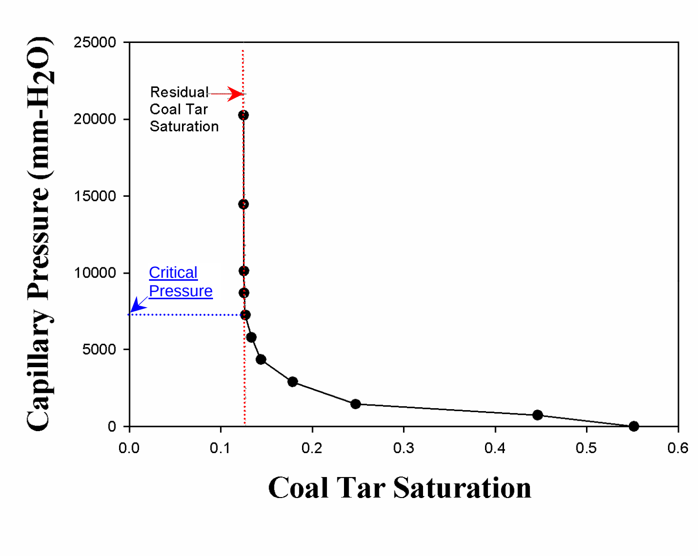

Figure 1-3
Sample DNAPL Drainage Curve

and mapping, whereby the conceptual site model can be developed or modified in real-time as the investigation unfolds.

During the development of the Res-SAT® Tool, additional assessments were performed to evaluate how data generated from the Res-SAT® Tool could be coupled with other site characterization information during a field program. During the 2004 field demonstration of the Res-SAT® Tool at the Waterbury, Connecticut MGP site, TarGOST™ was used to delineate coal tar-containing areas to map its subsurface distribution and to aid in selecting soil sample locations for Res-SAT® Tool testing. Additionally, Synthetic Precipitation Leaching Tests (SPLP) (USEPA Method 1312) were performed on Res-SAT® Tool leachates. Site-specific correlations were developed between TarGOST™ fluorescence response, Res-SAT® Tool test results and SPLP test results (EPRI, 2005).

1.3 Current Status of the Res-SAT® Tool Development

As described in Section 1.1, the Res-SAT® Tool has been developed through laboratory bench-scale tests (EPRI, 2004b) and a limited field trial (EPRI, 2005). The approach developed to deploy the Res-SAT® Tool included developing a site-specific DNAPL drainage curve in the laboratory for each impacted soil and coal tar type to identify the critical pressure at which residual saturation occurs. This critical pressure is then used in the field with the Res-SAT® Tool to determine whether selected soil samples contain DNAPL above the site-specific residual saturation point. This prior development work utilized relatively coarse-grained soils. The coal tar utilized in this prior development work had a relatively low specific gravity of 1.03. Soil samples used in the Res-SAT® Tool are remolded.

As the Res-SAT® Tool development progressed, the researchers identified a number of recommendations for further refinement or improvement of the Res-SAT® Tool and its operating protocol. These recommendations from prior research are summarized below:

- Expand the data set of soil types and coal tar properties tested with the Res-SAT® Tool and conduct field trials to validate its use as a field screening tool for coal tar mobility (EPRI, 2003).
- Develop a detailed protocol for Res-SAT® Tool testing (EPRI, 2005).
- Utilize the Res-SAT® Tool at additional MGP sites to provide further validation of the method, broaden the database of soil and NAPL property variations evaluated, and assist in making modifications to the equipment (EPRI, 2005).
- Conduct additional comparisons of the Res-SAT® Tool with leachability testing (EPRI, 2005).
- Modify the Res-SAT® Tool to allow testing of an undisturbed core sample and compare results to testing of remolded soil samples to evaluate the impact that disturbing the soil and pore fluid interactions has on the Res-SAT® Tool outcomes (EPRI, 2004c).
- Evaluate the potential to use the Res-SAT® Tool in the field without prior site-specific lab calibration by pressuring the cell to a maximum historical DNAPL head (EPRI, 2004c).

1.4 Project Objectives

The objectives of this research were to:

- Evaluate Res-SAT® Tool performance using a broader range of soil and DNAPL properties than previously tested;
- Evaluate whether Res-SAT® Tool performance characteristics lend themselves to establishing a fixed pressure endpoint that would be sufficient for testing most soils typically encountered with coal tar impacts, which would enable use of the Res-SAT® Tool for DNAPL mobility screening without site-specific laboratory calibration; and
- Identify options to modify the Res-SAT® Tool or its operating protocol to more closely represent undisturbed in-situ conditions.

1.5 Project Approach

For this project, the following approach was implemented to address the project objectives:

- Collecting soil and DNAPL samples for Res-SAT® Tool testing to broaden the data set of soil and NAPL characteristics tested. For this project, this included finer-grained soils and higher specific gravity DNAPLs than were used during prior development research;
- Comparing the Res-SAT® Tool response to the ASTM D425M centrifuge method of measuring fluid drainage from a soil sample;
- Evaluating the test cell construction materials and configuration for ease of operation in the field; and
- Defining the elements of a second field demonstration program to provide further validation of the methodology and to enable the development of a detailed field operating protocol.

