Characterization of Petroleum Contaminated Sites

Policy #WSC-26-xxx

BACKGROUND/SUPPORT DOCUMENTATION FOR THE DEVELOPMENT OF PUBLICATION GUIDELINES & RULES OF THUMB

May 2026

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Introduction, Background, and Purpose

The first draft of the MassDEP VPH/EPH Implementation Guidance was issued on October 31, 1997. Subsequently, a Final Draft was issued in June 2001, followed by the Final Policy on October 31, 2002. In May 2026, an expanded, updated, and revised draft of this document was prepared by MassDEP, now known as "Characterization of Petroleum Contaminated Sites".

The scope of subjects covered in the updated draft guidance has been expanded over time, as reflected in the number of pages contained in the various incarnations of this document, as detailed below:

Version	# Pages in Text	# Pages in Appendices
10/31/97 Public Comment Draft	33	5
6/01 Final Draft	43	12
10/31/02 Final Guidance (#WSC-02-411)	49	14
5/13/26 Updated Guidance (#WSC-26-xxx) – Aerial 10 font	70	14
5/13/26 Updated Guidance (#WSC-26-xxx) – Aptos 12 font	89	14

The origin, reference, and rationale for many of the guidelines and recommendations contained in the updated draft guidance document should be familiar to the intended reader (i.e., environmental consultants and Licensed Site Professionals). The purpose of this Support Document is to provide additional insight, reasoning, and justification for statements and recommendations contained in the updated guidance, including various "Rules of Thumb".

Relatively brief discussions on a range of subject areas are summarized within the body of this support document, in the order they exist in the updated draft guidance document, followed by a series of Appendices that address a specific issue in greater detail. Significant references are noted/footnoted in this support document, along with URL citations, where available.

Section 4.1.1 - Photoionization Detector (PID) Analytical Data

There are a number of different approaches to relate headspace concentrations of VOCs to soil concentrations, all of which rely basically upon the same concepts and equations. Examples include approaches by (i) Jury et. al. (Lyman et al., 1982), (ii) Rong, H., California Water Quality Control Board (1996), and (iii) the Fugacity approach by MacKay and Patterson (Lyman et al., 1982).

- A statement is made in the *Characterization of Petroleum Contaminated Sites* document that a PID jar headspace concentration of less than 10 ppmV as isobutylene will generally be associated with soil concentrations of benzene, toluene, ethylbenzene and xylenes (BTEX) of 2 µg/g or less, and that a PID jar headspace of 50 ppmV or less is associated with aqueous concentrations of BTEX compounds below their GW-2 standards. These statements are based upon partitioning calculations and site data. These partitioning calculations and site data are contained in Appendix 1.
- A statement is made in the *Characterization of Petroleum Contaminated Sites* document that "for diesel/#2 fuel oil spills, soil samples with less than 10 ppmV jar headspace concentrations will generally meet Method 1 S-1 soil cleanup standards, with the possible exception of naphthalene and 2-methylnaphthalene in S-1/GW-1 areas. This statement is

based upon field data, as detailed in Appendix 5.

Section 4.2 – Contaminants of Concern

Table 4-2 When to Test for VPH and EPH

The VPH test method was designed to characterize gasoline range organics (predominantly C5-C12), without the need for EPH testing. Conversely, heavier fuel oils are predominantly C9 and greater, the range addressed in the EPH method. Diesel/#2 Fuel Oil is on the dividing line of the VPH and EPH methods, as fresh Diesel/#2 Fuel Oil can contain low but potentially significant levels of < C9 aliphatics and BTEX. As such, criteria have been developed to differentiate "fresh" Diesel/#2 Fuel Oil (requiring testing by both VPH and EPH test methods) from "weathered" Diesel/#2 Fuel Oil (which only requires use of the EPH test method).

A MassDEP PID Jar Headspace reading of 100 ppmV (as isobutylene) has been designated as the dividing point between fresh and weathered diesel/#2 fuel oil contaminants in soil, based on theoretical considerations and the evaluation of real-world data. It is understood that soil below this threshold could be (a) indicative of a weathered hydrocarbon signature, where most of the volatile constituents of Diesel/#2 Fuel oil are no longer present, or (b) indicative of small quantities of a "fresh" Diesel/#2 Fuel oil. In either case, the concentrations of VPH hydrocarbon ranges and target analytes are likely to be low, and below Method 1 soil S-1 cleanup standard. As such, VPH testing is not necessary.

SOIL – "Weathered Diesel/#2 fuel oil" defined to be soil with jar headspace < 100 ppmV, and thus testing by VPH method is not necessary

- In an internal MassDEP study report dated April 2007 examining data from sites contaminated by a release of #2 fuel oil (MassDEP, 2007 included in Appendix 5), data from 141 soil samples with synoptic PID, VPH, and EPH concentration data were examined. Of those soil samples with a jar headspace reading less than 100 ppmV:
  - All VPH Target Analytes (MtBE and BTEX), when detected, were present well below their most stringent Method 1 soil cleanup standards (i.e., S-1/GW-1);
  - All reported detections of C9-C12 Aliphatic Hydrocarbons were below its most stringent Method 1 soil cleanup standard (1000 mg/kg);
  - 107 of 110 samples reported concentrations of C5-C8 Aliphatic Hydrocarbons less than its most stringent Method 1 cleanup standard (100 mg/kg);
  - 100 of 110 samples reported concentrations of C9-C10 Aromatic Hydrocarbons less than its most stringent Method 1 cleanup standard (100 mg/kg):
    - Of the 10 samples where concentrations of C9 – C10 Aromatic Hydrocarbons exceeded 100 mg/kg, 9 contained concentrations of C11-C22 Aromatic Hydrocarbons (via EPH method) in excess of its most stringent Method 1 cleanup standard (200 mg/kg), indicating that such problematic levels of aromatic hydrocarbons would have been identified in the mandatory EPH samples, and that use of the VPH test method was unnecessary

- The single exception (site 3-24,734) appears to an analytical reporting error or anomalous data point, given the low concentrations of C11-C22 Aromatic Hydrocarbons (39.1 mg/kg) relative to the reported concentrations of C9-C18 Aliphatic Hydrocarbons (179 mg/kg) and C19-C36 Aliphatic Hydrocarbons (117 mg/kg).
- On average, and consistent with product chemistry, the concentrations of C11-C22 Aromatic Hydrocarbons were 4.1 times higher than the reported concentrations of C9-C10 Aromatic Hydrocarbons. This ratio would tend to increase with time as the product weathers in the environment.
- Due to a systemic bias in the VPH test method, it is likely that the ratio of C11-C22 Aromatic Hydrocarbons to C9-C10 Aromatic Hydrocarbons is even greater than the above finding would suggest. Specifically, the VPH method use a PID to quantify eluting compounds as aromatic in nature, given the increased sensitivity of these compounds to a PID. While PID response to aliphatic compounds is substantially less, it is nonetheless measurable, and, when numerous aliphatic compounds are present in this elution range (as in the case of #2 Fuel Oil), the collective aliphatic response (quantified by the method as C9 – C10 Aromatic Hydrocarbons) can become appreciable. This further reinforces the finding that use of the VPH test method is unnecessary when total PID headspace vapor concentrations are less than 100 ppmV.

Table 4-3: Recommended Target Analyte List for Petroleum Product

SOIL

500 ug/g TPH Criteria to Determine Need to Test for 4 Diesel/#2 Fuel Oil PAHs:

The 2007 MassDEP study confirmed that PAH contamination at fuel oil contaminated sites were almost completely comprised of the 4 Diesel/#2 fuel oil PAHs listed below, with only a few detections of the remaining 17 PAH Target Analytes in the EPH method, and almost all pyrogenic PAHs unrelated to the fuel oil spill. With respect to the 4 Diesel/#2 fuel oil PAHs:

- **Acenaphthene** was less than the current S-1/GW-1 standard of 4 µg/g in all but one of 283 samples containing less than 500 µg/g of TPH (i.e., summation of all EPH fractions and Target Analytes). It was not reported in excess of 10 µg/g in any sample – well below S-1 standards in non-GW-1 areas - even when total EPH values exceeded 38,000 mg/kg.
- **Phenanthrene** was less than the current S-1/GW-1 standard of 10 µg/g in all but two of 283 samples containing less than 500 µg/g of TPH. It was not reported in excess of 500 µg/g in any sample – well below S-1 standards in non-GW-1 areas.
- **Naphthalene** exceeded the current S-1/GW-1 standard of 4 µg/g in a significant portion of all samples, including when TPH was less than 500 µg/g. However, no sample exceeded the next lowest S-1 standard of 80 µg/g.

- Contrary to the three previous PAH compounds, **2-methylnaphthalene** was frequently detected above the current S-1/GW-1 standard of 0.7 µg/g in soil samples containing less than 500 µg/g of TPH. This value is however controlled by the leaching pathway, with S-1/GW-2 and S-1/GW-3 standards of 80 µg/g and 300 µg/g, respectively, and no sample containing less than l0,000 µg/g TPH contained 2-methylnaphthalence greater than 80 µg/g. Accordingly, the recommendation to test for the 4 diesel/#2 fuel oil PAHs was limited to GW-1 areas only.

GROUNDWATER

- The water-soluble fraction of fresh diesel/#2 fuel oil is predominated by the BTEX compounds. As presented in Appendix 1, a PID jar headspace reading of less than 50 ppmV will likely be associated with a BTEX concentration in groundwater of less than 1000 µg/L, which is less than the most stringent GW-2 value (for benzene).

Testing in GW-1 Areas

- As indicated in Tables 7-1 and 7-2 in the *Characterization of Petroleum Contaminated Sites* document, the limited solubility of diesel/#2 fuel oil negates the general need for groundwater testing in non-GW-1 areas. This is reflected in Tables 4-2 and 4-3. Insufficient information and uncertainty exist for the heavier oils, dielectric fluids, waste oils, and unknown oils (e.g., #6 oil may be cut with lighter distillates).
- Conversely, given receptor sensitivity, VPH and EPH testing is recommended for all samples obtained within 500 feet of a public or private drinking water well.

Section 4.2.4: Gasoline Additives

Leaded Gasoline

Leaded gasoline historically contained substantial concentrations of tetra-alkyl lead (primarily tetraethyl lead, TEL) to increase octane and prevent engine knock. Ethylene Dibromide (EDB) was added with the lead to function as a lead scavenger (to prevent buildup of lead oxides in engines). Peak lead content past and present is about 4-5 grams/gallon, with EDB at 0.4-0.8 grams/gallon. Typical lead additions were and are in the 1-2.5 gram/gallon range (US EPA, 1985).

Beginning in the late 1970s, the USEPA began to enforce regulations to reduce the use of lead in gasoline. The allowable lead content of gasoline began to drop from 1-2.5 grams/gallon (average of all gasoline) to a limit of 0.8 grams/gallon in 1979, followed by a continued reduction through the early 1980s. However, it wasn't until December 31, 1987, that all leaded gasoline for general automotive use was removed from the market (Gibbs, 1990).

Considerations used in the drafting of *Characterization of Petroleum Contaminated Sites* document include the following:

- **Alkyl leads are not likely to remain in the environment after more than 15 years**. While few quantitative data are available on the breakdown of alkyl lead in soil and groundwater, it is not considered a persistent compound (USEPA, 1997). Based upon MassDEP experiences and inquiries, it is expected that alkyl lead contaminants will be degraded to stable inorganic lead salts within this period of time, though it can persist for

years in the environment in gasoline NAPL

- **The lead content in gasoline is unlikely to contaminate soils to levels significantly higher than the S-1 soil standard of 200 ug/g for a single release.** This is based upon agency experiences, and calculations presented in Appendix 2. However, multiple releases can lead to a build-up of lead, to levels in excess of the S-1 soil standard
- **Dissolved concentrations of lead in groundwater are unlikely to persist after a 15-year period of time.** This is due to the fact that the more soluble organic leads will have degraded to less soluble salts, in combination with dispersion effects. However, due to the toxicity of lead and environmental sensitivity considerations, confirmation of this assumption is recommended in GW-1 areas.
- Ethylene Dibromide (EDB): The updated guidance recommends testing groundwater samples for EDB in GW-1 areas. While EDB levels are likely to be significantly attenuated over time, due to this compound's high-water solubility, concern still exist because of its extremely low GW-1 standard (0.02 □g/L).

MtBE

The updated guidance still recommends testing for MtBE for all releases of unleaded gasoline after 1979, even though it has been largely phased out and is seldom a risk driver at sites, since it remains an analyte in the MassDEP VPH test method. However, the recommendation in 2002 to test for MtBE in GW-1 areas for #2 fuel oil releases (due to contamination of fuel oil placed in tanks/tankers that previously contained gasoline) has been eliminated.

Section 4.3: Vapor Intrusion Pathway

Significant additions have been made to this section, including revisions necessitated by the issuance of the MassDEP Vapor Intrusion Guidance in 2016 (#WSC-16-435).

4.3.1 - Modified Inclusion Distance Approach (IDA)

A modification to the EPA IDA was needed to reflect the Substantial Release Migration notification criteria at 40.0313(4)(f). A thickness metric was also added to volatile LNAPL - 1/8-inch – consistent with MCP notification requirements.

4.3.2 - Screening Data Approach for Limited On-site Fuel Oil Spills

The 2002 guidance (#WSC-02-411) focused heavily on PID screening of sub-slab soil gas probes, providing action levels ranging from 4 ppmV (as isobutylene) for ethylbenzene to 29 ppmV (as isobutylene) for C9-C10 Aromatics. This was based upon a then-available estimated "background" values of hydrocarbon compounds and fractions within indoor air, and sub-slab to indoor air dilution and attenuation factor of 1300. With the increased use of the MassDEP APH test method after its finalization and release in 2008, the need to rely upon PID screening data has been diminished, and the use of such data in Section 4.3.2 of the 2026 guidance is now limited to use as one component of a "screening out" step for the vapor intrusion pathway.

The 2016 MassDEP Vapor Intrusion guidance also provided compound and hydrocarbon-range

sub-slab soil gas concentrations of interest in ppbV and µg/m^3 units, which have replaced the PID-based criteria in #WSC-02-411. Moreover, #WSC-16-435 incorporated a sub-slab to indoor air dilution factor of 70, considerably less than the value used in #WSC-02-411 in 2002. As a result, a significant portion of the 2002 Background document has been deleted from this update, as have Figure 4-1, Table 4-9, and Table 4-10 from #WSC-02-411.

While the "weight of evidence" approach in #WSC-16-435 will be the primary means to address vapor intrusion pathways at petroleum contaminated sites, a screening approach has been developed for small spills (<10 gallons) from on-site consumptive use fuel oil tanks. A component of this approach is screening sub-slab soil vapor probes with a PID meter, with a *de minimis* PID reading of 1 ppmV for residential settings and 4 ppmV for commercial/industrial settings.

The starting point for the calculation of these *de mini*mis levels is the Sub-Slab Soil Gas Screening Values from #WSC-16, reproduced below as Table 1:

Table 1 - MassDEP Sub-Slab Soil Gas Screening Values (MassDEP #WSC-16-435)

Compound/Range	Residential		Commercial/Industrial	
	µg/m^3	ppbV	µg/m^3	ppbV
Benzene	160	50	800	250
Ethylbenzene	520	120	62,000	14,000
MtBE	2700	760	190,000	520,000
Naphthalene	42	8	190	36
Toluene	3800	1000	310,000	82,000
Xylenes (mixed isomers)	1400	320	6200	1400
C5-C8 Aliphatic Hydrocarbons	4100	NA	23,000	NA
C9-C12 Aliphatic Hydrocarbons	4800	NA	16,000	NA
C9-C10 Aromatic Hydrocarbons	700	NA	3100	NA

Since a PID meter reads in parts per billion by volume (ppbV), it is necessary to convert the hydrocarbon range data from µg/m^3 to ppbV. This can be approximated by using the Equivalent Carbon Number Molecular Weight (ECMW) approach developed by the Total Petroleum Hydrocarbon Working Group (Gustafson et. al., 1997):

ppbV = [µg/m3] x 24.45 / ECMW

These values are presented below in Table 2:

Table 2 - MassDEP Sub-Slab Soil Gas Screening Values in ppbV			
Compound/Range	ECMW	Residential	Commercial/Industrial
		ppbV	ppbV
Benzene	N/A	50	250
Ethylbenzene	N/A	120	14,000
Methyl Tertiary Butyl Ether (MtBE)	N/A	760	520,000
Naphthalene	N/A	8	36
Toluene	N/A	1000	82,000
Xylenes (mixed isomers)	N/A	320	1400
C5-C8 Aliphatic Hydrocarbons	93	1100	6000
C9-C12 Aliphatic Hydrocarbons	149	790	2600
C9-C10 Aromatic Hydrocarbons	120	140	630

PID Meter Response

Once the soil gas action levels are established, it is necessary to determine how to measure such levels using PID screening instrumentation, which provide concentration data for total ionizable constituents at a given uV lamp emission level (generally around 10.5 eV +/-). Since most of these ionizable constituents are organic compounds, the resultant readings are generally referred to as "total organic vapors (TOV)", and are given in units of ppbV or ppmV, based upon an isobutylene standard. Response factors (RFs) are available for a wide range of organic compounds; for example, the response factor for benzene is around 0.53, relative to isobutylene. That means a reading of 100 ppbV as isobutylene would equate to a reading of 53 ppbV, if the sample was known to contain 100% benzene

Table 3 lists the RFs for constituents of diesel/#2 fuel oil, as well as the "Normalized" RFs, which are the RF values relative to isobutylene (RF=1). For example, benzene, with an RF of 0.53, has a normalized RF value of 1/0.53, or 1.89. In this manner, a reading of 100 ppbV on a PID meter calibrated with isobutylene would equate to concentration of 189 ppbV (100 x 1.89) of benzene, if benzene was the only compound in the sample being analyzed.

As indicated in Table 3, an average normalized RF can be determined for C5-C8 Aliphatics, C9-C12 Aliphatics, and C9-C10 Aromatics, based upon the average RFs of constituents within those ranges.

Using these normalized RFs, the Sub-slab Soil Gas Screening Values of #WSC-16-435, and the likely concentration of diesel/#2 fuel oil vapors (MassDEP, 2019), the protective PID values for soil gas screened with a PID meter containing a 10.5 +/- eV lamp at residential sites are provided in Table 4, and at commercial/industrial sites in Table 5.

Table 3 - PID Response Factors for PID meter with at 10.6 eV Lamp (RAE Systems)						
	Compound	No. Carbons	Ionization Energy	Response Factor[a]	Normalized Response[b]	Average Response[c]
ALIPHATICS	n-pentane	C5	10.35	8.4	0.119	**C5-C8 Aliphatics** 0.4
	cyclopentane	C5	10.51	N/A		
	n-hexane	C6	10.13	4.3	0.233	
	cyclohexane	C6	9.86	1.4	0.714	
	n-heptane	C7	9.92	2.8	0.357	
	n-octane	C8	9.82	1.8	0.556	
	n-nonane	C9	9.72	1.4	0.714	**C9-C12 Aliphatics** 0.64
	n-decane	C10	9.65	1.4	0.714	
	n-undecane	C11	9.56	2	0.500	
AROMATICS	benzene	C6	9.25	0.53	1.89	
	toluene	C7	8.82	0.5	2.00	
	ethylbenzene	C8	8.77	0.52	1.92	
	avg xylene	C8	8.52	0.49	2.04	
	1,3,5-TMB	C9	8.41	0.35	2.86	**C9-C10 Aromatics** 2.36
	Cumene	C9	8.73	0.54	1.85	
	naphthalene	C10	8.13	0.42	2.38	

Table 4 - PID Action Levels - Residential					
Parameter	Soil Gas Action Level (ppbV)	Normalized PID Response (isobutylene)	PID response at Action Level (ppbV)	Likely % of soil gas by volume	PID at expected composition (ppbV)
C5-C8 Aliphatics	1100	0.4	440	15	66
C9-C12 Aliphatics	790	0.64	506	60	304
C9-C10 Aromatics	140	2.35	329	20	66
Benzene	50	1.89	95	1	1
Toluene	1000	2.0	2000	1	20
Ethylbenzene	120	1.9	20228	1	202
Average Xylene	320	2.0	640	1	6
Naphthalene	8	2.38	19	1	1
				Total	670

Table 5 PID Action Levels – Commercial/Industrial					
Parameter	Soil Gas Action Level (ppbV)	Normalized PID Response (isobutylene)	PID response at Action Level (ppbV)	Likely % of soil gas by volume	PID at expected composition (ppbV)
C5-C8 Aliphatics	6000	0.4	2400	15	360
C9-C12 Aliphatics	2600	0.64	1664	60	998
C9-C10 Aromatics	630	2.35	1481	20	296
Benzene	250	1.89	473	1	5
Toluene	82000	2.0	164000	1	1640
Ethylbenzene	14000	1.9	26600	1	266
Average Xylene	1400	2.0	2800	1	28
Naphthalene	36	2.38	86	1	1
				Total	3600

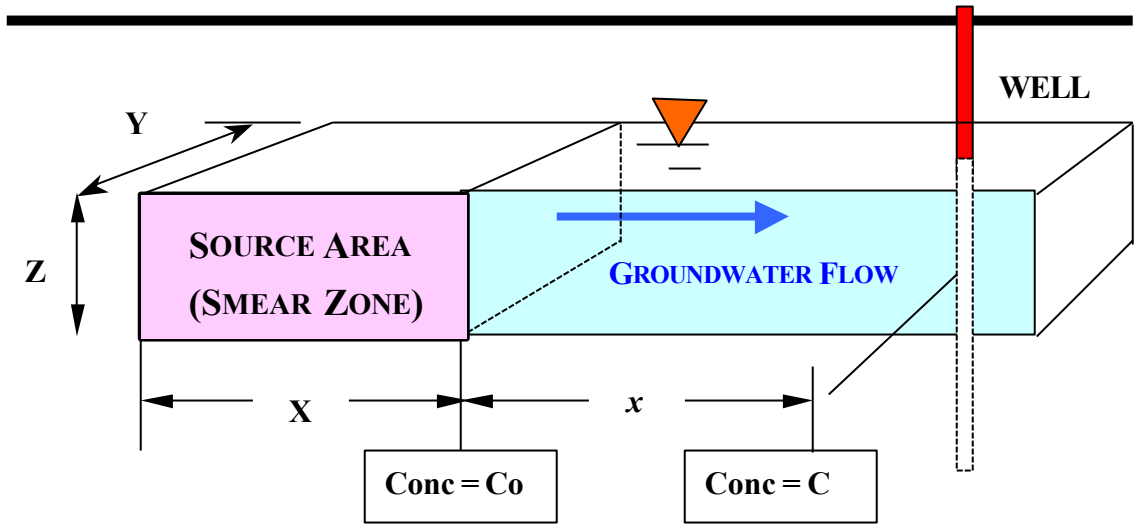
Expressed as 1 significant figure, the protective PID value for soil gas beneath a residential structure would be 1 ppmV, and 4 ppmV beneath a commercial/industrial building.