2
METHODS AND MATERIALS

A Res-SAT® Tool used in prior development research was provided by Lehigh University to PTS Laboratories, Inc. (PTS) in Santa Fe Springs, California to perform the testing for this project. Two soils samples were obtained for the project: medium sand from the Gorham Sand & Gravel pit in Gorham, Maine, and a fine sand sample from the URS Geotesting Laboratory in Totowa, New Jersey. Four coal tar samples were collected from separate MGP sites in Fort Wayne, Indiana, Portland, Maine, Manchester, New Hampshire, and Concord, New Hampshire. These soil and coal tar samples were also sent to PTS for testing.

2.1 Soil Analyses

Soil properties were characterized utilizing the ASTM methods described in Table 2-1.

Table 2-1
Test Methods for Analyzing Soil Properties

Soil Property	Methods
Particle Size Analysis	ASTM D422/D4464M
Atterberg Limits	ASTM D4318/D2487
Specific Gravity	ASTM D854
Moisture, Ash, Organic Matter	ASTM D2974

2.2 Coal Tar Analyses

Coal tar properties were characterized utilizing the ASTM and American Petroleum Institute (API) methods described in Table 2-2. These properties were used to select two of four samples collected to cover the desired range of specific gravity and viscosity.

Table 2-2
Test Methods for Analyzing Coal Tar Properties

Coal Tar Property	Methods
Kinematic Viscosity	ASTM D445
Density	ASTM D1481
Specific Gravity	API RP40
Interfacial/Surface Tension	DuNuoy Method – ASTM D971

2.3 Res-SAT® Tool Testing

The construction of the Res-SAT® test cell is as described in the method development report (EPRI, 2004b). The test cell essentially consists of a bottom and top plate, a cylindrical body to hold the soil sample, a mesh screen, a porous stone, Teflon o-rings, and threaded support rods and nuts. A schematic of the Res-SAT® Tool components is shown in Figure 2-1.

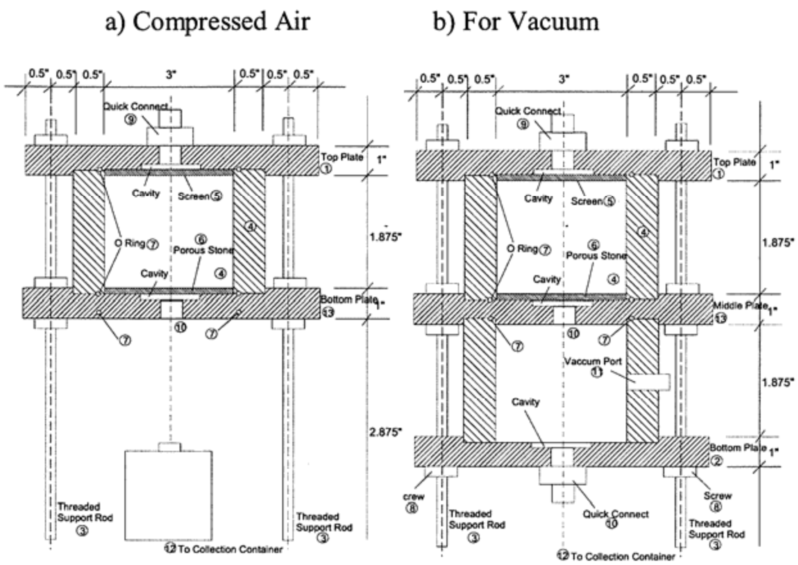

Figure 2-1
Res-SAT® Tool Configuration Schematic (EPRI, 2004b)) (Registered Patent KD053285-01-01)

PTS Laboratories adapted their laboratory fluids delivery and control system to replicate the performance characteristics of the control panel used during prior research. The laboratory apparatus used with the Res-SAT® Tool test cell is depicted in Figure 2-2. A couple of "like" modifications to the test cell were made during this project to facilitate filling the cell with soil and to prevent leakage of fluids where the cell body meets the end plates. An aluminum alignment ring was fabricated to facilitate packing of the soil sample into the cell body and to secure the cell body to the bottom plate while filling and prior to assembly of the top plate to the body and the bottom plate. This retaining ring is illustrated on Figure 2-3. Viton o-rings were substituted for the Teflon o-rings originally used with the equipment.

Figure 2-2
Res-SAT® Tool Test Setup

Figure 2-3
Aluminum Retaining Ring

The testing with the Res-SAT® Tool for this project was performed as described below.

Water & Coal Tar Imbibition

The following steps were performed to imbibe soil samples with coal tar:

1. The bottom plate, porous stone, Viton o-rings, and the test cell body were assembled and held together with the aluminum retaining ring, threaded rods and nuts.
2. The cell body was packed with clean dry soil by gently tamping in approximately 1 centimeter lifts.
3. The aluminum retaining ring was removed and replaced with the mesh screen and top plate and secured with the threaded rods and nuts.
4. The soil was imbibed with laboratory tap water through the bottom plate and porous stone in an upflow manner until water was observed rising through the top plate orifice.
5. The cell was then flipped over so the porous stone was on top and the screen was on the bottom. Coal tar was imbibed incrementally over a one- to two-week duration from the bottom in an upflow manner until breakthrough of coal tar through the porous stone was observed.
6. Based on the soil porosity and the coal tar volume imbibed, the initial water and coal tar saturation levels in the sample were determined.

Coal Tar Drainage

The coal tar saturated soil specimen in the Res-SAT® Tool cell was allowed to sit for two days prior to applying pressure to observe gravity drainage of DNAPL, which would confirm that the DNAPL content of the soil specimen was above the residual saturation point. The coal tar drainage testing was performed in the following manner:

1. Air pressure was applied through the top plate of the cell and porous stone incrementally over a five to seven day period. The pressure range applied was from zero to 10,000 millimeters of water (mm H_2O).
2. Each pressure increment was held stable for several hours (up to 48 hours in some cases) until fluid production through the bottom port of the cell ceased, at which time the air pressure was increased to the next increment.
3. Drained fluid volumes were measured at each test pressure increment. The extracted fluid was weighed, and distilled to determine the water and DNAPL content of the fluid using ASTM Method D95-05e1.

2.4 Centrifuge Tests

An alternate oil/water capillary pressure laboratory procedure was also performed on the soil/DNAPL samples provide further insight into the performance characteristics of the Res-SAT® Tool and to compare drainage curve characteristics. Oil/water drainage and imbibition tests were performed using the centrifugal method, a modified version of ASTM D6836E suitable for DNAPL and water drainage tests. The procedures used for this test are summarized below:

1. One-inch diameter prepared samples were used for this test. Laboratory tap water and DNAPL samples were filtered prior to use in the tests.

2. The one-inch diameter soil samples were packaged in a Teflon jacket with stainless steel end screens (i.e., a flexible wall permeameter) and vacuum saturated with 0.45 micron (μm) filtered laboratory tap water. Specific permeability (intrinsic) to water was measured at 25 pounds per square inch (psi) confining stress to achieve complete water saturation.
3. Water-saturated samples were loaded into imbibition-type centrifuge cups, immersed under filtered DNAPL, then spun at increasing angular velocities to residual water saturation or to a maximum of 2,500 revolutions per minute (RPM). Fluid production or average saturation in the sample was measured for each incremental rotational speed. Between eight and twenty pairs of pressure head/moisture data were obtained at pressure heads up to 1,000 centimeters (cm). A drainage curve was then generated from water displaced by DNAPL entering the pore space.
4. Following the DNAPL imbibition by centrifuge, the DNAPL-saturated soil samples were loaded into drainage-type centrifuge cups and immersed under 0.45μm-filtered water and allowed to spontaneously imbibe overnight. The samples were then spun at increasing angular velocities to residual DNAPL saturation or to a maximum of 2,500 RPM. Fluid production or average saturation in the sample was measured for each incremental rotational speed. Between eight and twenty pairs of pressure head/moisture data were obtained at negative pressure heads up to 500 centimeters. An imbibition curve was then generated from DNAPL displaced by water entering the pore space.
5. Following completion of each centrifuge test, the samples were extracted with toluene (Dean-Stark method) for fluid saturation determination. Following Dean-Stark extraction, the soil samples were dried to a stable weight and sample properties (i.e., hydraulic conductivity and porosity) determined by Archimedes Method.

3
RESULTS AND DISCUSSION

3.1 Soil and DNAPL Properties

The properties of the two soil samples used in this research are summarized below in Table 3-1. The coal tar characterization results are provided in Table 3-2. Two of the four DNAPL samples were selected for capillary pressure saturation testing using the Res-SAT® Tool and the centrifugal method. The Portland, Maine MGP and the Manchester, New Hampshire MGP DNAPL samples were selected to provide variation in viscosity (27–67 centipoise [cP]), specific gravity (1.05–1.07), and interfacial tensions (14–22 dynes/cm). Prior Res-SAT® Tool development work utilized coal tars with a specific gravity of approximately 1.03. The soil samples used for the prior development work consisted of poorly graded silica sands (in laboratory experiments) and medium sands with a hydraulic conductivity in the range of 3.4×10^{-3} cm/sec to 3.8×10^{-3} centimeters/second (cm/sec) (field experiments).