Section 5.3.2 - Groundwater Dilution Factors for Dissolved Hydrocarbons – Figure 5-1

The dilution factors and plots detailed in Figure 5-1 were developed using the Domenico and Robbins analytical transport model (Domenico, P.A., and Robbins, G.A., 1985). To be conservative, this evaluation was premised upon an infinite source assumption, and considered ONLY solute attenuation that results from hydrodynamic dispersion processes (i.e., additional attenuation from sorption, biodegradation, volatilization, etc., was NOT considered). In this manner, a number of site-specific factors (e.g., soil type) are not relevant, and the only factor that affects dilution is the configuration of the source area (i.e., contaminated soil).

The scenario that was modeled is graphically illustrated below in the figure below.

The objective of this effort was to determine the concentration of a dissolved contaminant at the water table at distance ***x*** from the source area, as a function of the concentration of that contaminant at the source area (i.e., C/C_o). To simulate a site where an underground storage tank had impacted soil and groundwater, the thickness of the source area (dimension **Z**) was assumed to be 6 feet, consistent with a conservative NAPL "smear zone". In assuming an infinite source condition, the dimension of the source area parallel to groundwater flow (dimension **X**) is not relevant.



Thus, the only remaining variable is the width of the source area perpendicular to the groundwater flow direction (dimension **Y**). In this regard, three scenarios were assumed:

Y = 10 feet, to simulate a small residential fuel oil UST site
Y = 30 feet, to simulate a mid-sized commercial UST site; and
Y = 60 feet, to simulate a larger multi-tank UST site.

The results and complete details on this modeling effort are provided in Appendix 5. Two details are worth noting:

- The dilution graphs included in Figure 5-1 of *Characterization of Petroleum Contaminated Sites* contain not only the **Y** dimension, but also the **X** dimension, assuming a square source area (e.g., 10 foot by 10 foot). Even though the **X** dimension is irrelevant because of the assumption of an infinite source, use of an area term was chosen to minimize confusion.
- MassDEP has chosen to prohibit use of these graphs for an evaluation of subsurface saturated zone transport over a distance (***x***) of less than 100 feet, in recognition of the modeling assumption of a homogeneous and isotropic aquifer. Specifically, the existence of preferred flow paths and/or small-scale heterogeneities could lead to situations where application of these graphs over such a short distance could result in a non-conservative conclusion.

Appendix 3 contains additional details, equations, and calculations in this regard.

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Appendices

Appendix 1 –Soil/Groundwater Headspace Partitioning

SOIL

Using the Fugacity Approach developed by Mackay and Patterson (1981), evaluate the predicted headspace partitioning of volatile hydrocarbons in petroleum contaminated soils via the MassDEP Jar Headspace procedure

Assumptions

CONTAMINANT

- Benzene (representative component of gasoline)

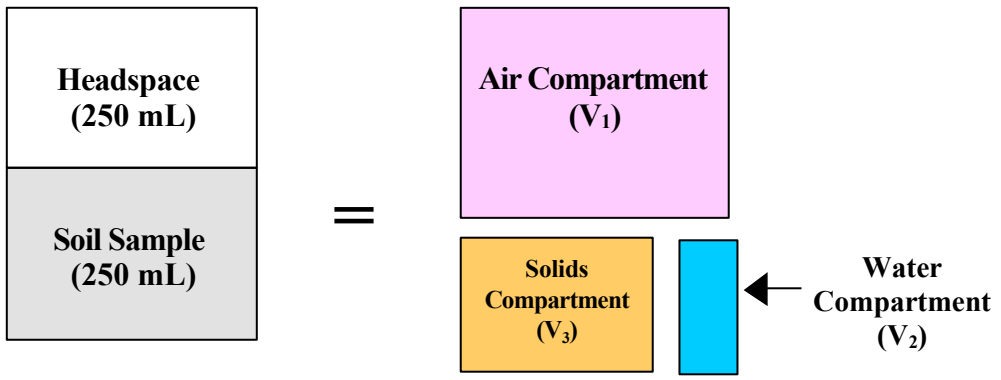
SOIL

- soil particle density = 2.65 g/cm3
- soil porosity = 0.3 cm3/cm3
- volumetric soil moisture content = 10%
- soil organic carbon content (oc) = 0.005

HEADSPACE/PID UNIT

- Headspace Development Temperature = 20ºC
- assume 50% of equilibrium headspace conditions were achieved during the jar headspace development period (Fitzgerald, 1989)
- assume the jar headspace reading by the PID unit represents 50% of the true jar headspace reading of benzene (Fitzgerald, 1989)
- assume soil is filled exactly halfway in a 500 mL (approximately 16 oz) sampling jar
- assume 10.5 +/- eV PID calibrated to an isobutylene standard

STEP 1 - Determine Volumes of 3 Compartments of Interest:



(A) Volume of Solids Compartment (f_3)

250 mL x 0.3 = 75 mL = volume of void spaces in soil sample 250 mL - 75

mL = 175 mL = 175 cm3 = volume of soil solids

$$175\ cm^3 \times \frac{1\ m^3}{10^6\ cm^3} = 1.75 \times 10^{-4}\ m^3 = \text{volume of soil solids compartment} = V_3$$

(B) Volume of Water Compartment (f_2)

250 mL x 0.1 = 25 mL = 25 cm3 = volume of water in soil sample

$$25\ cm3\ x\ \frac{1\ m3}{10^6\ cm3} = 2.5 \times 10\text{-}5\ m3 = \text{volume of soil water compartment} = V_2$$

(C) Volume of Air Compartment (f_1)

volume of void spaces in soil sample = (250)(0.3) = 75 mL
volume of water in soil sample = (250)(0.1) = 25 mL
Thus, volume of air-filled pore spaces = 75mL - 25 mL = 50 mL

250 mL (headspace volume) + 50 mL (pore air volume) = 300 mL = 300 cm 3 = total volume of air

$$300\ cm3\ x\ \frac{1\ m3}{10^6\ cm3} = 3.0 \times 10\text{-}4\ m3 = \text{volume of air compartment} = V_1$$

Step 2 - Determine Fugacity Capacity of Compartments

$Z_1 = 1/RT = 1/(8.21 \times 10\text{-}5)(293) = 41.5$ mol/atm-m3

$Z_2 = 1/H = 1/5.6 \times 10\text{-}3 = 179$ mol/atm-m3

$Z_3 = (\rho\ Kd)/H$

$Kd = (Koc)(oc) = (83)(0.005) = 0.415$ mL/g

$Z_3 = (1.58)(0.415)/5.6 \times 10\text{-}3 = 117$ mol/atm-m3

$\Sigma(ViZi) = V_1Z_1 + V_2Z_2 + V_3Z_3|$

$= (3 \times 10\text{-}4)(41.5) + (2.5 \times 10\text{-}5)(179) + 1.75 \times 10\text{-}4)(117)$

$= 3.74 \times 10\text{-}2$ atm/mol

Step 3 - Determine Mole Fraction Distribution Among Compartments

M_1/M = Soil Air Fraction = $V_1Z_1/\Sigma(ViZi) = (3 \times 10\text{-}4)(41.5)/3.74 \times 10\text{-}2 = 0.33 = 33\%$ in air compartment
M_2/M = Soil Water Fraction = $V_2Z_2/\Sigma(ViZi) = (2.5 \times 10\text{-}5)(179)/3.74 \times 10\text{-}2 = 0.12 = 12\%$ in soil water compartment
M_3/M = Soil Solids Fraction = $V_3Z_3/\Sigma(ViZi) = (1.75 \times 10\text{-}4)(117)/3.74 \times 10\text{-}2 = 0.55 = 55\%$ in soil solids compartment

Step 4 - Determine Concentration Distributions Among Compartments

100 ppmv headspace = 100,000 ppbv headspace

ug/m3 = (ppbv)(MW)/24.45 = (100,000)(78)/24.45 = 319,000 = headspace conc = conc in air compartment

(319,000)(3 x 10-4) = 96 ug = total mass of benzene in air compartment

96 ug x 1 mg/1000 ug x 1 g/1000 mg = 9.6 x 10-5 g = total mass of benzene in air compartment

$$9.6 \times 10\text{-}5\ g\ x\ \frac{1\ \text{mole benzene}}{78\ g\ \text{benzene}} = 1.2 \times 10\text{-}6\ \text{moles benzene in air compartment}$$

moles benzene in soil solids = (1.2 x 10-6) x $\frac{55\%}{33\%}$ = 2.0 x 10-6

moles benzene in soil water = (1.2 x 10-6) x $\frac{12\%}{33\%}$ = 4.4 x 10-7

grams benzene in soil solids = 2.0 x 10-6 mol x $\frac{78 \text{ g benzene}}{1 \text{ mol benzene}}$ = 1.6 x 10-4 g

1.6 x 10-4 g x $\frac{1000 \text{ mg}}{1 \text{ g}}$ x $\frac{1000 \text{ ug}}{1 \text{ mg}}$ = 160 ug benzene is soil solids

grams benzene in soil water = 4.4 x 10-7 mol x $\frac{78 \text{ g benzene}}{1 \text{ mol benzene}}$ = 3.4 x 10-5 g

3.4 x 10-5 g x $\frac{1000 \text{ mg}}{1 \text{ g}}$ x $\frac{1000 \text{ ug}}{1 \text{ mg}}$ = 30 ug benzene is soil water

TOTAL MASS BENZENE IN SOIL SAMPLE = mass in solid compartment + mass in soil water compartment

= 160 + 30 = 190 ug

CONCENTRATION IN SOIL SAMPLE = mass benzene in soil sample/mass soil

sample mass soil sample = (2.65 g/cm3)(175 cm3) = 464 grams

concentration = 190 ug/464 g = 0.41 ug/g

- ASSUMING HEADSPACE READING = 50% EQUILBRIUM CONDITIONS

Soil Concentration = (0.04)(2) = 0.82 ug/g

- ASSUMING JAR HEADSPACE PROCEDURE YIELDS 50% OF TRUE HEADSPACE CONCENTRATION

Soil Concentration = (0.82)(2) = 1.64 ug/g

Thus, 100 ppmV jar headspace benzene equates to an approximately 2 ug/g bulk soil benzene concentration, indicating a 1-2 order of magnitude partitioning relationship between gasoline in soil and gasoline in a PID jar headspace using the recommended MassDEP jar headspace screening procedure.

Assuming PID response to benzene (relative to isobutylene) is 0.53, 100 ppmV benzene in jar headspace would be a reading of 100/0.53 = 189 ppmV on a PID meter calibrated to an isobutylene response standard. Thus, a 100 ppmV jar headspace reading on a PID calibrated to isobutylene would equate to an approximately 1 ug/g bulk soil benzene concentration.

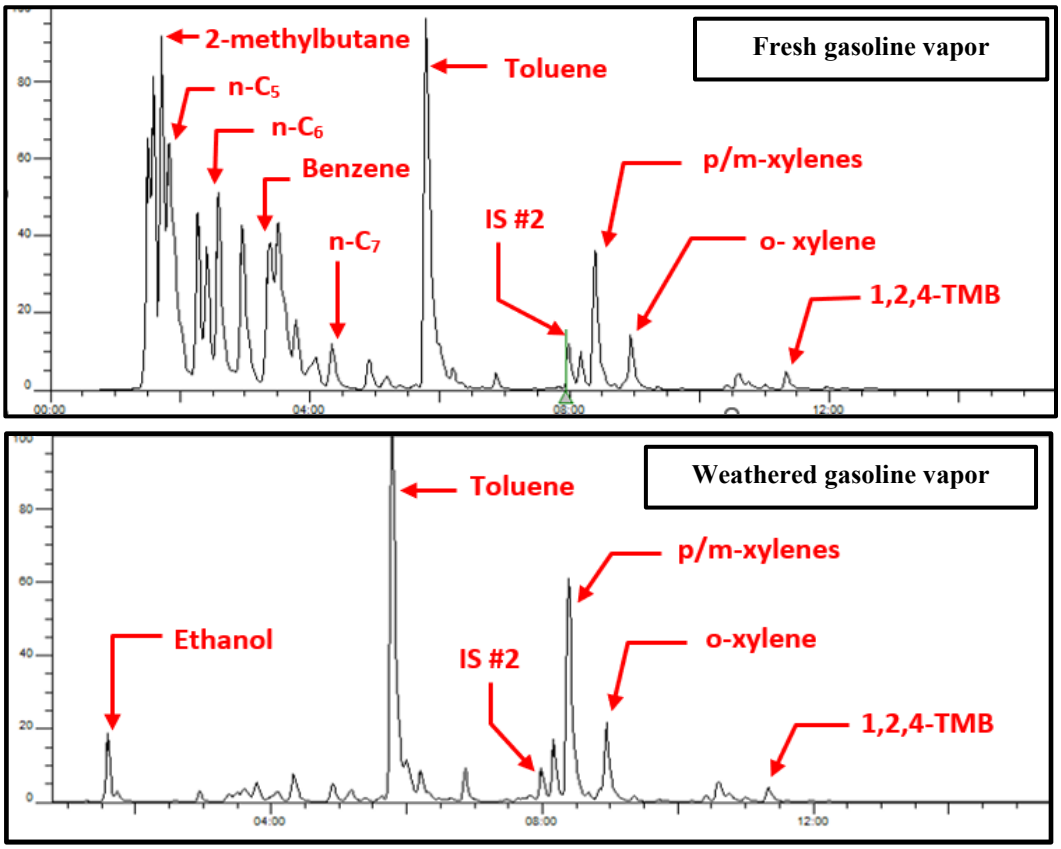
While benzene is the most toxic constituent of gasoline, the partitioning of the BTEX compounds and trimethylbenzenes are less robust than benzene, based upon their Henry's Law Constants and Koc values (see table below).

Using the Henry's Law Constant and Koc for o-xylene would give a more conservative distribution of BTEX compounds. In conducting these calculations, 100 ppmV of xylenes in the headspace would equate to 3.9 ug/g of xylenes in soil. For a PID calibrated to isobutylene, a PID headspace of 100 ppmV would equate to about 2 ug/g bulk soil xylene concentration (mixed xylenes PID RF = 0.5), a good surrogate for BTEX response.

To account for soils with higher organic carbon content and/or less than optimum headspace development and measurement procedures, a conservative rule of thumb would be that 2 ug/g BTEX in soil will produce a headspace of between 10 and 100 ppmV via the recommended MassDEP jar headspace procedure, using a 10.5 /- eV PID calibrated to an isobutylene standard. In soils where BTEX is the risk driver, a PID jar headspace reading of less than 10 ppmV as isobutylene would suggest that all BTEX compounds are below Method 1 S-1 standards.

Although BTEX contaminants often drive risk and remedial decisions in gasoline contaminated soils, the VPH aliphatic and aromatic hydrocarbon fractions can occasionally be a driver. A consideration of the chemistry and physical properties of gasoline mixtures, PID response factors, and MCP Method 1 soil cleanup standards provide some insights in this regard.

The chemistry of a fresh and weather gasoline vapor is presented below as total ion chromatograms (Fitzgerald, 2019).



Published and estimated properties of the BTEX and hydrocarbon fractions are provided below (Gustafson et al., 1997)

Henry's Law Constants and Koc values at 25ºC			
Compound	**Vapor Pressure (atms)**	**Henry's Law Constant ($atm \cdot m^3/mol$)**	**Approximate Koc (mL/g)**
Benzene	0.13	0.0045	80
Toluene	0.04	0.0032	100
Ethylbenzene	0.01	0.0028	125
Xylenes (mixed)	0.01	0.0022	125
1,2,3-Trimethylbenzene	3×10^{-3}	0.00436	630
1,2,4-Trimethylbenzene	3×10^{-3}	0.00616	1000
1,3,5-Trimethylbenzene	3×10^{-3}	0.00871	1000
C5-C8 Aliphatics	0.10	1.32	2265
C9-C12 Aliphatics	8.7×10^{-4}	1.59	1.5×10^{5}
C9-C10 Aromatics	2.9×10^{-3}	0.008	1778
C9-C18 Aliphatics	1.4×10^{-4}	1.69	6.8×10^{5}
C11-C22 Aromatics	3.2×10^{-5}	0.0007	5000

Available PID response factors (RAE Systems) are provided below.

PID Response Factors for PID meter with at 10.6 eV Lamp (RAE Systems)						
	Compound	No. Carbons	Ionization Energy	Response Factor[a]	Normalized Response[b]	Average Response[c]
ALIPHATICS	n-pentane	C5	10.35	8.4	0.119	**C5-C8 Aliphatics** 0.4
	cyclopentane	C5	10.51	N/A		
	n-hexane	C6	10.13	4.3	0.233	
	cyclohexane	C6	9.86	1.4	0.714	
	n-heptane	C7	9.92	2.8	0.357	
	n-octane	C8	9.82	1.8	0.556	
	n-nonane	C9	9.72	1.4	0.714	**C9-C12 Aliphatics** 0.64
	n-decane	C10	9.65	1.4	0.714	
	n-undecane	C11	9.56	2	0.500	
AROMATICS	benzene	C6	9.25	0.53	1.89	
	toluene	C7	8.82	0.5	2.00	
	ethylbenzene	C8	8.77	0.52	1.92	
	avg xylene	C8	8.52	0.49	2.04	
	1,3,5-TMB	C9	8.41	0.35	2.86	**C9-C10 Aromatics** 2.36
	Cumene	C9	8.73	0.54	1.85	
	naphthalene	C10	8.13	0.42	2.38	

[a] Response Factor relative to isobutylene

[b] Response normalized to isobutylene = 1/RF

[c] Average of normalized responses within hydrocarbon range

With respect to gasoline releases, in GW-1 areas, the current MCP Method 1 S-1 cleanup standards for the BTEX compounds are 2 µg/g for benzene, 30 µg/g for Toluene, 40 µg/g for ethylbenzene, and 100 for xylenes, with the most stringent hydrocarbon range standards at 100 µg/g (C5-C8 Aliphatics and C9-C10 Aromatics). In S-1/GW-2 areas, these values increase to 40, 500, 500, respectively, with xylenes at 100 µg/g. BTEX standards in S-2 soils are substantially higher (100 to 1000 µg/g), though the C5-C8 Aliphatics standard remains at 500 µg/g)

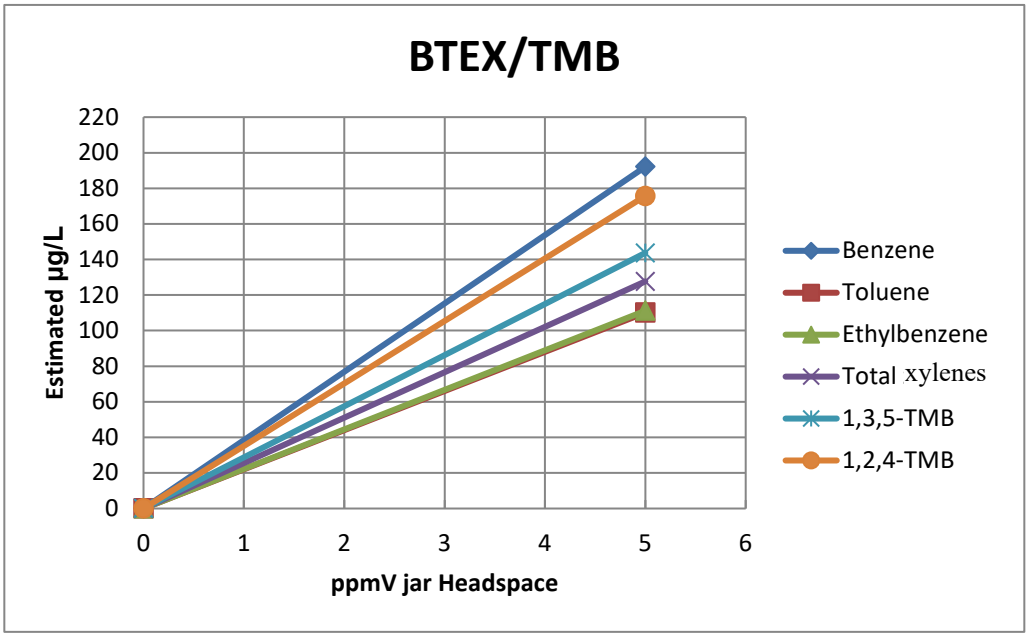
On the basis of the above, the high vapor pressure and elevated Henry's Law constants suggest that the headspace of wet to moist soil and/or soil containing fresh gasoline NAPL droplets within its pore spaces will generate significant levels of C5-C8 Aliphatic compounds, though the PID response will be only about 20% of the BTEX and C9-C10 Aromatic compounds. In S-1 and/or GW-1 locations, the BTEX compounds will likely be the risk drivers, given their low MCP Method 1 standards.