Table 3-1
Soil Sample Characterization

Soil Property	Gorham Sand & Gravel Sample	URS Geotesting Lab Sample
USCS Description	Medium Sand	Fine Sand
Median Grain Size (mm)	0.531	0.290
Particle Size Distribution (wt %)	Gravel 6.88 Coarse Sand 9.23 Medium Sand 44.29 Fine Sand 32.04 Silt/Clay 7.56	Gravel 1.72 Coarse Sand 4.31 Medium Sand 30.95 Fine Sand 44.68 Silt/Clay 18.35
Atterberg Limits	LL 15.6 Non-Plastic	LL 18.2 PL 10.4 PI 7.8 Fines <#40 sieve lean clay with sand
Porosity Range, from pressure-saturation tests (% bulk volume)	32.3 - 47.1	29.3 - 31.6
Hydraulic Conductivity Range, from centrifuge tests (cm/sec)	6.7×10^{-4} to 1.8×10^{-3}	2.76×10^{-7} to 3.68×10^{-7}
Specific Gravity @ 208C	2.63	2.69
Moisture Content (% dry wt)	5.34	10.43
Ash Content (% dry wt)	99.97	99.96
Organic Content (% dry wt)	0.03	0.04

Table 3-2
Coal Tar Sample Characterization

Coal Tar Property		Ft. Wayne, IN MGP	Portland, ME MGP	Manchester, NH MGP	Concord, NH MGP
Viscosity @ 708F (cP)		37.6	66.8	27.2	69.7
Specific Gravity		1.061	1.069	1.053	1.075
Density (g/cc)		1.059	1.067	1.051	1.072
Interfacial Tension @ 758F (dynes/cm)	Air-DNAPL	35.4	36.26	36.2	35.7
	Water-DNAPL	15.6	14.4	21.8	14.1

3.2 Centrifuge Tests

The centrifuge tests were run to a maximum of 2,500 RPM, which results in capillary forces of approximately 1,000 times the force of gravity (i.e., 1,000 Gs). This results in a very conservative test for DNAPL drainage since typical subsurface pressures at an MGP site would not approach the 1,000 Gs of force that are generated by the centrifuge. Hence, this test could result in substantially less residual DNAPL in the centrifuged sample than might actually occur in the environment, yielding a conservatively low estimate of the residual saturation point (EPRI, 2006). The ASTM centrifuge method tests a two-phase system (i.e., water and DNAPL) using water to drive the DNAPL from the sample. The Res-SAT® Tool method tests a three-phase system (i.e., air, water, and DNAPL), using air to drive the DNAPL and water from the sample. As shown on Table 3-2, the interfacial tensions between air and DNAPL are much greater than between water and DNAPL, which will also affect the residual saturation levels achieved with the tests. Nonetheless, the centrifuge test can be used to compare the general drainage characteristics obtained with the Res-SAT® Tool among different soil-DNAPL combinations.

For the centrifuge tests, the results of the water-displacing-DNAPL (i.e., DNAPL drainage tests) are illustrated on Figure 3-1. The following observations were made from this testing:

1. The more permeable soil (i.e., the Gorham Sand & Gravel medium sand) could be saturated to a much greater extent (i.e., 71 percent of the pore volume) with DNAPL than the finer grained URS Geotesting Lab fine sand. With the more viscous and denser coal tar (Portland), the DNAPL saturation achieved in the fine sand was only 7.3 percent of the pore volume and no DNAPL drainage could be induced during the DNAPL drainage step. With the Manchester coal tar, the initial DNAPL saturation in the fine sand achieved was 9 percent, which was reduced to 6 percent during the DNAPL drainage step. As would be expected, the ability to saturate or drain fine-grained soils with DNAPL (i.e., transmit) is limited as compared to the coarser grained soil.
2. In the medium sand, a lower residual saturation level was achieved in the test with the more dense higher viscosity DNAPL (Portland). While it was expected that the less

viscous and less dense coal tar would be mobilized and drained to a greater extent, the lower water-DNAPL interfacial tension of the Portland DNAPL may have contributed to the observed result.

3. In both the fine and medium sands, the majority of DNAPL that could be mobilized occurred at an applied pressure substantially less than 10,000 mm H_2O.

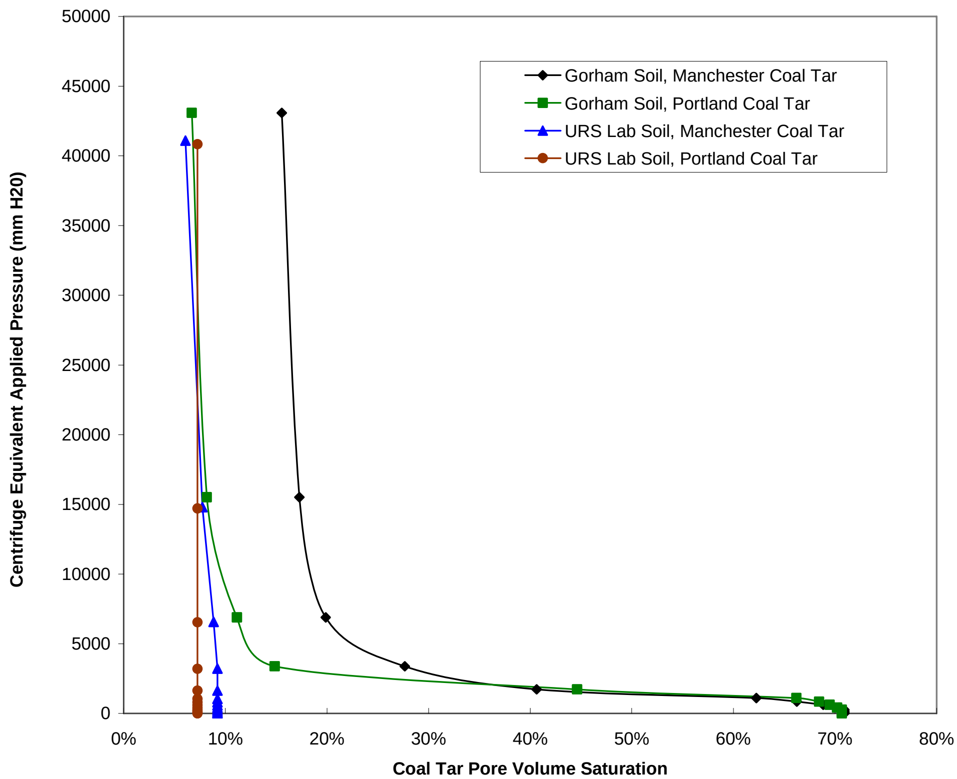

Figure 3-1
Centrifuge Test Results, Water Displacing DNAPL

3.3 Res-SAT® Tool Tests

Based on the results of the centrifuge tests presented in Section 3.2, it was determined that the permeability of the fine sand was too low for use with the Res-SAT® Tool; specifically, the low permeability would require a long time to saturate and drain. Therefore, only the Gorham Sand and Gravel medium sand was used for the Res-SAT® Tool tests. The results of the DNAPL drainage tests using air as the pressurized displacing fluid are shown on Figure 3-2. The following observations were made from this testing:

1. The Res-SAT® Tool operates at a lower pressure range than the centrifuge method and therefore, the DNAPL saturation levels achieved during imbibition were lower than in the centrifuge method. The DNAPL residual saturations in the centrifuge method were also lower than those achieved with the Res-SAT® Tool. The 10,000 mm H_2O upper pressure limit used in the Res-SAT® Tool is equivalent to a static head of approximately 33 feet of water, (i.e., 1 psi) more typical of field conditions at MGP sites.

2. The majority of DNAPL that could be mobilized from the soil was drained at pressures substantially below 10,000 mm H_2O; approximately 4,000 mm H_2O for the Manchester coal tar, and approximately 6,000 mm H_2O for the Portland coal tar.
3. Air breakthrough appeared to occur early in the tests, at a 200 mm H_2O pressure with the Manchester coal tar, and at 400 mm H_2O with the Portland coal tar.
4. As with the centrifuge method, the more viscous coal tar (Portland) was drained to a lower residual saturation than the Manchester coal tar. This may have been caused by one or more conditions: a) differing interfacial tensions in the water and DNAPL phases, and b) quicker air channeling through the lower density and viscosity coal tar (Manchester).
5. The relative shape of centrifuge and Res-SAT® Tool curves are remarkably similar indicating that once residual saturation is achieved, very little additional tar will be extracted at higher pressure/G-forces.

3.4 Discussion

This project evaluated the performance of the Res-SAT® Tool using finer grained soils and DNAPLs of higher density than were evaluated in prior tool development research. The centrifuge test results indicated that the ability to imbibe and drain DNAPL from soils is significantly affected by the soil permeability, with low permeability soils having limited ability to transmit coal tar DNAPL, as would be expected. What the centrifuge tests also indicated was that at applied pressures of less than 10,000 mm H_2O, the majority of drainable DNAPL is mobilized. These results are consistent with the critical pressures determine during the Res-SAT® Tool development (i.e., a range of 6,000 to 8,000 mm H_2O) (EPRI, 2004b and EPRI, 2005) using lighter tars and somewhat coarser soils. The viscosity and interfacial tension values for coal tars were not reported for prior Res-SAT® Tool research, however, for this project, it appears that these coal tar properties, in addition to density, play a role in the coal tar residual saturation level achieved in the soil sample, as well as the critical pressure value of the DNAPL drainage curve.

The consistency of soil sample preparation (i.e., tamping effort) can affect the test specimen porosity and hydraulic conductivity, and therefore the test results. As previously identified, the use of remolded samples is a limitation of the method, however, it would be expected to result in a positive bias to test outcomes (i.e., could overstate the potential for mobility). However, for the range of coal tars tested to date, coal tar drainage occurred below an applied pressure of 10,000 mm H_2O.