In S-2 and S-3 soils and/or GW-2 or GW-3 areas, the C5-C8 Aliphatics and/or C9-C12 Aliphatic Hydrocarbon standards may be the risk drivers for fresh gasoline spills. For more weathered products, and in S-1 or GW-1 areas, BTEX and C9-C10 Aromatics will be the likely risk/remedial driver.

GROUNDWATER

Research has demonstrated that short-term (10 minute) dynamic headspace development can achieve close to 90th percent of ultimate BTEX equilibrium conditions (Fitzgerald, l989).

A conservative assumption of achieving 75% of Henry's Law equilibrium condition would result in the headspace relationships provided below:



The BTEX components comprise a dominant portion of the water-soluble fraction of petroleum fuels, with an effective solubility in the range of 50 to 230 mg/L (EPA, 2017). Equilibrium evaluation of fuel in contact with water has demonstrated that benzene is not the most dominant constituent within the BTEX grouping, constituting less than 33% of BTEX in gasoline/water evaluations, and less than 10% in diesel/water evaluations. (Potter, 1993)

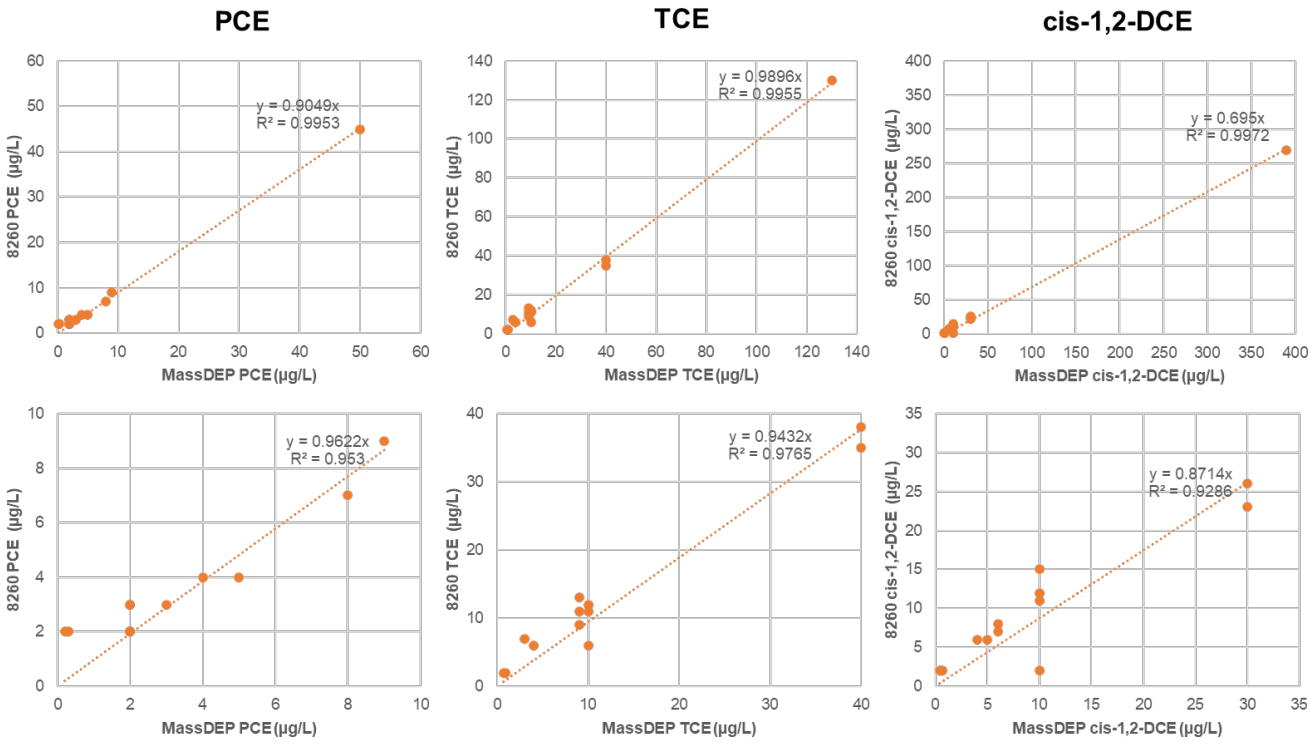
As previously discussed, use of the Henry's Law Constant for o-xylene would give a more conservative distribution of BTEX compounds. The above indicates a dissolved xylenes (and thus BTEX) concentration of 130 µg/L would be expected to yield a jar headspace concentration of 5 ppmV. Using a PID meter calibrated to isobutylene, 5 ppmV as BTEX will create a Total Organic Vapor reading about 10 ppmV. Using the MassDEP jar headspace procedure, where sampling is accomplished by inserting the PID meter probe through an aluminum foil seal can reduce the headspace reading by up to 50% (Fitzgerald, 1989), suggesting a reading of about 5 ppmV would be expected.

Extrapolating, if 130 µg/L of BTEX will yield a jar headspace value of 5 ppmV, 1000 µg/L would produce 39 ppmV. Given that the lowest BTEX GW-2 standard is 1000 µg/L for benzene, a jar headspace value of less than 39 ppmV would suggest aqueous a BTEX concentration less than GW-2 standards, i.e., even if benzene represented 100% of BTEX, the conservative estimate of the benzene concentration would be just under 1000 µg/L Given the likely presence of other volatile hydrocarbons that may elicit a PID response (e.g., C9-C10 Aromatics), and the highly conservative nature of this evaluation, a value of 50 ppmV appears appropriate.

For gasoline and diesel/#2 fuel oil contaminated groundwater, partitioning calculations suggest that a PID jar headspace of than 50 ppmV (as isobutylene) is a reasonably conservative metric to demonstrate that MCP Method 1 GW-2 cleanup standards have been met

Beyond these partitioning calculations, MassDEP has been using a short-term dynamic headspace development technique (assuming development of 75% of the Henry's Law equilibrium condition) for over 20 years to "screen" aqueous samples for the presence of dissolved VOC compounds, generally using GC/MS instrumentation. Results are periodically compared to split-sampling analyses by EPA Method 8260, which uses a purge and trap sample preparation technique. Such comparisons almost always show correlation to within +/- 30%.

An example is provided below of 8 stream samples obtained from a site in Beverly, MA on March 26, 2021. Data from the MassDEP headspace samples and split samples analyzed via EPA Method 8260 are plotted below, showing very good correlation, except at very low levels, which are generally below risk-based action levels.



Appendix 2 –Maximum Concentrations of Lead in Soils from Releases of Leaded Gasoline

Assumptions:

SOIL

- soil particle density =2.65 g/cm3
- soil porosity = 0.3 cm3/cm3
- volumetric soil moisture content = 0% (i.e., all pore spaces filled with gasoline)

GASOLINE

- lead conc. in gasoline product = 4.3 grams/gallon (peak allowable level; 1959, per Gibbs, 1990)
- density of gasoline = 6.5 pounds/gallon (API, 1993)

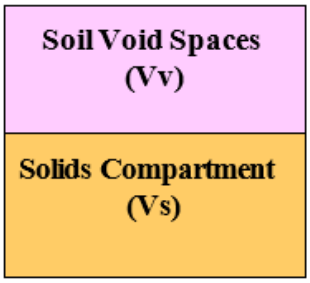
PARTITIONING

- Assume 100% of lead from NAPL sorbs onto soil solids

CALCULATIONS

6.5 pounds/gal gasoline X 454 grams/pound = 2951 grams gasoline/gallon

4.3 grams lead/2951 grams gasoline = 0.0015 (0.15%) = level of lead in gasoline



Assume 1 cm^3 soil block

@ 0.3 porosity, Vv = 0.3 cm3 and Vs = 0.7 cm^3

mass of soil solids = [Vs] [2.65 g/ cm^3] = 1.86 g = 0.00186 kg

0.3 cm^3 X 6.5 lb/gal X 1 gal/3785 cm^3 X 454 g/lb = 0.23 g = mass of gasoline in pore space (assuming worst case condition of 0% moisture)

0.23 g X 0.0015 = 0.00035g X 1000 mg/g = 0.35 mg = mass of lead in gasoline in

pore space [0.35 mg lead] / [0.00186 kg soil] = 188 mg/kg lead concentration in soil

Thus, up to 200 ug/g lead possible in soil in contact with leaded gasoline NAPL. Continued releases of new NAPL over a number of years could "enrich" soil with additional lead.

Appendix 3

BASIS FOR DERIVATION OF THE METHOD-2 GW-3 DILUTION FACTORS/ Figure 5-1

CHARACTERIZATION OF PETROLEUM CONTAMINATED SITES

NIHAR MOHANTY, MASSDEP

JUNE 12, 2001

SUMMARY

In this paper, generalized groundwater transport Dilution Factors are developed for typical site conditions in Massachusetts using a conservative scenario. The Domenico & Robbins simplified 3-dimensional analytical groundwater transport model is used to derive a family of curves for three different source configurations under steady-state conditions. The use of these curves is illustrated by an example. Site conditions where the derived dilution curves may not be applicable are also identified.

BACKGROUND AND OBJECTIVE

The MCP Method 1 GW-3 groundwater standards were derived by assuming that a disposal site is located upgradient from a surface water body and that groundwater from the disposal site will eventually reach and discharge into the surface water body. A Dilution and Attenuation Factor (DAF) was then designated for each Method 1 standard, as a conservative estimate of contaminant attenuation via (1) subsurface transport to, and (2) dilution in, the surface water body. For evaluated contaminants, groundwater attenuation factors ranged between 2.5 to 100, depending upon Koc values, with an additional 10-fold dilution between groundwater and surface water. The Method 1 GW-3 standards were then simply calculated as the total Dilution Factor multiplied by the acceptable ambient water concentration of the contaminants of concern.

Using a Method 2 Risk Characterization process, a Method 1 GW-3 standard can be modified by justifying a different site-specific Dilution and Attenuation Factor. The objective of this evaluation is to develop a means for parties to quickly and easily justify a conservative groundwater transport Dilution Factor for a disposal site, based upon the size and configuration of the contaminated soil "source area", and distance to the nearest downgradient surface water body, using the Domenico and Robbins transport model, and a series of conservative assumptions on site hydrogeological conditions. This effort is limited to dilution that occurs via groundwater transport only, and does NOT consider additional dilution effects that may be present at a site due to the flowrate and/or volume of the receiving surface water body.

THE DOMENICO & ROBBINS MODEL

The mass balance equation (commonly called the dispersion-convection equation) governing the transport of an ideal non-reactive conservative solute by a homogeneous fluid flow through saturated porous medium is given by:

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial x} - D_x\frac{\partial^2 C}{\partial x^2} - D_y\frac{\partial^2 C}{\partial y^2} - D_z\frac{\partial^2 C}{\partial z^2} = 0 \qquad (1)$$

where:

C = the solute concentration,

v = seepage velocity

D_X, D_Y and D_Z = the principal values of the dispersion tensor, and

t = time.

Domenico and Robbins (1985(b)) used an extended pulse approximation to the continuous finite source problem. The source has constant dimensions in a transverse and a vertical direction with respect to the groundwater flow direction, and has infinite dimension in the groundwater flow direction. It describes a semi-infinite contaminated area that moves with a one-dimensional velocity in the positive x direction under uniform flow conditions. Contaminant concentrations at distances x, y, z from a source at time t may be estimated from equation 2 given below. The equation accounts for advection and dispersion only and does not account for biodegradation.

$$C(x, y, z, t) = \left(\frac{C_0}{8}\right) erfc\left[\frac{(x - vt)}{2\sqrt{\alpha_x vt}}\right]\left\{erf\left[\frac{y + \frac{Y}{2}}{2\sqrt{\alpha_y x}}\right] - erf\left[\frac{y - \frac{Y}{2}}{2\sqrt{\alpha_y x}}\right]\right\} * \left\{erf\left[\frac{z + \frac{Z}{2}}{2\sqrt{\alpha_z x}}\right] - erf\left[\frac{z - \frac{Z}{2}}{2\sqrt{\alpha_z x}}\right]\right\} \qquad (2)$$

where:

x = distance of the point of compliance from the source in the direction of groundwater flow
y = distance transverse to the groundwater flow
z = distance vertical (in the direction of gravity) to the groundwater flow v
= groundwater velocity
Y = width of the source in a direction transverse to the groundwater flow
Z = thickness of the source in a direction vertical to the groundwater flow
α_x = longitudinal dispersivity in the direction of flow
α_y = transverse dispersivity in the direction transverse to the flow
α_z = vertical dispersivity in the vertical direction to the flow
erf = error function
erfc = complementary error function

Equation (2) may be simplified for estimating contaminant concentrations along the plume center line (y =0) in the direction of groundwater flow (x) at the water table (z= 0). For a source at the water table, Z/2 is replaced by Z (Domenico and Robbins (1985(b)) in equation 2. Under steady-state conditions i.e., at receptor distances x << vt, the *erfc* term (second term) of equation 2 approaches 2. The simplified equation is given below:

$$C = C_0\left\{erf\left(\frac{Y}{4\sqrt{\alpha_y x}}\right)\right\} * \left\{erf\left(\frac{Z}{2\sqrt{\alpha_z x}}\right)\right\} \qquad (3)$$

Under a steady-state condition, as seen from equation 3, contaminant concentrations at distances x from a source is solely a function of source geometry (width and thickness) and dispersivity (transverse and vertical). Note that to estimate contaminant concentrations using equation 3, the longitudinal dispersivity coefficient is not a variable and is not required directly. However, transverse dispersivity and vertical dispersivity are directly related to longitudinal dispersivity, and are usually expressed as a fraction of the longitudinal dispersivity value. Using equation 3, aquifer properties (e.g. organic carbon content of aquifer material, porosity, hydraulic conductivity, hydraulic gradient) and the partitioning coefficient of a contaminant do not affect predicted contaminant concentrations.

MODELING SCENARIO AND INPUT ASSUMPTIONS

A. Scenario and source

Common scenarios were evaluated for leaking underground storage tank (LUST) sites. At such sites, petroleum products leak from an underground storage tank and contaminate surrounding soils. It is not uncommon for non-aqueous phase liquids (NAPL) to exist at the water table interface, creating a "smear zone" as the groundwater elevation rises and falls. Contamination within this smear zone then acts as a continuing source of contamination of the groundwater.

A reasonably conservative "smear zone" for Massachusetts was assumed to be 6 feet, which was used as "source thickness" term (Z) for all modeling scenarios. Three scenarios were then evaluated with different combinations of length and width, as indicated below

10ft. (length) x 10ft(width) x 6ft. (thick)..... Residential USTs
30ft. x 30ft. x 6ft. .....Commercial USTs at gas stations
60ft. x 60ft. x 6ft .....Larger Commercial USTs

B. Dispersivity coefficients:

Once the source configuration parameters were established, it was necessary to designate dispersivity coefficients, which are the key input variables in equation 3, and controlling element in all models which seek to characterize contaminant transport solely on the basis of dispersion.

Dispersivity coefficients may be estimated by two approaches: theoretical derivation and empirical observation. Ideally, values derived by both means should be roughly comparable.

Theoretical Derivation

Dispersion in groundwater occurs as a consequence of two different processes: mechanical dispersion and molecular diffusion, as shown in equation 4. (Pickens and Grisak, 1981):

$$D_x = \alpha_x \, v + D^* \qquad (4)$$

$$D_x = \alpha_x \, v + D^* \qquad (4)$$

Where:

D_X = coefficient of hydrodynamic dispersion,
α_x = longitudinal dispersivity in the x-direction; and
D^* = coefficient of molecular diffusion.

Mechanical dispersion is caused by local variations in velocity, which in turn is caused by the non-idealities or heterogeneity of a medium. Some of the geological features contributing to heterogeneity of a medium are pore size distribution, non-uniform stratification, directional and non-uniform permeability, etc. Hydraulic conductivity is the most important variable contributing to the heterogeneity of a medium.

In an available geo-statistical approach (Domenico, Swartz, 1998), longitudinal macro-dispersion, A^* is given as follows:

$$A_L^* = A_L + \alpha_L \cdot \frac{D_d^*}{v} \qquad (5)$$

where

α_L = local scale (Sudicky, 1986), pore scale (Domenico and Schwartz, 1998), microscopic and column scale dispersion (Smith and Schwartz,1980). [Local scale dispersion is generally assumed to be insignificant (Gelhar and Axness, 1983).]

D_d^* = diffusion coefficient; is generally assumed to be negligible (Domenico and Schwartz, 1998), (Pickens and Grisak, 1981).

A_L = asymptotic longitudinal dispersivity (Gelhar and Axness, 1983) given by:

$$A_L = \frac{\sigma_Y^2 \lambda}{\gamma^2} \qquad (6)$$

where:

$\gamma = 1$ (Dagan, 1982)

σ_Y^2 = variance of the log-transformed hydraulic conductivity ($Y = \ln K$)

λ = correlation length in the mean direction of flow.

In the same manner, A_T^*, transverse macro-dispersivity, is given by:

$$A_T^* = A_T + \alpha_T + \frac{D_d^*}{v} \qquad (7)$$

A similar derivation does not currently exist for vertical dispersivity.

From equation 6, the asymptotic longitudinal dispersivity, A_L is affected by the heterogeneity or variability of a medium. The spatial mean and variance of hydraulic conductivity and correlation lengths have been used to describe the heterogeneity of a medium. The correlation length is a measure of spatial persistence of zones of similar properties.

Empirical Observations and Scale Effects

Empirical data are available from laboratory experiments and a limited number of (well characterized) sites. A review of this data indicates that dispersion varies with distance. Specifically, the greater the distance over which dispersivity is measured, the greater the observed value, which is called the *scale effect* (Anderson, 1979).

In laboratory column experiments, dispersion is reported to be controlled by fluid flow velocity and grain size distribution. Local scale dispersion is in the centimeter range and is generally two or more orders of magnitude smaller than dispersivity at a macro scale (Smith and Schwartz, 1980). For example, longitudinal dispersivities for a *medium sand* were measured using an in-situ single - well injection-withdrawal tracer test and a laboratory column test (Pickens and Grisak, 1981). Longitudinal dispersivities were found to be an order of magnitude higher when measured in-situ (0.7 cm) than the column scale study (0.035 cm). Based on the scale of measurements reported by researchers, there is evidence that dispersivity coefficients are scale dependent (Pickens and Grisak, 1981, Gelhar et.al. 1985).

Theoretically, from equation 6, longitudinal dispersivity initially increases linearly with distance and gradually approaches a constant asymptotic value (Gelhar and Axness, 1983, Dagan, 1986, 1988). Therefore, groundwater must move a substantial distance before it is able to fully interact with the heterogeneity to the extent necessary to produce a macro-scale mixing. That would explain the increase in dispersivity away from a source before approaching an asymptotic (or fixed) value. For example, the asymptotic value had not been reached even after 90m (300ft) of contaminant travel at the Borden site (Freyberg, 1986).

Gelhar et al. (1992) reviewed 106 field observations of dispersivities from 59 sites and classified the data points into three groups of varying reliability levels: high, intermediate, and low. They concluded that, in general, field scale dispersion appears to be scale - dependent although the relation may not be linear.

Xu and Eckstein (1995) proposed a weighted least-squares data fitting method using the data reviewed by Gelhar to provide an improved statistical model of the relationship between field scale and dispersivity given as equation 8.

$$\alpha_x = 3.28 * 0.83 \left[\log_{10}\left(\frac{L_p}{3.28}\right) \right]^{2.414} \qquad (8)$$

Where:

L_P = Scale of study, feet; and

α_x = Longitudinal dispersion coefficient, feet.

Their equation incorporates the general asymptotic nature of dispersion; their analysis indicates when the flow distance exceeds 1,000 meters (300 feet), the increase in longitudinal dispersivity is practically negligible.