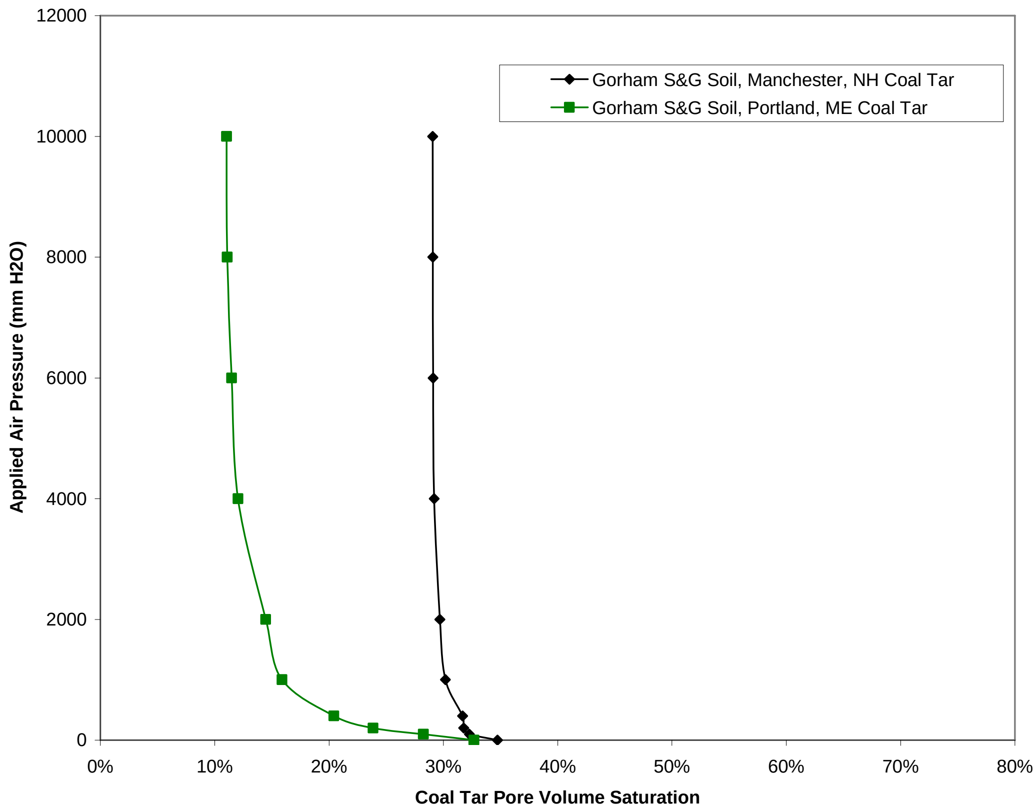

Figure 3-2
Res-SAT® Tool Test Results, Air Displacing DNAPL

The observation of air channeling during Res-SAT® Tool testing is an issue that should be further evaluated. At fairly low air pressures (i.e., 200-400 mm H_2O), air and fluid spattering at the bottom plate outlet were observed. The significance of this occurrence and its effect on the soil-DNAPL residual saturation level or the critical pressure to drain mobile DNAPL should be further evaluated.

4
CONCLUSIONS AND RECOMMENDATIONS

This research has provided additional evaluation of the operating protocol for the Res-SAT® Tool as a rapid field screening methodology for coal tar DNAPL mobility. In this project, the effect of soil property variation and DNAPL property variation on test outcomes was evaluated to assess the efficacy of using the Res-SAT® Tool without site-specific field calibration. The following conclusions and recommendations are drawn from this research.

- The Res-SAT® Tool test cell was used to evaluate DNAPL drainage and residual saturation characteristics of two coal tar samples of higher specific gravity and viscosity in a finer-grained sand (i.e., significantly lower permeability soils compared to the soil used during initial tool development). Testing of the fine-grained sand (permeability ~$7x10^{-4}$ cm/sec) produced DNAPL drainage curves similar in shape to those developed in the initial tool development testing. Initial evaluation of the finer-grained silty sand (permeability ~$3x10^{-7}$ cm/sec) indicated that it was not amenable to Res-SAT® Tool testing due to the low permeability and the difficulty achieving oil saturation in the preliminary centrifuge testing. This soil was not tested with the Res-SAT® Tool because of the extended run times required to achieve oil imbibition and to complete drainage curves.
- It appears that with a fairly broad range of soil types and coal tar physical properties, the Res-SAT® Tool could be used with a maximum pressure setting of 10,000 mm H_2O without site-specific laboratory calibration to perform field screening for potential DNAPL mobility.
- Testing to date indicates that very little additional DNAPL is extracted when the Res-SAT® Tool cell is pressurized above the critical pressure of the DNAPL/water/soil mixture. Sample-specific capillary pressures have ranged from 4,000 to 8,000 mm H_2O (5.7-11.4 psi), however, even on the samples exhibiting the lowest capillary pressure, the residual DNAPL content changed less than 5 percent when pressure was increased from the critical pressure to a termination pressure of 9,000 to 10,000 mm H_2O.
- The Res-SAT® Tool appears to produce comparable results for a variety of DNAPLs and a range of soil gradation. The resulting Res-SAT® Tool data set derived in the field will provide valuable information on the relative saturation and potential mobility of DNAPLs in subsurface soils during the preliminary site assessment activities at a MGP site.
- Use of the Res-SAT® Tool test cell in the field is anticipated to require up to an hour per soil sample based on prior field testing. Further evaluation of the pressure application regime is recommended. Testing should compare the incremental application of increasing pressures (or vacuum) up to the termination pressure over the test period to the application of the termination pressure for the duration of the test. Comparison of the DNAPL volumes extracted and the time period over which DNAPL drainage occurs will aid in refining the field application protocol.
- The significance of air channeling observed early in each of the tests at pressures ranging from 200 to 400 mm H_2O is not well understood. While air channeling may indicate

short-circuiting of airflow, it is not clear how the channeling affects pressure distribution and DNAPL displacement throughout the cross-section and depth of the soil sample in the test cell. Potential modifications to the test protocol can provide insights into both the significance of and potential to suppress channeling. Modifications would focus on modifying the pressure field at the outlet end of the test cell by inducing partial vacuum and/or positive pressure at the test cell outlet.