Field-measured variance of hydraulic conductivity, correlation lengths, and longitudinal dispersivities of four well-characterized sites are shown in Table 1:

Table 1
Field measured variance of hydraulic conductivity, correlation lengths and longitudinal dispersivities

Site Location	Variance of conductivity	Horizontal correlation scale, m	L,T,V[a] Dispersivity, m	Reference
Cape Cod, MA	0.24	2.6	0.96, 0.018, 0.0015	Garabedian et.al., 1991
Borden, Canada	0.29	2.8	0.43,0.039	Freyberg et.al., 1986
Borden, Canada	0.29	2.8	0.5, 0.05, 0.0022	Gelhar et.al. 1991
Columbus, MI	4.5	12.8	7.5	Gelhar et.al., 1992
Denmark	0.37	1.5	0.45, 0.001,0.0005	Jensen et.al., 1993

[a]Independently measured longitudinal, transverse, and vertical dispersivity, where reported.

As discussed earlier (also equation 6), longitudinal dispersivity is proportional to heterogeneity, which is indicated by variance of conductivity. Based on the estimated variances of hydraulic conductivity measurements of the four sites presented in Table 1, the Columbus site is the most heterogeneous (highest value of variance) with a field-measured longitudinal dispersivity (7.5m) an order of magnitude higher than the rest of the sites. In a reliable study conducted at a sand and gravel aquifer in Cape Cod, at a scale of 250m (820 feet), the longitudinal, transverse, and vertical dispersivities were measured to be 0.96m, 0.018m, and 0.0015m, respectively. For the Cape Cod site, using equation 6, the estimated longitudinal dispersivity value is 0.63m, which is close to the measured value of 0.96m.

For groundwater modeling of contaminant migration in the subsurface, it is a common practice to select constant values for the ratio of longitudinal-to-transverse dispersivities. Gelhar et al. (1992) in a review of all available field-scale studies noted that transverse dispersivities are at least an order of magnitude smaller than the longitudinal dispersivity values. From field data considered to be highly reliable, the ratio of horizontal to transverse dispersivity was observed to be approximately 10.

From results of available field studies, vertical dispersivity was noted to be 1-2 orders of magnitude smaller than the transverse dispersivity. In media with pronounced horizontal stratification, values of vertical dispersivity may be similar to diffusion (Sudicky, 1986). For

this evaluation, 9 field-scale vertical dispersivity data points reported in the literature have been utilized. Of the 9 points, only 2 data points were classified as highly reliable: the Borden (Freygerg, 1986) and the Cape Cod (Garabedian, 1991) sites. All of the vertical dispersivities reported in the literature are less than 1 meter and the two highly reliable values (according to Gelhar et al.) are only a few millimeters, which is the same order of magnitude as the local transverse dispersivity for sandy materials.

Selected Dispersivity Coefficients

The Dispersivity coefficients selected for this modeling effort are indicated in Table 2.

TABLE 2
Dispersivity Assumptions

Dispersivity	Value
Longitudinal	Based on Xu & Eckstein's equation
Transverse	0.1* longitudinal dispersivity (Field scale data, Gelhar et. al. 1992)
Vertical	0.025 * longitudinal dispersivity (EPA, 1986)

Note that a slightly higher value of vertical dispersivity (0.025 * long. Disp. instead of 0.002 * long. Disp. measured at the Cape Cod site) is assumed for the following reasons:

- The Domenico model does not account for vertical mixing of contaminants in a plume due to infiltration and vertical velocity gradients found at sites. Such plumes are sometimes described as "diving plumes". Such vertical mixing in plumes would result in additional dilution (than predicted by dispersion) of contaminant concentrations at a site.
- The direction of groundwater flow is not constant and there are reports of temporal variations in the flow direction in field conditions (Garabedian, 1991). This change in flow direction would further dilute contaminant concentrations at a site.
- As discussed earlier, longitudinal dispersivity is a function of heterogeneity. Since most sites in Massachusetts are not as homogeneous as the Cape Cod site, dispersivity values measured at Cape Cod can, at best, be assumed to be a conservative estimate for most sites in the state.
- Currently, well screens in monitoring wells are typically of 10ft lengths and are seldom less than 5ft. When groundwater samples are collected from a monitoring well with a 10ft screen length placed below the water table, the measured contaminant concentration is expected to be lower due to dilution over a 10-foot stratum. The degree of dilution, however, is dependent on the vertical distribution of a contaminant.

C. Other Assumptions and Discussion:

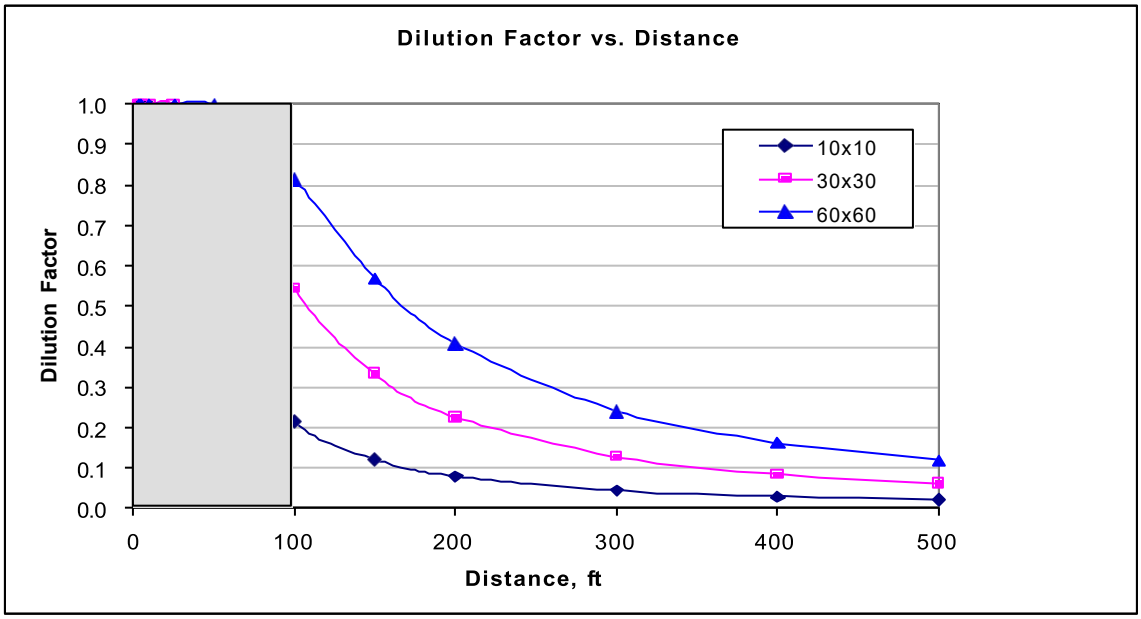
In addition to the source configuration and dispersivity values discussed above, additional key assumptions used during this effort and incorporated into the Dilution curves are identified below:

- ✓ The aquifer is assumed to be homogeneous and isotropic and the groundwater flow direction does not vary.
- ✓ Although it is known that petroleum hydrocarbon compounds biodegrade in the environment, as a conservative measure, it was assumed that biodegradation does not occur.
- ✓ The point of compliance is assumed to be located at the center of the plume at the water table.

MODELING RESULTS

Contaminant concentrations were estimated at the plume centerline at distances ranging from 3.3 ft. to 500 ft. from the edge of a source using equation 3 and Microsoft Excel. The graphs of three source widths (10 feet, 30 feet, and 60 feet) are shown in Figure 1. In the context of these graphs, the Dilution Factor is the [concentration of a solute at some distance]/[concentration at the source area.], which is C/Co in equation 3. Note that use of this generic Dilution Factor approach is not recommended for distances less than 100 feet, and is therefore not shown in the figure. At distances less than 100 feet from a source, it is usually possible (and preferable) to monitor site conditions directly.

Figure 1
Dilution Curves for 3 Different Source Configurations



Regression equations were fit to the three Dilution Factor curves for distances greater than 100 feet based on the sample coefficient of determination, R^2. The equation, R^2, and the type of equation are shown in Table 2.

Table 2
Regression Equations for Dilution Factor Curves

Source Width, ft.	Equation	R^2	Type Equation	Comments
10	$DF=177.2\ Distance^{(-1.4555)}$	0.9999	Power	For Distance >=100ft
30	$DF=303.33\ Distance^{(-1.3654)}$	0.999	Power	For Distance >=100ft
60	$DF=236.99\ Distance^{(-1.2137)}$	0.9936	Power	For Distance >=100ft

EXAMPLE

Groundwater at a site is contaminated with benzene at 15 mg/l. The source/site is 25 ft. wide in the direction transverse to the groundwater flow direction. The expected concentration of benzene based on the Dilution curve at a distance of 160 ft. from the edge of the source/site may be estimated as shown below:

From Table 3, for a source width of 30ft,

$$DF = 303.33 * Distance^{(-1.3654)} = 303.33 * 160^{(-1.3654)} = 0.3 = C/Co$$

Therefore, the concentration at 160ft = 0.3 * Co = 15 mg/l * 0.3 = 4.5 mg/l

SENSITIVITY ANALYSIS

Under a steady-state assumption, the DFs are sensitive to the source geometry and the dispersivity coefficients, particularly the transverse and vertical dispersivity coefficients

A. Effect of dispersivity coefficients on DFs

Different agencies and researchers have recommended and used different ratios of transverse to longitudinal (T:L) and vertical to longitudinal (V:L) dispersivity values. For example, T:L values of 0.33 (ASTM, 1995 and EPA, 1986), 0.12(EPACMTP, 1996), 0.1(BIOSCREEN, 1996, Gelhar, 1992) have been recommended for use. V:L ratios of 0.1 (Pickens and Grisack, 1981), 0.025 - 0.1(EPA, 1986), 0.05 (ASTM, 1995), 0.006 (EPACMTP, 1996) and 0.002 (measured at the Cape Cod site) have been recommended.

Figures 2 and 3 show the variation of DF with variation of the ratios of T:L and V:L.

Figure 2

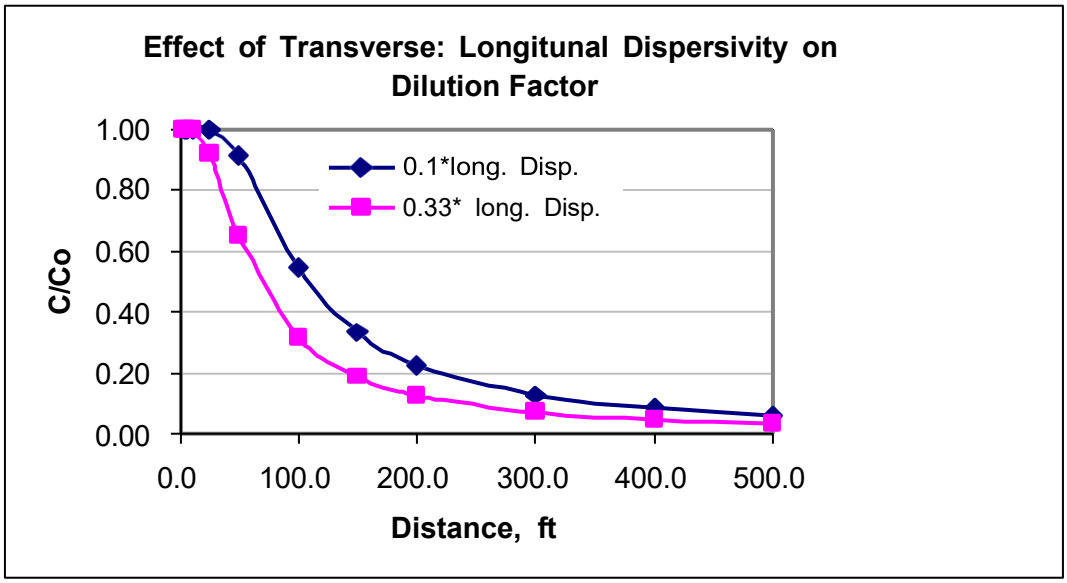
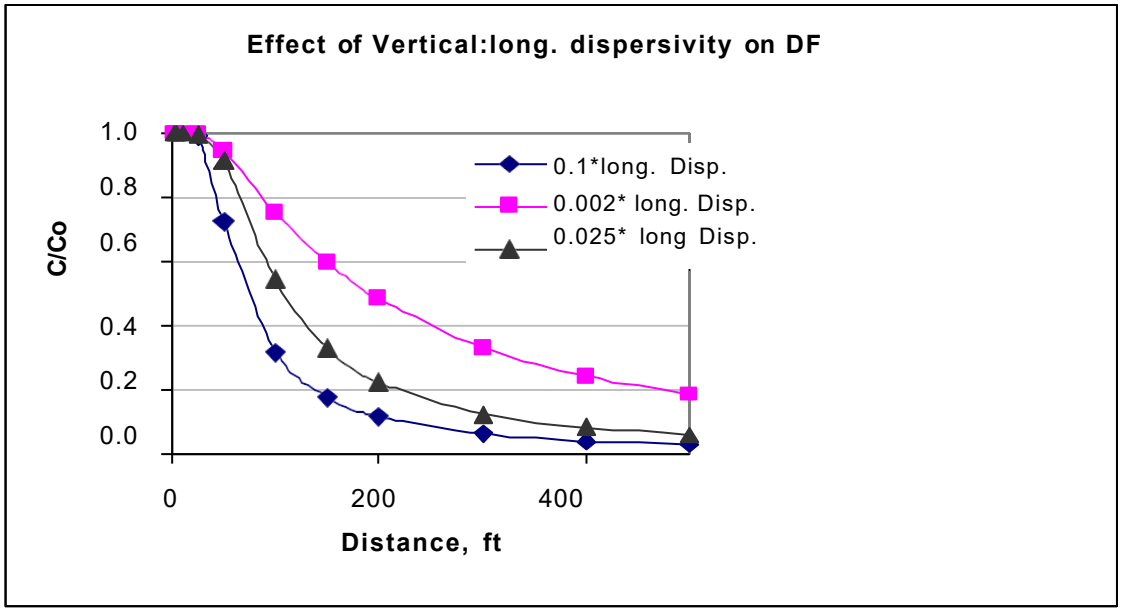


Figure 3



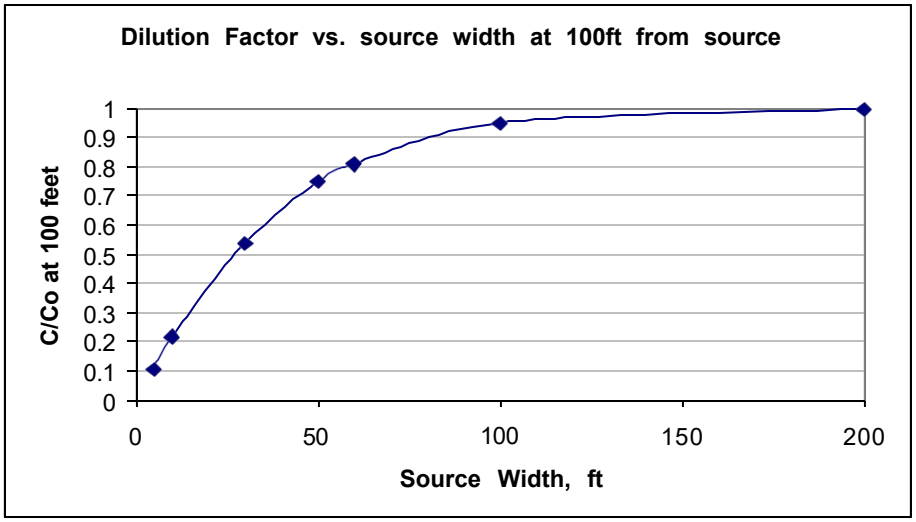
Using equation 3, unit changes in either transverse or vertical dispersivity results in similar values of predicted the DF. The ratios used for the sensitivity analysis (in Figures 2 and 3) have been selected from the sources mentioned above. In general, the effect of vertical dispersivity on the DF is more pronounced compared to the effect of transverse dispersivity. This may be explained by the variation of the input range reported in the

literature. For example, T:L ratios generally range between 0.1 and 0.33 (a smaller range) whereas the V:L ratios range between 0.002 and 0.1 (2 orders of magnitude). DFs are most affected between distances of 50 feet and 200 feet; at distances greater than 200 feet, the effect appears to be less significant.

B. Effect of source width and thickness on DF:

Figure 4 shows the variation of DF with source width at a distance of 100 ft. from a source edge. From Figure 4, generally, the DF decreases with source width, however, at distances greater than 75 ft. from the source, there is no significant increase in DF.

Figure 4



Figures 5a and 5b show the variation of DF with source thickness. Figure 5b shows the variation of DF at a distance of 100 feet from the source edge. From Figure 5b, it can be seen that the DF does not increase significantly at thickness greater than 6 feet.

Figure 5a

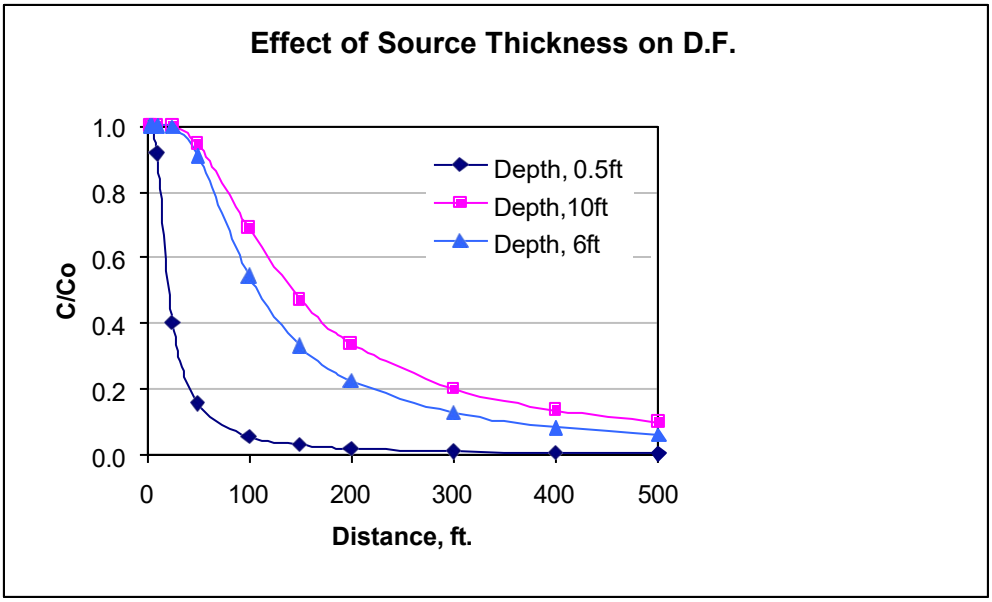


Figure 5b

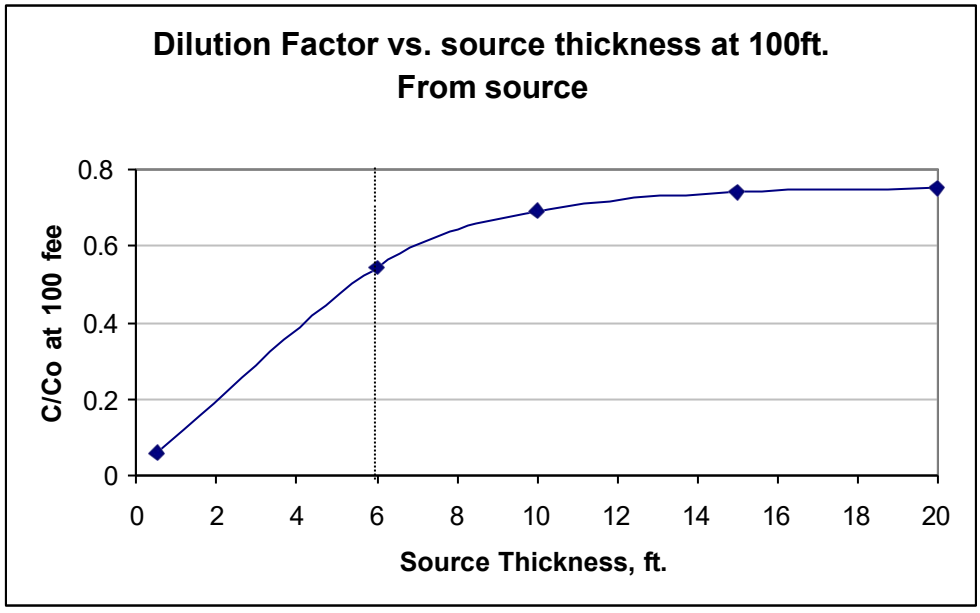


Figure 5b shows the variation of DF at a distance of 100 feet from the source edge. From Figure 5b, it can be seen that the DF does not change significantly at a thickness greater than 6 feet.

CONDITIONS WHERE DFs MAY NOT BE CONSERVATIVE

Based upon the preceding analysis, the use of the Dilution Factor/Curves may not be conservative under the following site conditions:

- The width of the contaminated zone is greater than 60 ft;
- Contaminant transport is occurring in bedrock;
- Contaminant transport is occurring along preferred flow paths; or
- The site otherwise has complex groundwater flow conditions.

CONCLUSIONS

The three source widths of 10 ft, 30 ft and 60 ft should be appropriate for most UST sites in Massachusetts. For sites that have unique conditions, for example, contaminant transport in bedrock, the Dilution Factor/Curves may not be conservative and site-specific modeling/ evaluation is recommended to establish site-specific dilution factors. On the other hand, at sites where flow is occurring in relatively homogeneous and isotropic formations, it should be possible to derive a site-specific dilution factor that is less conservative than the recommended values estimated using the Domenico's equation and yet be protective.

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Appendix 4

MassDEP

Field Assessment and Support Team (FAST)

EVALUATION OF #2 FUEL OIL VAPOR CHEMISTRY

October 2019

CHEMISTRY OF DIESEL/#2FUEL OIL VAPORS

In July 2019, a study was conducted by MassDEP FAST of "fresh" and "weathered" #2/diesel fuel vapors. The "weathered" sample was created by letting the fresh sample volatize in a laboratory hood for several days. Split vapor samples were then injected into Inficon HAPSITE GC/MS units. Units were run in a full scan (45 to 250 AMU). Total Ion Chromatograms from this study are provided in Figures 1 and 2.

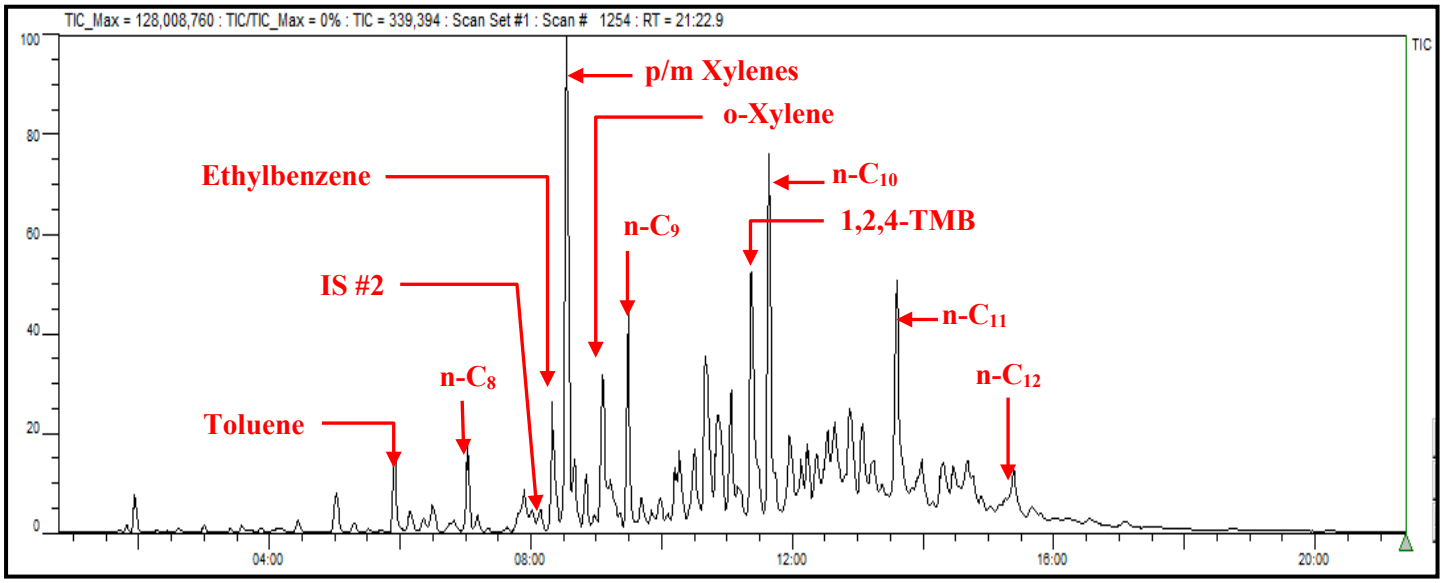


Figure 1 – Total Ion Chromatogram for Fresh #2/Diesel Fuel (HAPSITE ER)

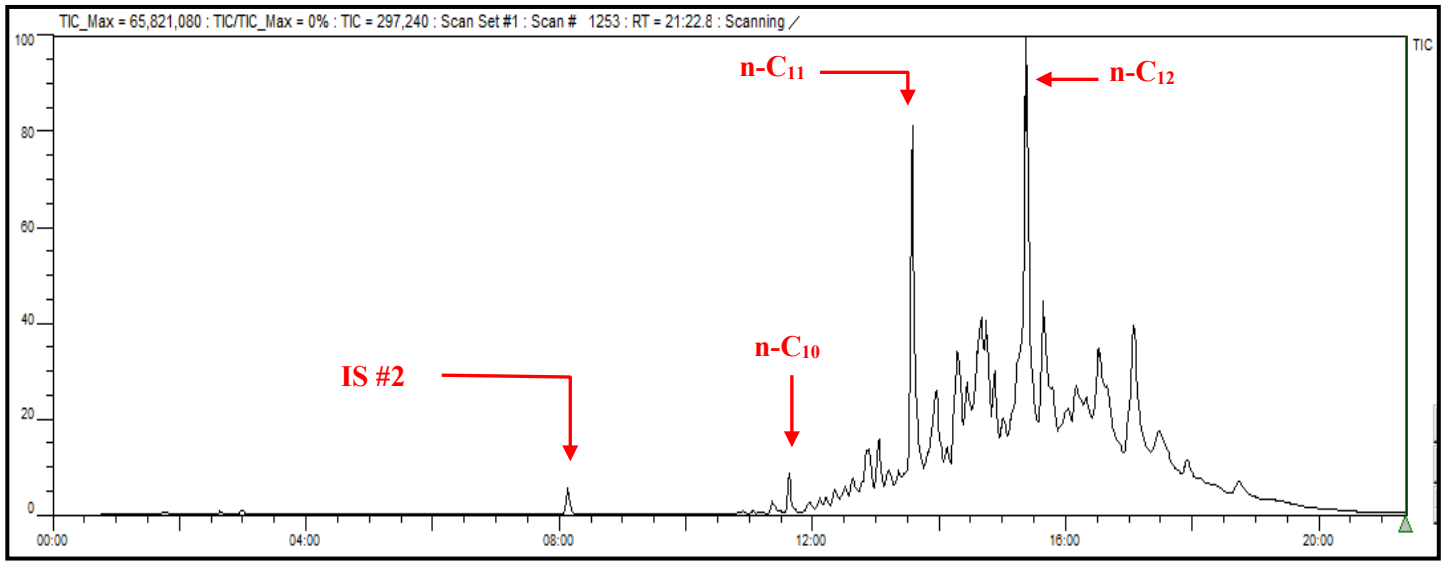


Figure 2 – Total Ion Chromatogram for Laboratory "Weathered" #2/Diesel Fuel (HAPSITE ER)

As can be seen, even for a fresh #2/Diesel fuel, the vast majority of hydrocarbons are greater than n-C_8. In a highly weathered sample, almost all of the hydrocarbons will be heavier than n-C_{10}. In the fresh product, the concentration of the APH Target Analytes (e.g., Toluene, Ethylbenzene, and xylenes) is significant, while they are much lower on the weathered sample. In both samples, the normal alkanes are significant peaks.

A “real world” sample of a (fresh) #2 Fuel Oil spill into a basement in Lowell MA is depicted in Figure 3. The concentration of target analytes in this basement sample is provided in Table 1. A listing of the largest peaks detected and tentatively identified compounds (TIC) in the basement sample total ion chromatogram is provided in Table 2.

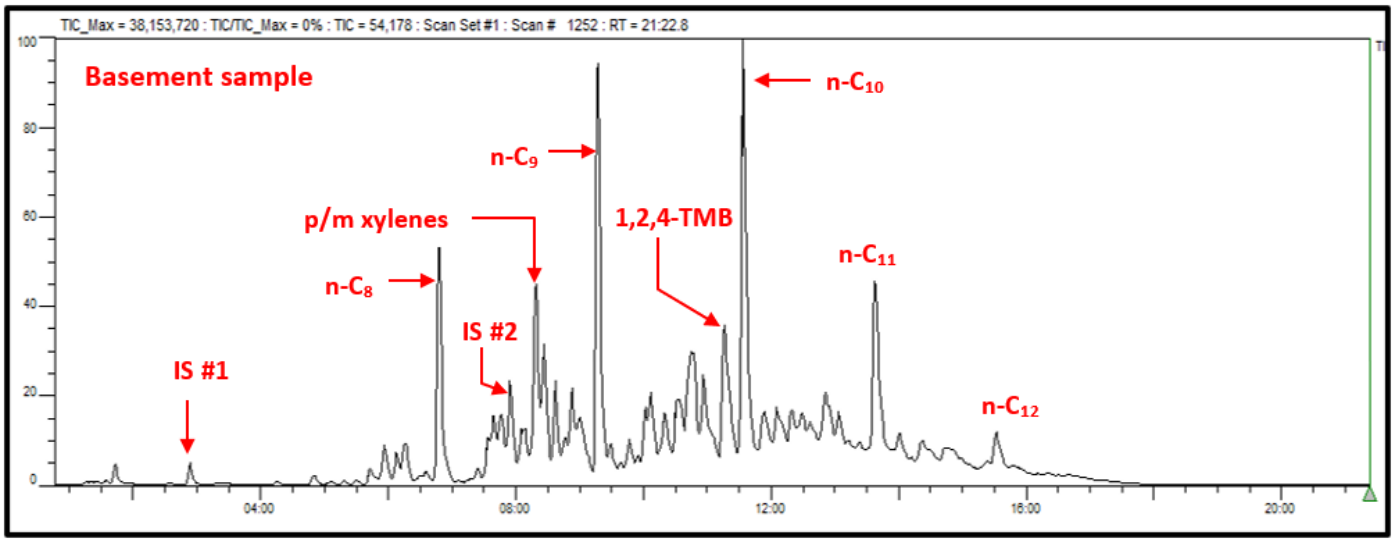


Figure 3 -Total Ion Chromatograms for Indoor Air Sample, Fuel Oil Spill, Lowell MA, 9/24/19

Table 2 - Target Analytes – Lowell MA Oil Spill – 9/24/19				
Analyte	1st Floor Sample µg/m³		Basement Sample µg/m³	
	SP	ER	SP	ER
Benzene	N.D.	N.D.	260	110
Toluene	3.4	2.9	1100	960
Ethylbenzene	6	7	1300	2100
Xylenes	26	31	6300	7200
Styrene	N.D.	N.D.	1200	Purity too low
1,3,5-Trimethylbenzene	12	19	1300	1500
1,2,4-Trimethylbenzene	31	68	2900	3700
Naphthalene (estimate)	2	2.2	11	12

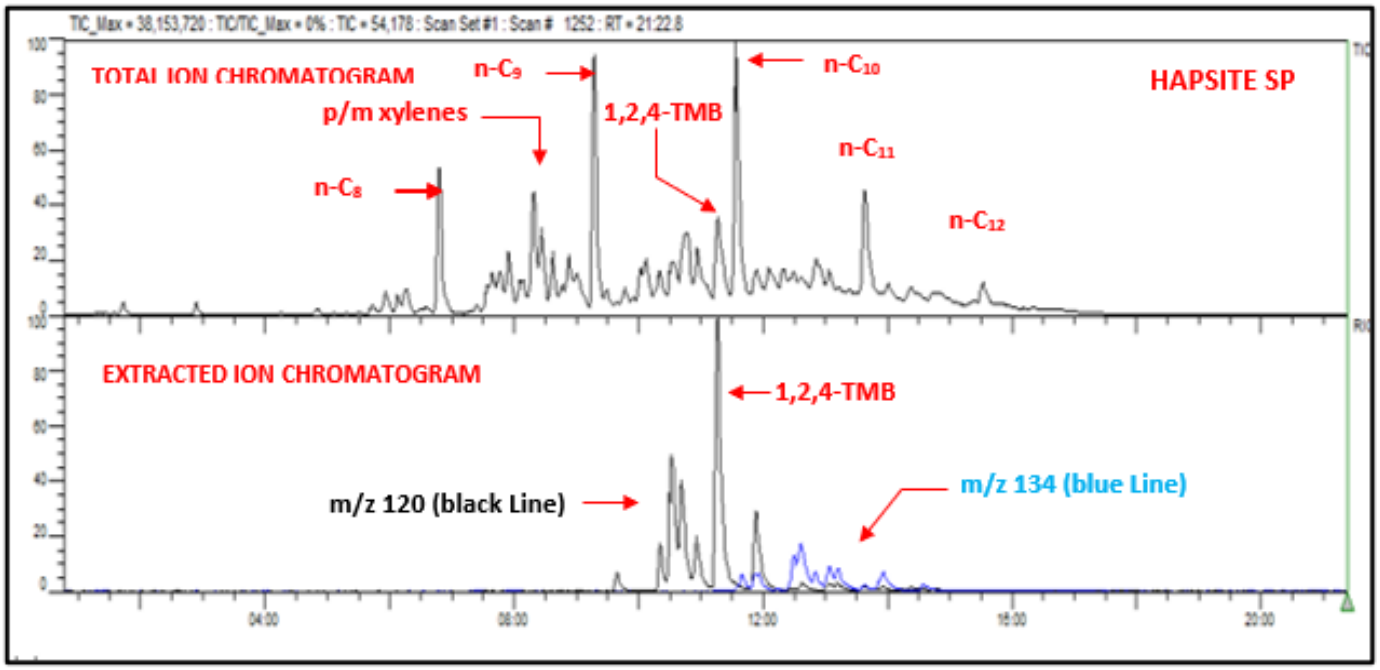
Table 3 – Lowell MA Basement Sample Peak Areas (BTEX, n-C, and > 0.45% compounds on TIC)				
Compound/TIC	HAPSITE SP		HAPSITE ER	
	RT	% Area	RT	% Area
I.S. #1	2:53	0.3	3:01	0.11
Benzene	3:20	0.03	3:26	0.01
n-Heptane	4:15	0.06	4:26	0.04
Toluene	5:42	0.26	5:55	0.14
2-methyl heptane	5:56	0.56	6:09	0.37
Dimethyl cyclohexane	6:15	0.69	6:29	0.51
Octane (n-C_8)	6:47	3.58	7:02	2.23
Ethyl cyclohexane	7:38	0.89	7:53	0.89
C3-cyclohexane	7:46	0.96	8:00	0.68
I.S. #2	7:54	1.22	8:08	0.86
Ethylbenzene	8:06	0.08	8:19	0.66
p/m xylenes	8:19	2.62	8:32	2.19
C9 aliphatic	8:26	1.75	8:39	1.09
C9 aliphatic	8:36	0.88	8:49	0.79
Styrene	8:46	0.1	ND	ND
o-xylene	8:52	0.77	9:05	0.76
C9 aliphatic	9:00	0.94	9:13	0.77
Nonane (n-C_9)	9:17	5.64	9:28	5.4
C9 aliphatic	10:01	0.6	10:11	0.59
C10 aliphatic	10:06	1.07	10:16	0.89
C9 aromatic	10:19	0.71	10:29	0.65
1,3,5-TMB	10:31	0.92	10:39	1.25
C10 aliphatic	10:44	0.18	10:51	2.68
C10 aliphatic	10:56	1.16	11:03	1.16
1,2,4-TMB	11:16	2.72	11:21	2.87
Decane (n-C_{10})	11:33	6.31	11:37	9.78
C9 aromatic	11:53	0.7	11:57	0.92
C11 aliphatic	12:05	0.71	12:07	0.7
C10 aliphatic	12:19	0.51	12:21	0.91
C10 aromatic	12:29	0.47	12:30	0.72
Aromatic	12:37	0.34	12:38	0.74
C10 compound	12:51	1.15	12:51	2.03
C10 Aromatic	13:03	0.48	13:03	0.77
Undecane (n-C_{11})	13:37	3.14	13:35	6.71
C11 Aromatic	14:00	0.32	13:57	0.99
Dodecane (n-C_{12})	15:32	0.86	15:22	2.27
Tridecane (n-C_{13})	ND	ND	17:05	0.44
Table Summation		44		55
Summation all HAPSITE peaks		46		62

Observations and conclusions on the above include:

- The "real word" basement sample total ion chromatogram in Figure 3 is consistent with a relatively fresh fuel oil (Figure 1), which is consistent with the recent spill event at the home in question. Of note are the lower levels of Toluene, Ethylbenzene, and Xylenes in the basement sample - perhaps because of volatilization losses of these aromatics, or perhaps because of their lower presence in the particular fuel oil spilled at the Lowell home.
- As in the "fresh" lab sample, the "real world" basement sample is dominated by the normal alkanes n-C_8 through n-C_{11}, consistent with published compositional data on #2/diesel fuels (e.g., TPHWG, 1998). As indicated in Table 3, 34 specific compounds comprised about 50% of the total ion chromatograms (44% on the SP, 55% on the ER). The normal alkanes n-C_8 through n-C_{11} comprised 19% of the SP chromatogram, and 24% of the ER chromatogram.
- There are relatively few peaks prior to n-Octane. The early eluting aliphatic peaks appear to be composed primarily of branched and cyclic alkanes, consistent with the predominance of these structures in gasoline and fuel oils.
- The most prominent C_9-C_{10} aromatic compound is 1,2,4-Trimethylbenzene (in both the fresh sample and basement sample), which is present at more than twice the concentration of any other C_9-C_{10} aromatic.
- With its higher sensitivity to heavier compounds, the ER unit was able to adequately resolve n-C_{13} (at 17:05).

C_9-C_{10} Aromatic Hydrocarbons

the presence of extracted ions m/z 120 and m/z 134 in the Lowell basement fuel oil sample – indicative of an aromatic structure -is presented below in Figure 4, and the peak distributions on the total ion chromatogram area analyzed in Table 4.



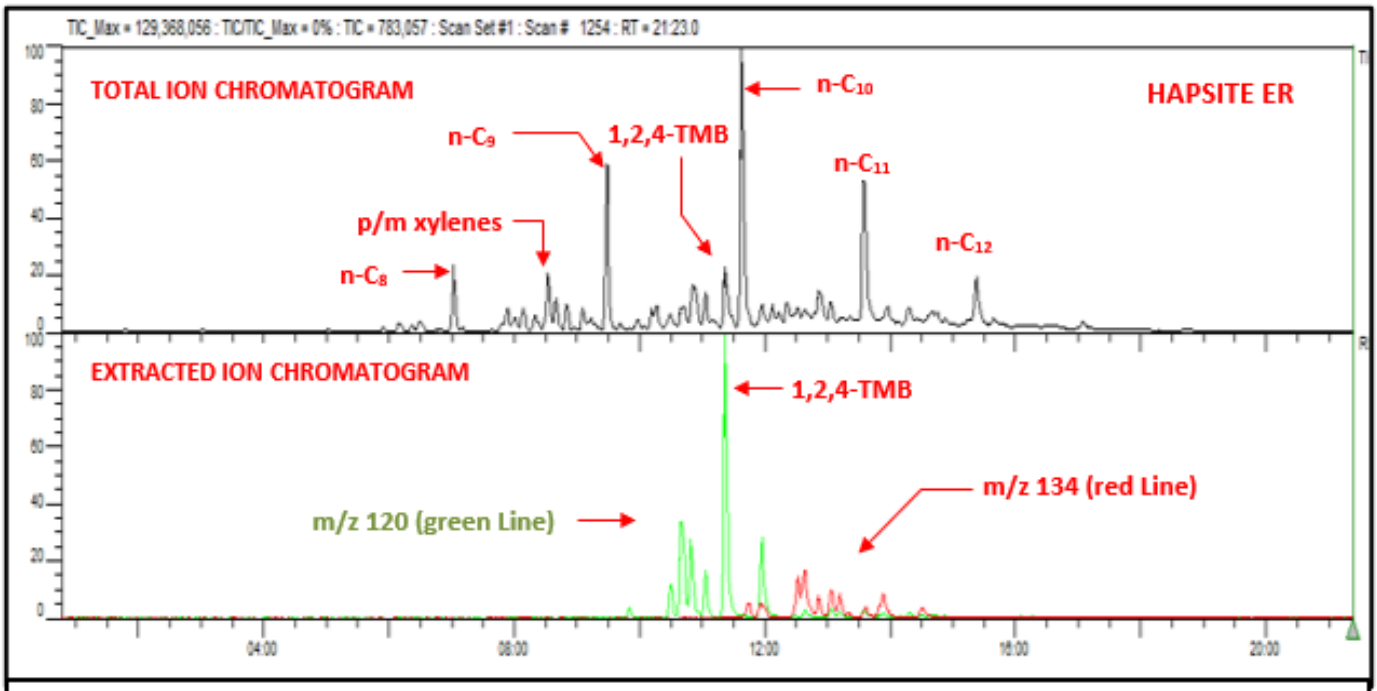


Figure 4 – Lowell Fuel Oil Basement Sample -Total and Extracted Ion Chromatograms