- Additional test cells will be needed for field trials. The test cells should be modified to incorporate a machined sleeve-retaining ring in the base to secure the sleeve in the base during soil placement and tamping and replacement of the Teflon o-rings with more flexible and chemically resistant Viton o-rings. PTS incorporated these modifications in the current Res-SAT® Tool test cell to speed cell loading and reduce seal leakage under pressure. Incorporation of these modifications will simplify and streamline test cell use under field conditions.
- The Res-SAT® Tool provides investigators with a means to measure the potential mobility of DNAPL in the field using a relatively simple test cell and compressed air or nitrogen. Use of an endpoint/termination pressure that exceeds the critical pressure of soil/DNAPL mixtures may create a positive bias to test results. However, this is offset by the ability to apply the method to a wide range of granular soils and DNAPLs with differing properties without first obtaining soil and DNAPL samples for laboratory calibration and then adjusting field test conditions based on the type of soil and DNAPL encountered in a particular soil.
- As an indicator of DNAPL mobility, the Res-SAT® Tool can be integrated into a preliminary site assessment program that makes use of in-situ soil characterization tools (e.g., cone penetrometers for mapping physical and hydrologic properties and TarGOST™ for detection and mapping of DNAPL constituents). These site characterization tools facilitate location of potential source areas and preferential migration pathways from which soil samples can be retrieved for field determination of potential mobility using the Res-SAT® Tool. The combination of rapid in situ mapping and in-the-field evaluation of potential DNAPL mobility can provide the investigator and site owner with a clear understanding of the nature and extent of DNAPL distribution on the site early in the site investigation process. Coupled with confirmatory soil and groundwater sampling and analyses, these field tools can enhance the quality of the resulting conceptual site model and subsequent evaluations of the need for and potential costs of remedial measures.

5

RES-SAT® TOOL FIELD DEMONSTRATION PROTOCOL

The following subsections describe the recommended field demonstration protocol to enhance the performance of the Res-SAT® Tool and to establish a detailed operating protocol for field screening of coal tar DNAPL mobility.

5.1 Phase I - Laboratory Refinement of Test Cell Operation

Prior to field deployment a brief laboratory calibration is recommended to optimize pressure conditions at the outlet end of the Res-SAT® Tool, as well as to improve the performance characteristics of the test cell. These laboratory tests will be performed in duplicate using a uniform medium sand (to minimize heterogeneity-related variations) and one of the lower viscosity DNAPL samples (which are more susceptible to air channeling). Additional test cells will be fabricated to perform these tests. Results of these calibration tests will be used to establish final field operating conditions for the Res-SAT® Tool.

Step L-1: Pressure Regime Assessment

The primary goal of this calibration is to determine whether application of either a low pressure or vacuum (i.e., slight back pressure) on the outlet can reduce and/or delay the onset of air channeling and the resulting volume of DNAPL drainage. Additionally, evaluation of the pressure application regime (i.e., increasing pressure incrementally versus commencing the test at the recommended termination pressure of 10,000 mm H_2O) will provide further insight into tool behavior that will need to be accounted for in the field protocol.

Step L-2: Test Cell Length-to-Diameter Ratio Evaluation

The 0.625:1 length to diameter ratio of the Res-SAT® Tool test cell was selected during the tool development based on standard Tempe cell configurations used to develop soil-water characteristic curves. For testing fluid drainage in a multi-phase fluid system (i.e., air, water, DNAPL) at the critical or termination pressure without the need to determine a pressure-saturation curve, increasing the length-to-diameter ratio to at least 2:1 or 3:1 (more typical of column test or permeability test equipment) may reduce the potential for air channeling and maintain more even pressure application across the diameter of the test specimen. Comparison of tool outcomes by varying the length of the test cell body but keeping the diameter constant will be performed in this step.

Step L-3: Undisturbed Field Core Retrofit

A previously identified development concept is to adapt the Res-SAT® Tool test cell to use available sampling cores as the pressure cylinder for field testing. This development exercise will include adapting the tool to use commercially available sampling core tubes that have been developed for conventional drilling equipment and for Geoprobe® sampling tools. Adaptation to core tubes will facilitate testing of undisturbed core samples, thereby minimizing potential positive biases associated with remolding (i.e., packing soil) in the Res-SAT® Tool test cell. As described above, increasing the length to diameter ratio of the test specimen may also reduce air channeling (short circuiting) by lengthening the travel path through the sample.