Table 4: Lowell Basement Fuel Oil Sample Peak TIC and RIC Areas (BTEX, n-C, and > 0.45% TIC)								
Compound	HAPSITE SP				HAPSITE ER			
	RT	% of total (TIC + m/z)			RT	% of total (TIC + m/z)		
		TIC	120	134		TIC	120	134
I.S. #1	2:53	0.3			3:01	0.11		
Benzene	3:20	0.03			3:26	0.01		
Heptane	4:15	0.06			4:26	0.04		
Toluene	5:42	0.26			5:55	0.14		
2-methyl heptane	5:56	0.56			6:09	0.37		
Dimethyl cyclohexane	6:15	0.69			6:29	0.51		
Octane (n-C_8)	6:47	3.58			7:02	2.23		
Ethyl cyclohexane	7:38	0.89			7:53	0.89		
C3-cyclohexane	7:46	0.96			8:00	0.68		
I.S. #2	7:54	1.22			8:08	0.86		
Ethylbenzene	8:06	0.08			8:19	0.66		
p/m xylenes	8:19	2.62			8:32	2.19		
C9 aliphatic	8:26	1.75			8:39	1.09		
C9 aliphatic	8:36	0.88			8:49	0.79		
Styrene	8:46	0.1			ND	ND		
o-xylene	8:52	0.77			9:05	0.76		
C9 aliphatic	9:00	0.94			9:13	0.77		
Nonane (n-C_9)	9:17	5.64			9:28	5.4		
C9 aliphatic	10:01	0.6			10:11	0.59		
C10 aliphatic	10:06	1.07			10:16	0.89		
C9 aromatic	10:19	0.71	3.29		10:29	0.65	3.56	
1,3,5-TMB	10:31	0.92	15.18		10:39	1.25	15.3	
C10 aliphatic	10:44	0.18			10:51	2.68		
C10 compound	10:56	1.16	5.49		11:03	1.16	5.36	
1,2,4-TMB	11:16	2.72	31.94		11:21	2.87	33.2	
Decane (n-C_{10})	11:33	6.31			11:37	9.78		
C9 aromatic	11:53	0.7	10.48		11:57	0.92	11.2	
C11 aliphatic	12:05	0.71			12:07	0.7		
C10 aliphatic	12:19	0.51			12:21	0.91		
C10 aromatic	12:29	0.47	0.26	9.5	12:30	0.72	0.28	10.42
Aromatic	12:37	0.34	1.13	20.17	12:38	0.74	1.24	19.1
C10 compound	12:51	1.15		4.76	12:51	2.03		5.2
C10 Aromatic	13:03	0.48	0.85	6.51	13:03	0.77	1.28	8.37
Undecane (n-C_{11})	13:37	3.14	0.58		13:35	6.71	0.62	
C11 Aromatic	14:00	0.32	0.15		13:57	0.99	N.D.	
Dodecane (n-C_{12})	15:32	0.86			15:22	2.27		
Tridecane (n-C_{13})	ND	ND			17:05	0.44		
Table Summation		44	69	41		55	72	43
Summations All Peaks		46	86	76		62	88	84

On the of the above, the following conclusions were made:

- The concentration of vapor-phase C5-C8 Aliphatics is expected to be in the range of 10 to 20% of the total ion chromatograms, with 15% a reasonable average.
- The concentration of vapor-phase C9-C10 Aromatics is expected to be in the range of 15 to 25% of the total ion chromatogram, with 20% a reasonable average
- The target analytes BTEX and naphthalene are expected to be less than 1% by volume
- The remainder of the vapors, about 60% of the total ion chromatogram, is expected to be C9-C12 Aliphatics

Appendix 5

Study of Residential Fuel Oil Spills

John Fitzgerald, MassDEP

April 2007

SUMMARY OF EFFORT

During April 2007, the writer retrieved and reviewed files in MassDEP Northeast Regional Office (NERO) for residential sites contaminated by a release of #2 fuel oil. The objective of this effort was to obtain a general sense of the nature and extent of residential fuel oil spills and remedial approaches, and assemble readily available EPH soil testing data, preferably in combination with PID Jar Headspace, VPH, and/or Petroflag data (i.e., split samples).

A printout of residential/fuel oil sites for which closure had been filed in the past 3 years was obtained. The 3-year timeframe was selected to focus on current trends, and, with respect to data mining, to get the best quality analytical data. An initial universe of 72 candidate sites were selected, on the basis of the reported volume of oil released, given the expectation that larger release volumes would likely mean a larger amount of soil test data. Of this universe, 7 site files could not be located, and 41 files did not have a significant amount of relevant and/or readily digestible (i.e., tabulated) data. The remaining 24 files contained the desired data in the desired format. During the course of evaluation, however, all data from one of these sites was rejected, due to a confusing sample naming convention and an unusually large amount of data anomalies.

The final listing of evaluated sites is provided in Table 1. In total, 23 sites files were reviewed, containing reports by 15 different consultants/contractors, and 378 EPH data sets in some combination with other analytical parameters. Data plots and tabulations are provided in attached figures and tables.

SUMMARY OF FINDINGS

Release and Site Conditions

- ☞ The cause of fuel oil releases at residential sites were predominantly due to holes in or ruptures of a free-standing Aboveground Storage Tank (AST); leakage from a buried transfer line; damage to the oil filter/outlet apparatus on an AST; and delivery of oil to fill pipes that were not connected to an AST.
- ☞ Assessment activities often involved soil borings, soil vapor points, and groundwater sampling points.
- ☞ The typical remedial response was excavation of soil, usually limited but occasionally extensive, followed in some cases by the addition of a chemical oxidant, usually hydrogen peroxide, or the addition of an oxygen-releasing compound (ORC).
- ☞ The level of effort expended in assessment and remedial efforts appears to be bi-modal - either “feast or famine” - and is likely a function of the availability of insurance funds.

Analytical Testing Data

Nature and Use of Data

- ☞ Of the 378 EPH data sets reviewed, 228 (61%) reported Not Detected, reflective of the fact that most EPH soil samples are obtained to confirm a "clean closure" condition. In this paper, the primary use and utility of Not Detected data are to evaluate "false positive" or "false negative" correlations with field screening results.
- ☞ Of the 378 EPH data sets reviewed, 150 had measurable concentrations of hydrocarbon fractions and/or Target (PAH) Analytes. In this paper, these data were used to evaluate sample chemistry, correlations between total hydrocarbons and Target (PAH) Analytes, and correlations with PID and/or Petroflag screening data.
- ☞ Associated with the 378 EPH data sets were 162 VPH (split-sample) data sets. Similar to the EPH data, about 60% of the VPH spilt-sample data sets were below or near Reporting Limits. On many occasions, VPH sample data were obtained even when soil headspace concentrations were well below the 100-ppmV threshold specified in the VPH/EPH Policy. The VPH data were used to evaluate correlations with EPH results, and review whether current headspace guidance is appropriate.

Data Correlations

- ☞ As expected, the overall correlations between comparative data parameters is not good. This is due to the nature of fuel oil as a complex, variable mixture, further complicated by site-specific weathering processes, split-sample homogenization issues, analytical variability, and, in the case of headspace screening, likely issues with operational efficacy of PID field instrumentation.
- ☞ Notwithstanding these limitations, overall trends and outer limits are discernable, especially within large data sets, with a given level of accuracy and uncertainty. Such findings have relevance and value in understanding and planning field investigative programs.

Aliphatic and Aromatic Fractions

- ☞ Of the 378 EPH data sets reviewed, 145 had measurable concentrations of hydrocarbons in the aliphatic and/or aromatic hydrocarbon fractions. Within this universe of data, there was good correlations between the chemistry of soil samples, with respect to the ratio of aliphatic and aromatic hydrocarbon fractions:
    - 46%: C9-C18 Aliphatic Hydrocarbons (%RSD = 30)
    - 19%: C19-C36 Aliphatic Hydrocarbons (%RSD = 44)
    - 34%: C11-C22 Aromatic Hydrocarbons (%RSD = 30)
    - 1%: Target (PAH) Analytes (%RSD = 2)

  This finding is consistent with the expected makeup of a moderately weathered #2 fuel oil, i.e., lower levels of the more volatile and biodegradable C9–C18 Aliphatic Hydrocarbons (typically around 60% of a fresh fuel oil) with commensurate relative

increases in the proportions of the more recalcitrant heavier aliphatic and aromatic hydrocarbon fractions.

- ☞ The observed proportions of hydrocarbon fractions suggest that a total EPH (or TPH) soil concentration of 500 mg/kg or less would likely equate to conditions that would be below all S-1 soil EPH cleanup standards (given that the most stringent S-1 fractional standard is for C11-C22 Aromatic Hydrocarbons, and assuming that fraction comprises about 1/3 of a total EPH or TPH value).

Individual PAH Analytes

- ☞ A significant number of EPH data sets included all (17) priority-pollutant/Method 1 PAH analytes, as opposed to the 4 fuel oil Target Analytes recommended by the VPH/EPH Policy, i.e., acenaphthene, phenanthrene, naphthalene, and 2-metylnaphthalene. In most cases, these additional PAH analytes were not detected; in a few cases, although detections were noted, they appeared more related to pyrogenic (not petrogenic) source, such as ash, cinders, or "urban fill".
- ☞ Acenaphthene was not reported to be present in contaminated soils in excess of 10 mg/kg, even when total EPH values exceeded 10,000 mg/kg. The lowest Method 1 soil standard for this compound (S-1/GW-1) is 20 mg/kg.
- ☞ Phenanthrene was not reported to be present in contaminated soils in excess of 30 mg/kg, even when total EPH values exceeded 10,000 mg/kg. The lowest Method 1 soil standard for this compound (S-1/GW-3) is 100 mg/kg.
- ☞ Both Naphthalene and 2-Methylnaphthalene were not reported to be present above 4 mg/kg in soils that contained less than 2000 mg/kg total EPH. The lowest Method 1 soil standard for both compounds (S-1/GW-1) is currently 4 mg/kg.
- ☞ Proposed changes to the MCP would lower the S-1/GW-1 standard for 2-Methylnaphthalene to 0.7 mg/kg. Based upon data reviewed during this effort, of 38 soil samples containing between 150 and 300 mg/kg total EPH, 22 exceeded 0.7 mg/kg of 2-Methylnaphthalene. Above 300 mg/kg of total EPH, 94 of 108 soil samples exceeded 0.7 mg/kg of 2-Methylnaphthalene. This finding suggests that lowering the 2-Methylnaphthalene standard to 0.7 mg/kg will force many sites to use a Method 2 risk assessment approach.

VPH Data

- ☞ Of the 162 VPH and EPH split samples, 141 data sets included jar headspace results. Of these 141 samples, 110 reported PID headspace screening results less than 100 ppmV, the threshold reading at which DEP requires testing by the VPH method for fuel oil contaminated soil samples. This indicates that many parties are testing via VPH when not mandated by agency guidance.
- ☞ Of the 110 VPH samples with reported PID headspace reading of less than 100 ppmV:
  - ➢ All VPH Target Analytes (MtBE and BTEX), when detected, were present well below their most stringent Method 1 soil cleanup standards (i.e., S-1/GW-1);

- All reported detections of C9-C12 Aliphatic Hydrocarbons were below its most stringent Method 1 soil cleanup standard (1000 mg/kg);
- 107 of 110 samples reported concentrations of C5-C8 Aliphatic Hydrocarbons less than its most stringent Method 1 cleanup standard (100 mg/kg);
- 100 of 110 samples reported concentrations of C9-C10 Aromatic Hydrocarbons less than its most stringent Method 1 cleanup standard (100 mg/kg):
  - Of the 10 samples where concentrations of C9 – C10 Aromatic Hydrocarbons exceeded 100 mg/kg, 9 contained concentrations of C11-C22 Aromatic Hydrocarbons (via EPH method) in excess of its most stringent Method 1 cleanup standard (200 mg/kg), indicating that such problematic levels of aromatic hydrocarbons would have been identified in the mandatory EPH samples, and that use of the VPH test method was unnecessary. The single exception (site 3-24,734) appears to an analytical reporting error or anomalous data point, given the low concentrations of C11-C22 Aromatic Hydrocarbons (39.1 mg/kg) relative to the reported concentrations of C9-C18 Aliphatic Hydrocarbons (179 mg/kg) and C19-C36 Aliphatic Hydrocarbons (117 mg/kg).
  - On average, and consistent with product chemistry, the concentrations of C11-C22 Aromatic Hydrocarbons were 4.1 times higher than the reported concentrations of C9-C10 Aromatic Hydrocarbons. This ratio would tend to increase with time as the product weathers in the environment.
  - Due to a systemic bias in the VPH test method, it is likely that the ratio of C11-C22 Aromatic Hydrocarbons to C9-C10 Aromatic Hydrocarbons is even greater than the above finding would suggest. Specifically, the VPH method use a Photoionization Detector (PID) to quantify eluting compounds as aromatic in nature, given the increased sensitivity of these compounds to a PID. While PID response to aliphatic compounds is substantially less, it is nonetheless measurable, and, when numerous aliphatic compounds are present in this elution range (as in the case of #2 Fuel Oil), the collective aliphatic response (quantified by the method as C9 – C10 Aromatic Hydrocarbons) can become appreciable. This further reinforces to finding that use of the VPH test method is unnecessary when total PID headspace vapor concentrations are less than 100 ppmV.

Naphthalene

- Naphthalene is a Target Analyte in both the VPH and EPH methods. In both procedures, accurate quantification is challenging. In the VPH method, naphthalene is prone to under-reporting, given purging difficulties, while at the same time being prone to over-quantification, given co-elution of non-aromatic peaks. This bias is likely to be more pronounced in fuel oil than in gasoline contaminated samples, given the prevalence of C9-C12 Aliphatic Hydrocarbons in #2 fuel oil, and more pronounced in soil samples than groundwater samples, given the limited solubility of C9-C12 Aliphatic Hydrocarbons. Conversely, in the EPH method, naphthalene is more likely to be reported with a negative bias, given losses during extract concentration and silica gel fractionation processes.

- ☞ In this evaluation, there were 153 split soil samples analyzed by both VPH and EPH test methods. Most of these split samples reported naphthalene below or near detection limits, in one or both test methods. However, 36 data sets reported naphthalene concentrations at or above 0.5 mg/kg (greater than virtually all indicated Reporting Limits). Within this comparison set, higher naphthalene concentrations were reported via the VPH procedure in 32 samples (i.e., 89% of the split samples). Generally, reported naphthalene concentrations via the VPH methods were 1-3 times higher than values reported in split-samples by the EPH method.
- ☞ Given the controls that are now in place within the EPH method to limit and monitor naphthalene losses (i.e., use of matrix and fractionation surrogates), the degree of magnification of naphthalene concentrations in split samples analyzed by the VPH method suggests a systemic analytical bias within the VPH method, with respect to soil samples contaminated by fuel oil. In the case of split samples, the EPH quantification of naphthalene would appear to be more accurate than the VPH procedure.

PID Headspace Screening Data

- ☞ In total, 357 EPH data sets had associated PID headspace results for split samples.
- ☞ Although the overall correlation between PID headspace and Total EPH was not good (R^2 of approximately 0.1), only 7 of 225 soil samples with a jar headspace of less than 10 ppmV exceeded a total EPH concentration of 500 mg/kg, suggesting that headspace concentrations less than 10 ppmV will likely conform to all EPH and Target Analyte Method 1 standards, with a low (< 5%) probability of "false negatives".
- ☞ An increased rate of "false positive" results were noted for higher headspace readings. Specifically, 11 of 43 soil samples with PID headspace values greater than 100 ppmV had total EPH concentrations of less than 500 mg/kg.

Petroflag Screening Data

- ☞ In total, 44 EPH data sets had associated Petroflag results for split samples.
- ☞ In general, Petroflag data displayed a positive-bias, without evidence of false negative reporting. On the low end, 16 Petroflag values were less than 100 mg/kg, all correlating to a Not Detected EPH test data result. With respect to false positives, 4 of 25 EPH "Not Detected" data points correlated with elevated levels (> 300 mg/kg) via the Petroflag method. Of 5 Petroflag results indicating > 2000 mg/kg, one EPH value was less than 2000 mg/kg (460 mg/kg).

CONCLUSIONS

1. There is considerable variability in responses to releases of fuel oil at residential sites, which appears to be primarily a function of the availability of funds (e.g., via insurance settlements).
2. Parties at fuel oil contaminated sites are consistently and unnecessarily analyzing soil samples by the VPH test method when jar headspace PID concentrations are less than 100 ppmV, in contravention to the recommendations contained in the VPH/EPH Implementation Policy.
3. Parties at fuel oil contaminated sites are on occasion unnecessarily analyzing soil samples for the presence of all Method 1/priority pollutant PAH compounds, in contravention to the recommendations contained in the VPH/EPH Implementation Policy.
4. Fuel-oil contaminated soil with less than 500 mg/kg of total hydrocarbons is unlikely to contain concentrations of hydrocarbon fractions or Target Analytes in excess of any Method 1 cleanup standard.
5. Fresh to moderately-weathered fuel-oil contaminated soil with less than 10 ppmV PID jar headspace vapor concentrations is unlikely to contain concentrations of hydrocarbon fractions or Target Analytes in excess of any Method 1 cleanup standard.
6. The VPH Method will generally over-quantify naphthalene in fuel oil contaminated soil samples; more accurate results can generally be obtained using the EPH test method.
7. Acenaphthene and Phenanthrene are almost never an issue or driver in the cleanup of fuel oil contaminated soils.
8. Naphthalene and 2-Methylnaphthalene are unlikely to exceed any Method 1 soil cleanup standard when total hydrocarbon concentrations are less than 2000 mg/kg.

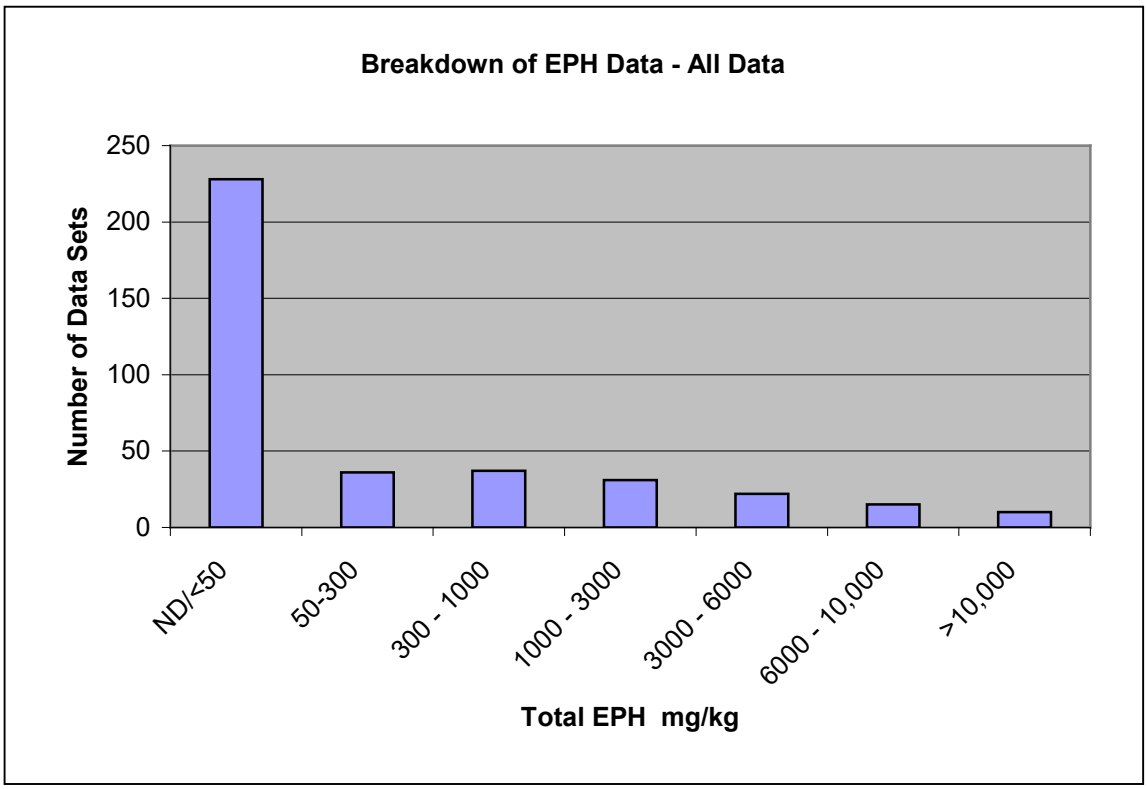
LIMITATIONS AND UNCERTAINTIES

The findings and conclusions of this effort are biased and limited in the following respects:

- ☞ Observations and data were obtained from files covering significant spill events at residential sites in only one region/area of the state.
- ☞ Data values were taken directly from tabular report summations without independent verification from laboratory report sheets.
- ☞ Assumptions were made that split samples were properly obtained and/or homogenized.
- ☞ Assumptions were made that screening headspace data were obtained via the MassDEP jar headspace procedure, utilizing a properly cleaned and calibrated PID unit.

DATA PLOTS AND TABULATIONS

Detailed data plots are provided in Figures 1 through 9. Tabulations of all data referenced in this report are provided in Tables 1 through 4.



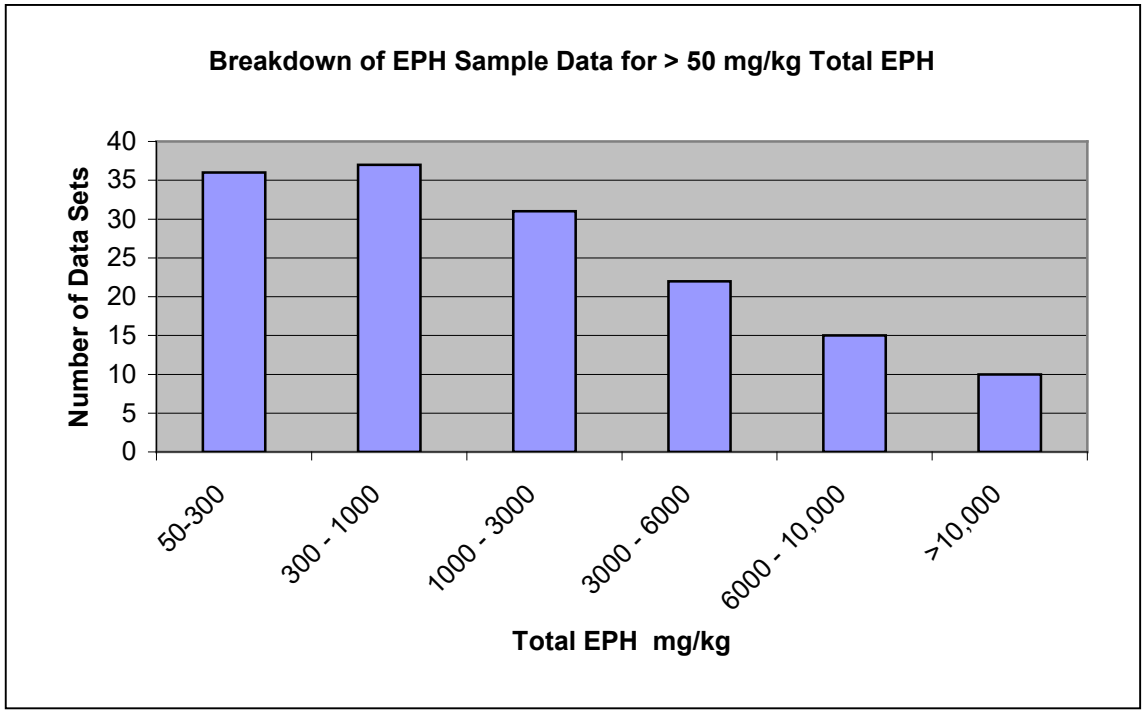
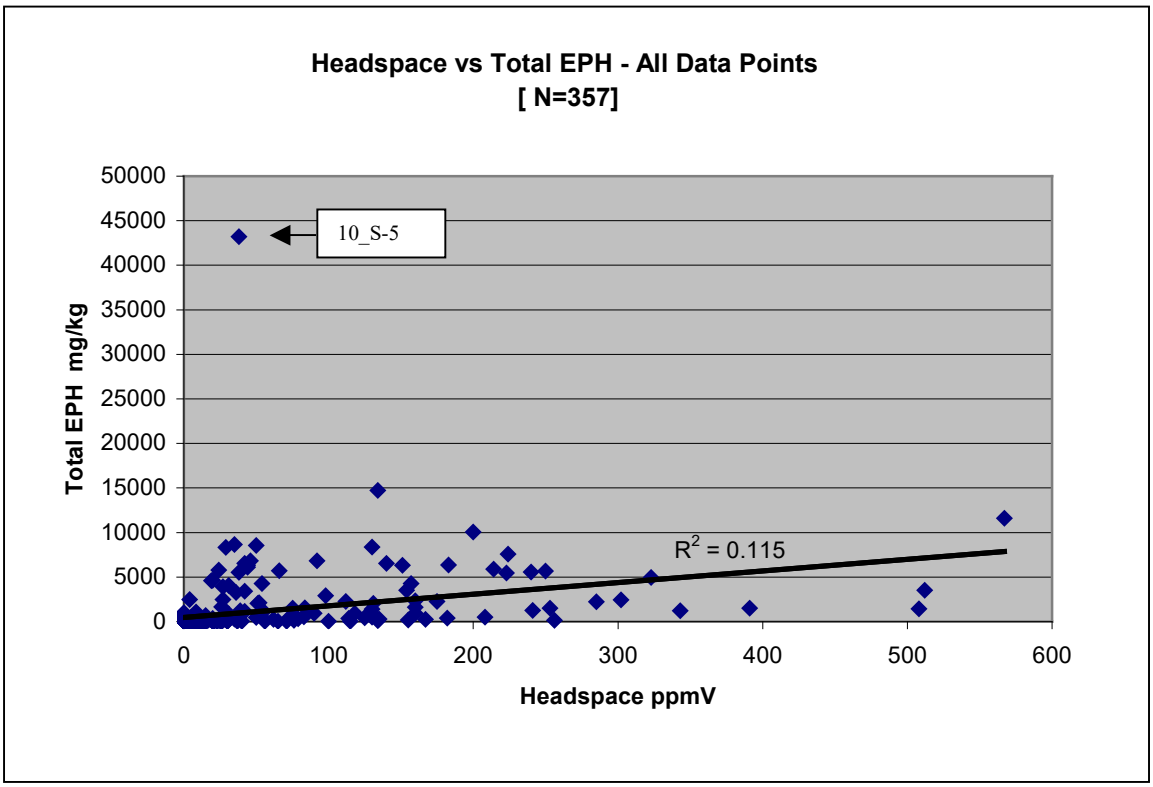


Figure 1 – Breakdown of EPH Data Sets



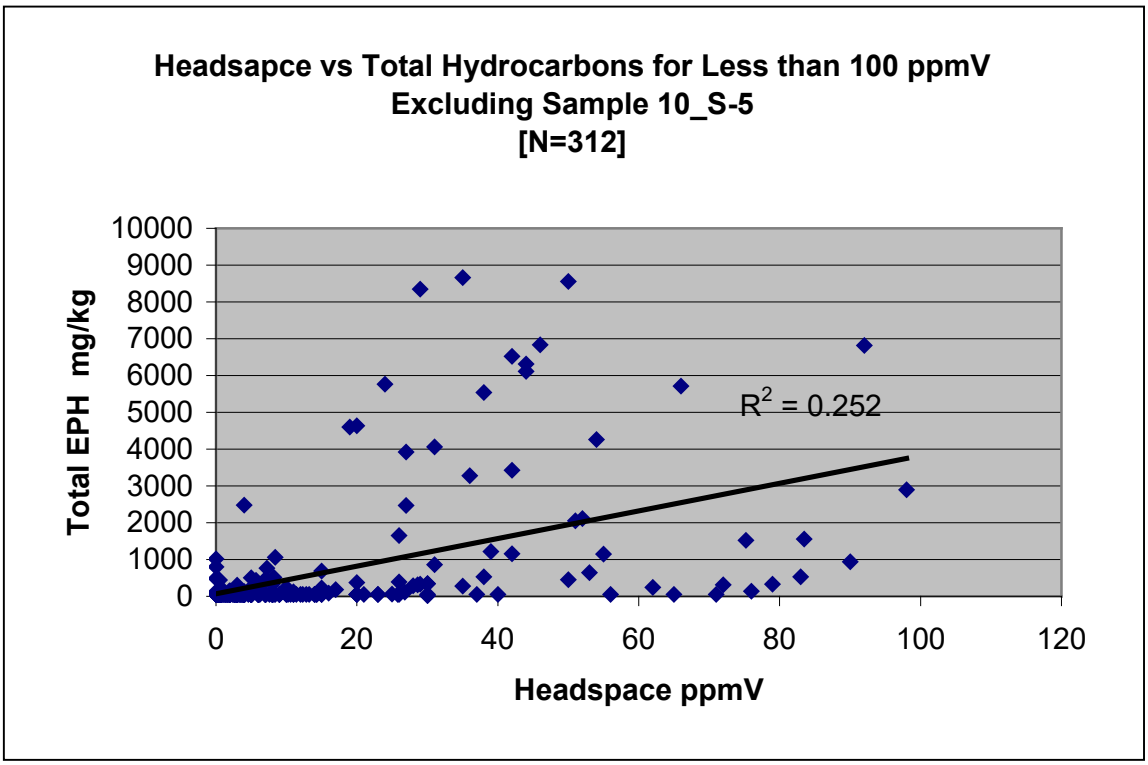
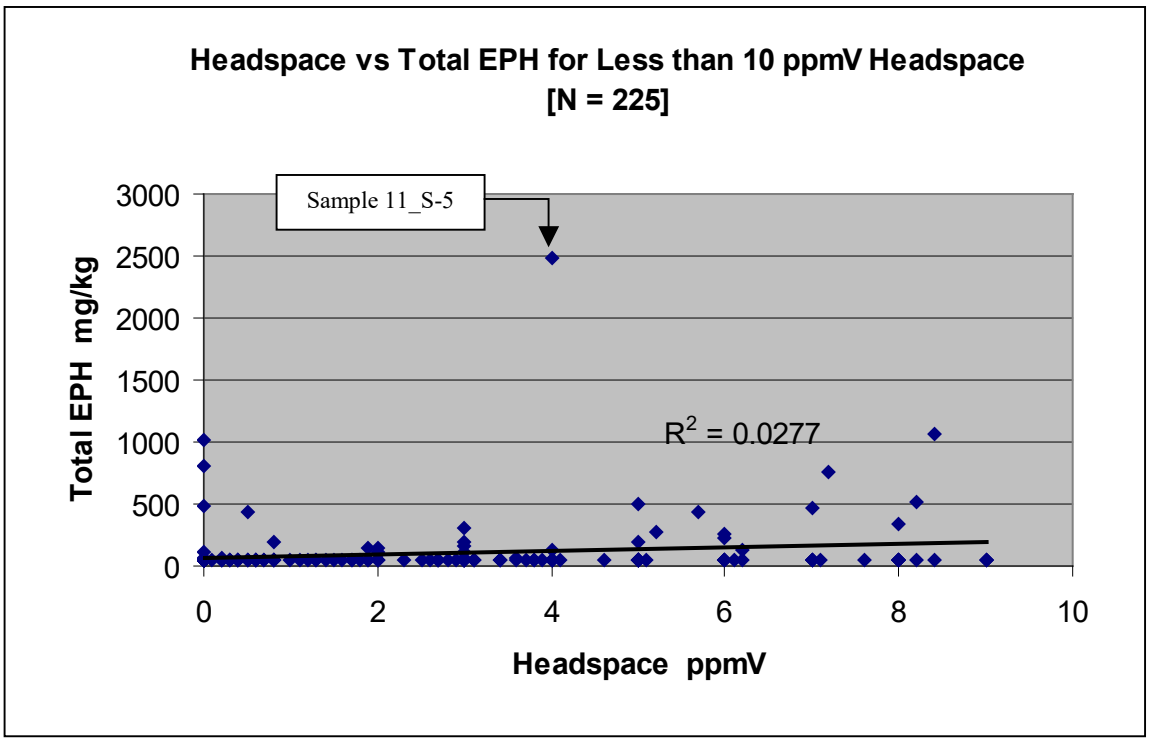


Figure 2 – Headspace vs Total EPH



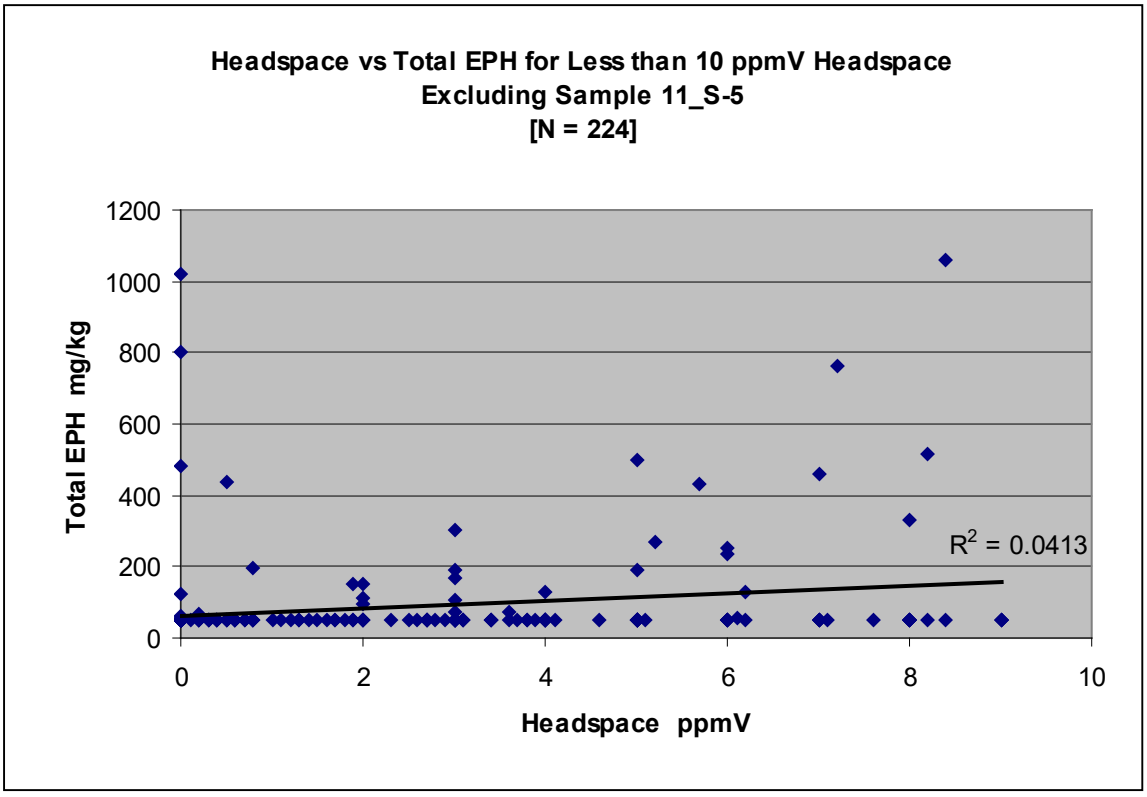
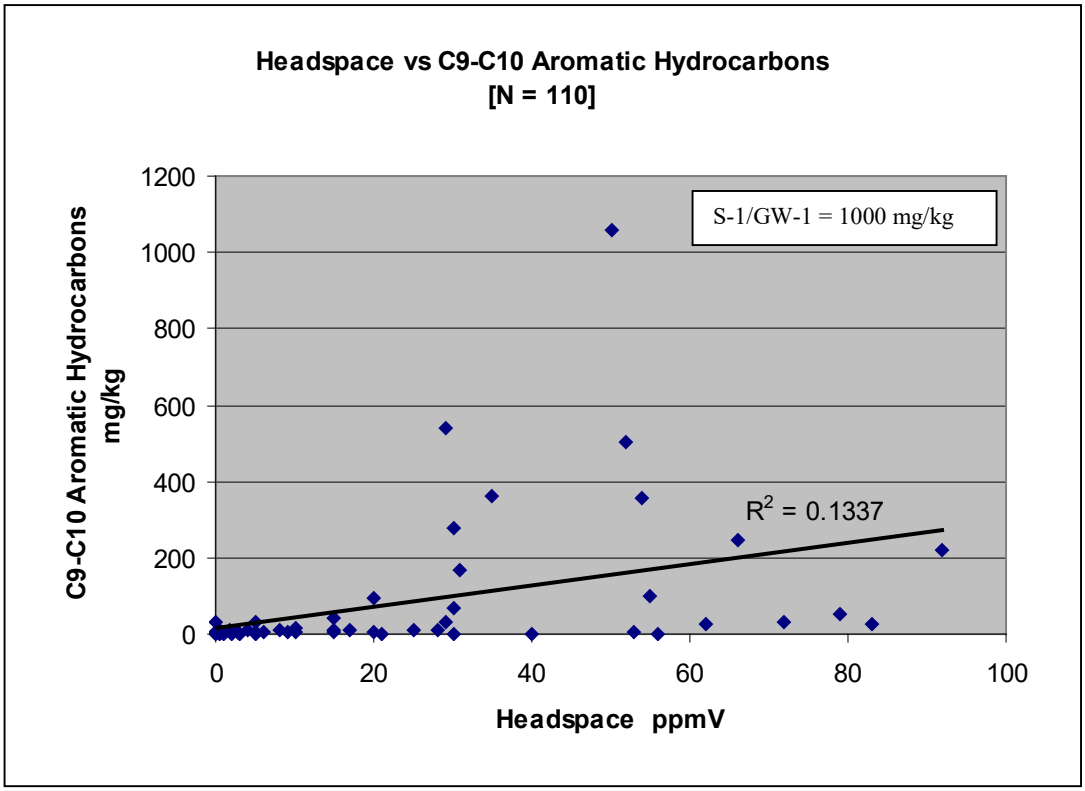


Figure 3 – Headspace vs. Total EPH for Headspace less than 10 ppmV



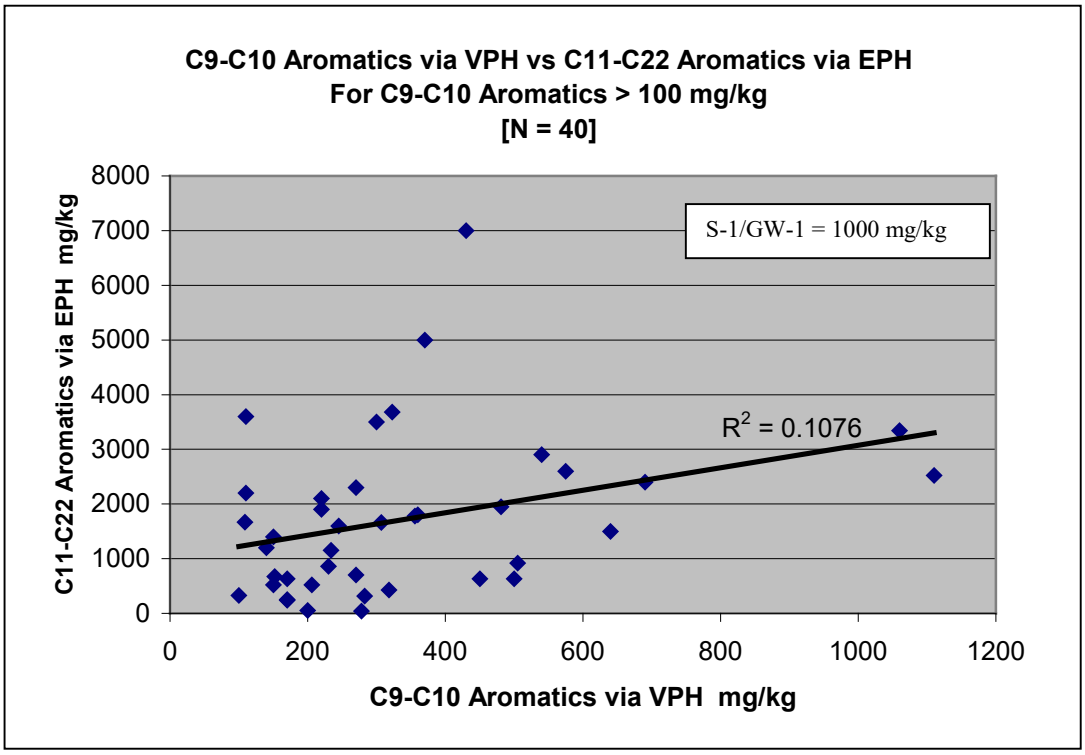
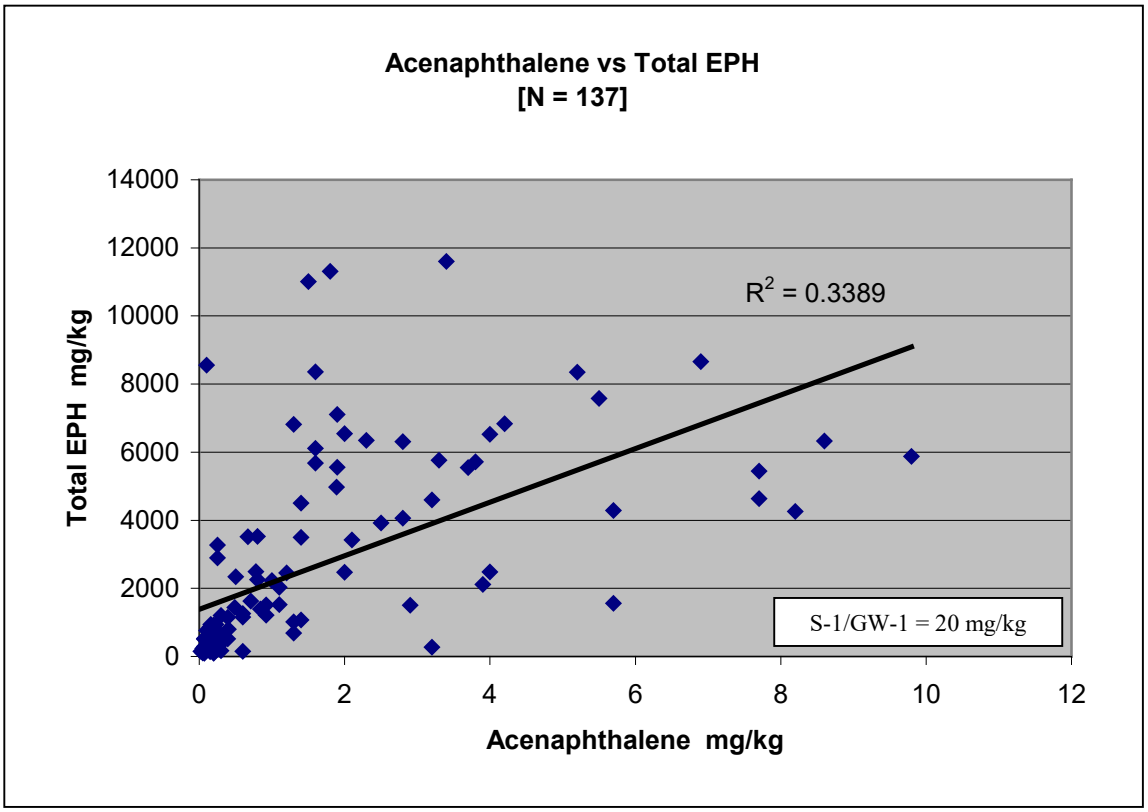