5.2 Phase II - Field Demonstration of Res-SAT® Tool

Upon completion of the laboratory calibration work described above, the Res-SAT® Tool will be ready for expanded field trials coupled with other site characterization technologies. The three key field applications to assess during the field demonstration are described below. Target sites for field trials are likely to be small to medium-sized former MGP sites located over sandy or sand and gravel formations, ideally with a finer-grained confining layer situated within 30 to 50 feet of the ground surface. The smaller sized sites are less complex and generally have more limited subsurface contamination. Focusing on shallow granular site geology will facilitate explorations (i.e., greater spatial coverage in a limited amount of time). Conducting field trials on two heretofore uncharacterized sites and two previously characterized (i.e., having completed either a preliminary assessment or Phase I site investigation) sites will provide insights into the performance and limitations of the Res-SAT® Tool under a variety of field conditions and will highlight the usefulness of the tool as part of a site investigators "toolbox" of rapid site investigation/characterization technologies.

Step F-1: Res-SAT® Tool Use to Guide DNAPL Plume Mapping

As a component of preliminary site assessments where in-situ detection tools (e.g., TarGOST™) will be used to detect and generally characterize the nature and extent of coal tar on the site, the Res-SAT® Tool is ideally suited to assess the potential mobility of the detected DNAPLs. Soil cores can be collected from areas exhibiting the presence of DNAPL, specifically targeting transition areas where the relative DNAPL content appears to be changing (an indication of the potential change in the residual NAPL content that potentially defines the limits of DNAPL mobility). Res-SAT® Tool testing of soil samples retrieved from these transition areas will provide additional insight into potential mobility of the soils and an opportunity to correlate the DNAPL mobility results with in situ data to map areas most likely to contain mobile DNAPL. It may also be possible to use Res-SAT® Tool test results to provide real-time feedback to focus and guide the in situ mapping work (e.g., TarGOST™) depending on the timing and throughput/capacity of the Res-SAT® Tool field lab. Evaluation of areas where NAPL transitions from mobile to non-mobile can allow investigators and site owners to focus and prioritize their evaluation of the potential need for and range of remedial actions to address DNAPL.

Step F-2: Res-SAT® Tool Use to Characterize DNAPL Mobility Profile

As a supplemental investigation tool on sites where site investigations have already encountered and mapped areas of potentially mobile DNAPL, soil cores will be retrieved from areas exhibiting varying amounts of DNAPL based on an interpretation of available visual observations and soil and groundwater analytical data. The Res-SAT® Tool can provide further insight into the DNAPL architecture vertically and horizontally, and correlations may be developed with TarGOST™ fluorescence data to enable more detailed mapping of the plume core (i.e., the zone of greatest mobility and long-term dissolution potential).

Step F-3: Res-SAT® Tool Calibration to DNAPL Well Areas

For previously characterized sites, collection of soil cores for Res-SAT® Tool testing adjacent to DNAPL recovery wells or monitoring wells with observed DNAPL accumulation would provide additional field calibration of the Res-SAT® Tool, especially of samples are collected adjacent to highly productive and marginally productive recovery wells. This tool would also be useful to pre-screen areas where DNAPL recovery wells are planned to evaluate to potential for recovery at the selected location prior to well installation.

6
REFERENCES

Cohen, R.M., and J.W. Mercer, 1993. *DNAPL Site Evaluation*. C.K. Smoky/CRC Press Inc, Boca Raton, FL.

Electric Power Research Institute (EPRI), 2004a. *Residual Saturation of Coal Tar in Porous Media*. EPRI Report 1009426, Palo Alto, CA. April 2004.

EPRI, 2004b. *Development of a Coal Tar Residual Saturation (Res-SAT™) Field Tool for Manufactured Gas Plant Sites: A Quantitative Rapid-Assessment Screening Tool for the Field*. EPRI Report 1005285, Palo Alto, CA. March 2004.

EPRI, 2004c. *New 'Tool Box' Approaches for Innovative Characterization of NAPL at MGP Sites*. EPRI Report 1011375, Palo Alto, CA. December 2004.

EPRI, 2005. *Application of the EPRI Coal Tar Residual Saturation (Res-SAT™) Tool at the Waterbury South Manufactured Gas Plant Site, Waterbury, Connecticut: Evaluation of the Res-SAT™) Tool to Delineate Mobile and Leachable Coal Tar in Subsurface Soils*. EPRI Report 1010138, Palo Alto, CA. November 2005.

EPRI, 2006. *Development of a Characterization and Assessment Framework for Coal Tar at MGP Sites: Coal Tar Management Framework*. EPRI Report 1010137, Palo Alto, CA. March 2006.

Hoag, G.E., and M.C. Marley, 1986. *Gasoline Residual Saturation in Unsaturated Uniform Aquifer Materials*. J. Env. Eng. 112(3): 586-604.

United States Environmental Protection Agency (USEPA), 2000. *A Resource for MGP Site Characterization and Remediation – Expedited Site Characterization and Source Remediation at Former Manufactured Gas Plant Sites*. EPA/542/R-00/005.

Zytner, R.G., N. Biswas, and J.K. Bewtra, 1993. *Retention Capacity of Dry Soils for NAPLs*. Env. Tech. 14: 1073-1080.

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