Figure 4 – C9-C10 Aromatic Hydrocarbons



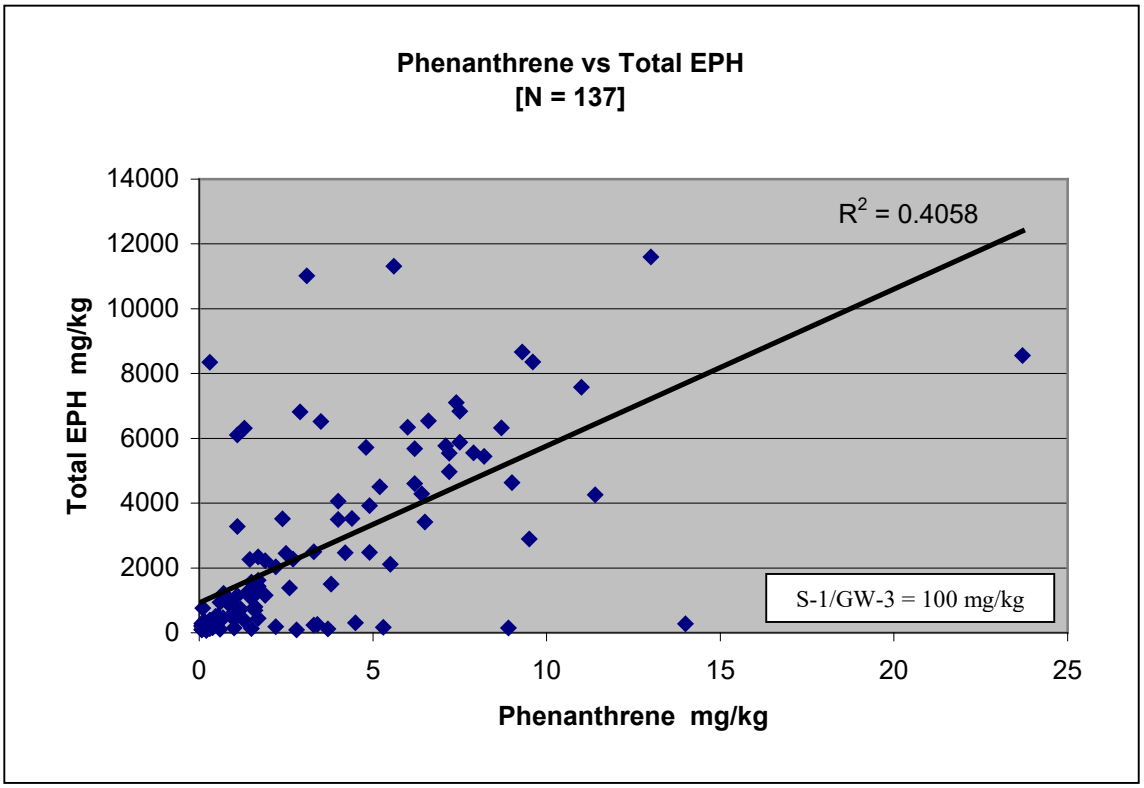
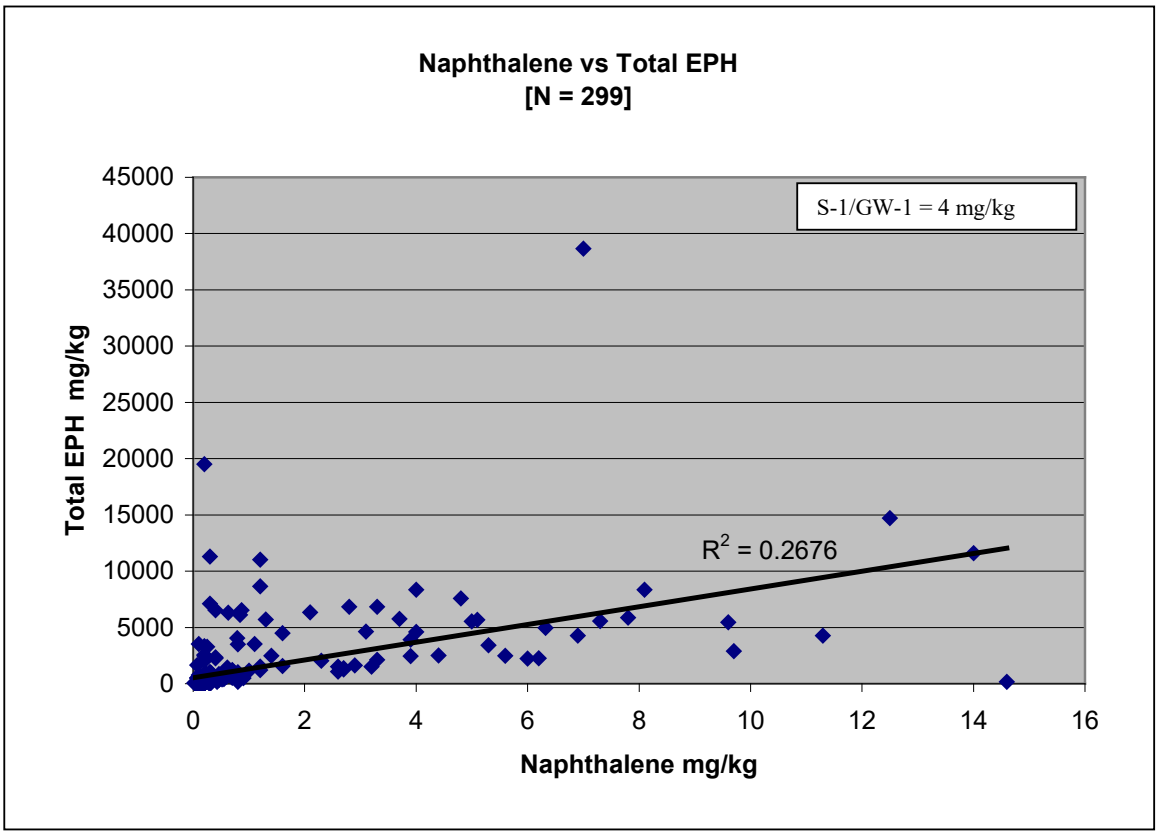


Figure 5 – Total EPH vs Acenaphthene and Phenanthrene



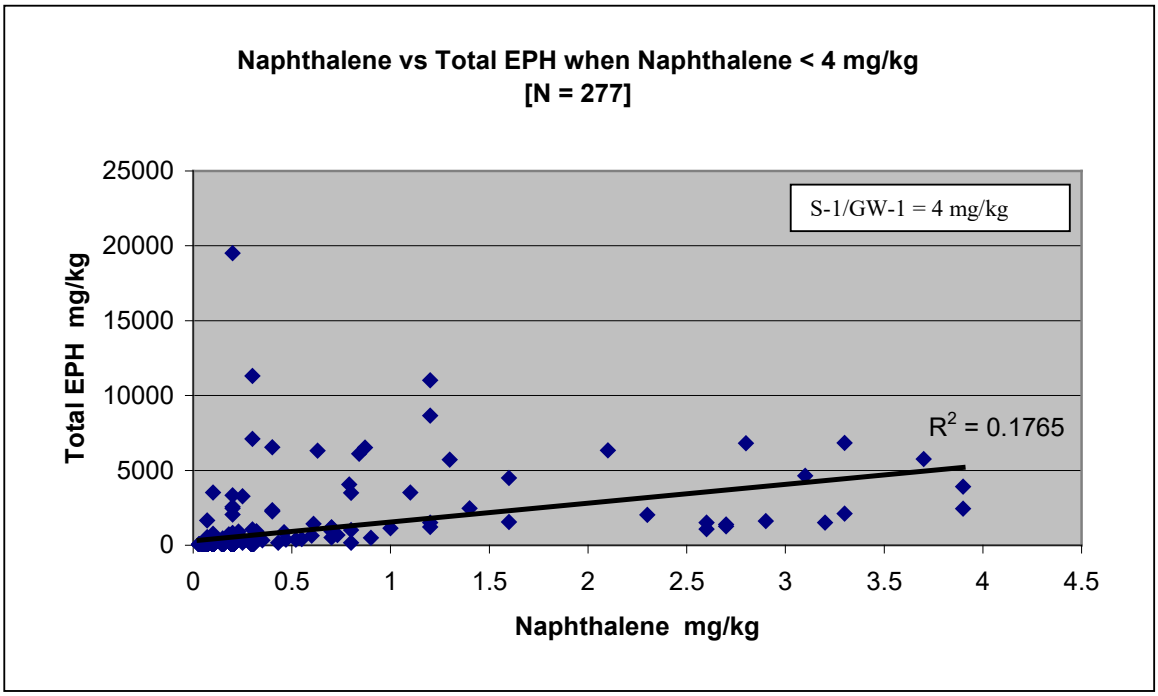
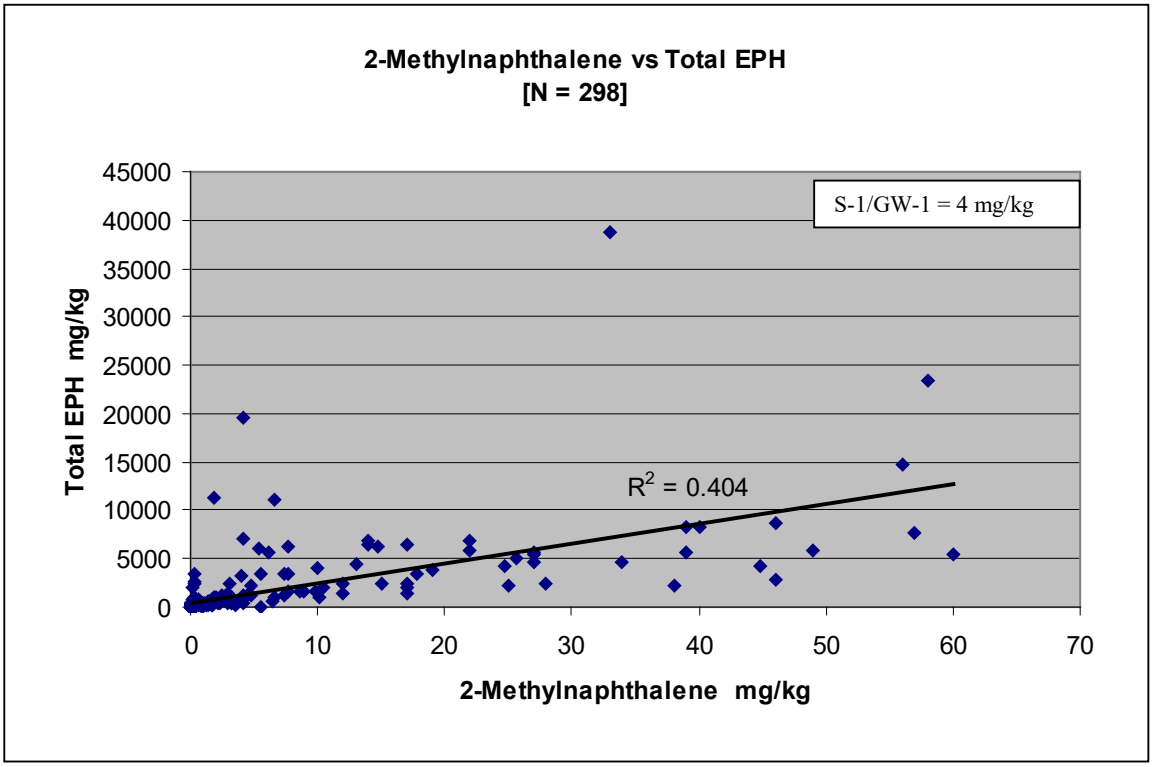


Figure 6 – Naphthalene vs. Total EPH



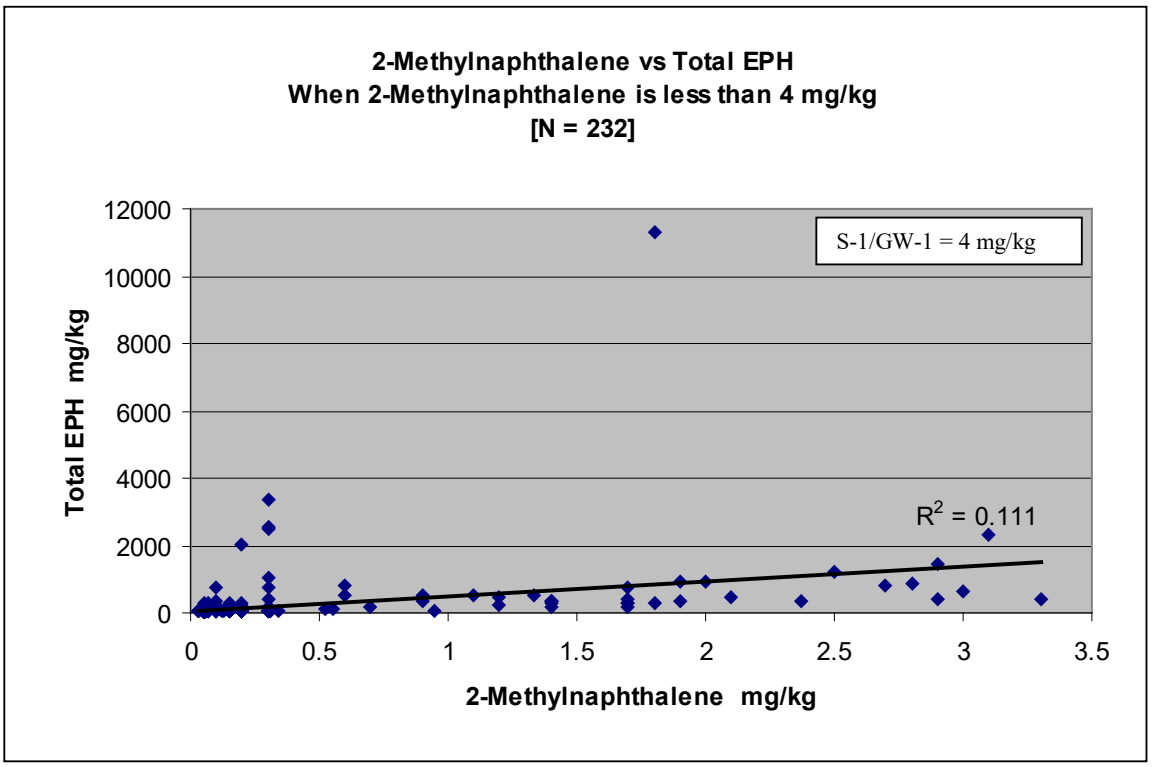
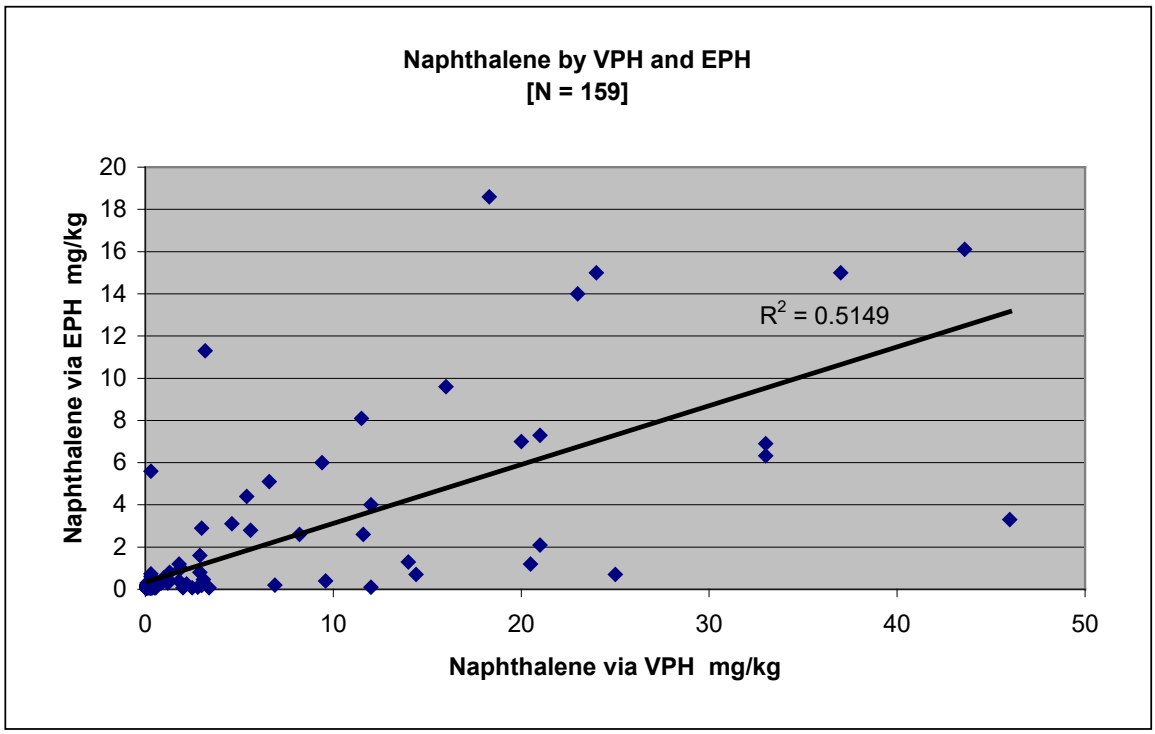


Figure 7 – 2-Methylnaphthalene vs. EPH



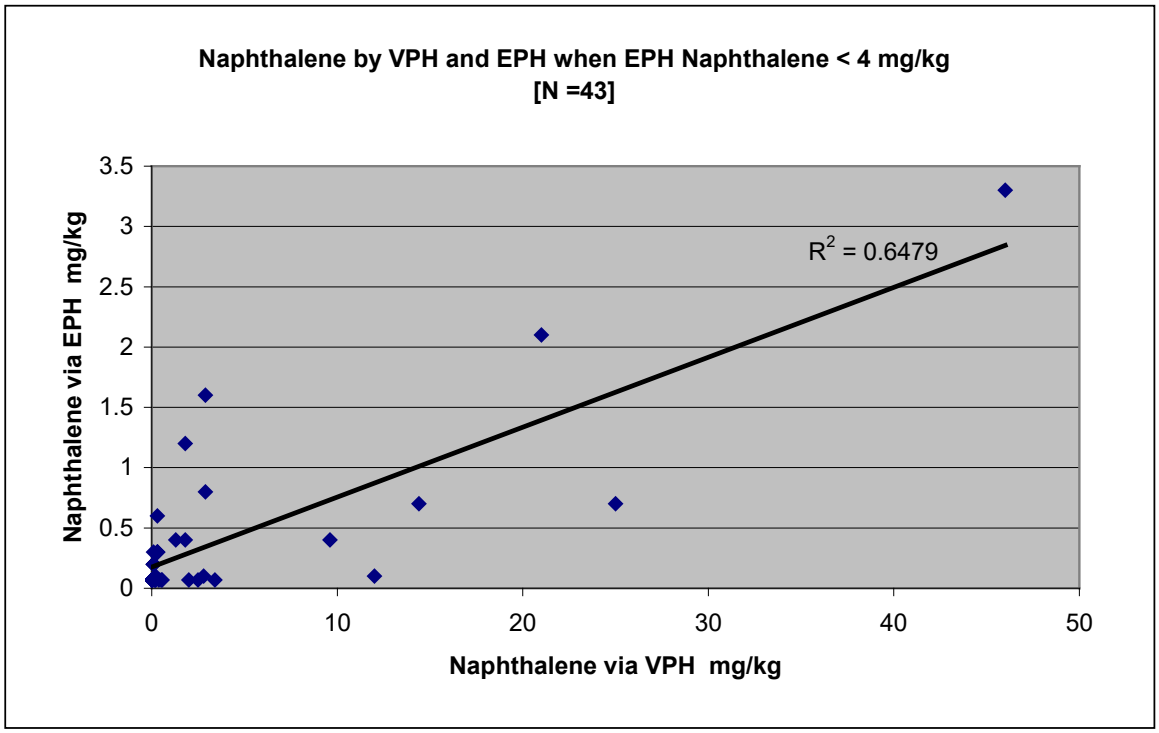
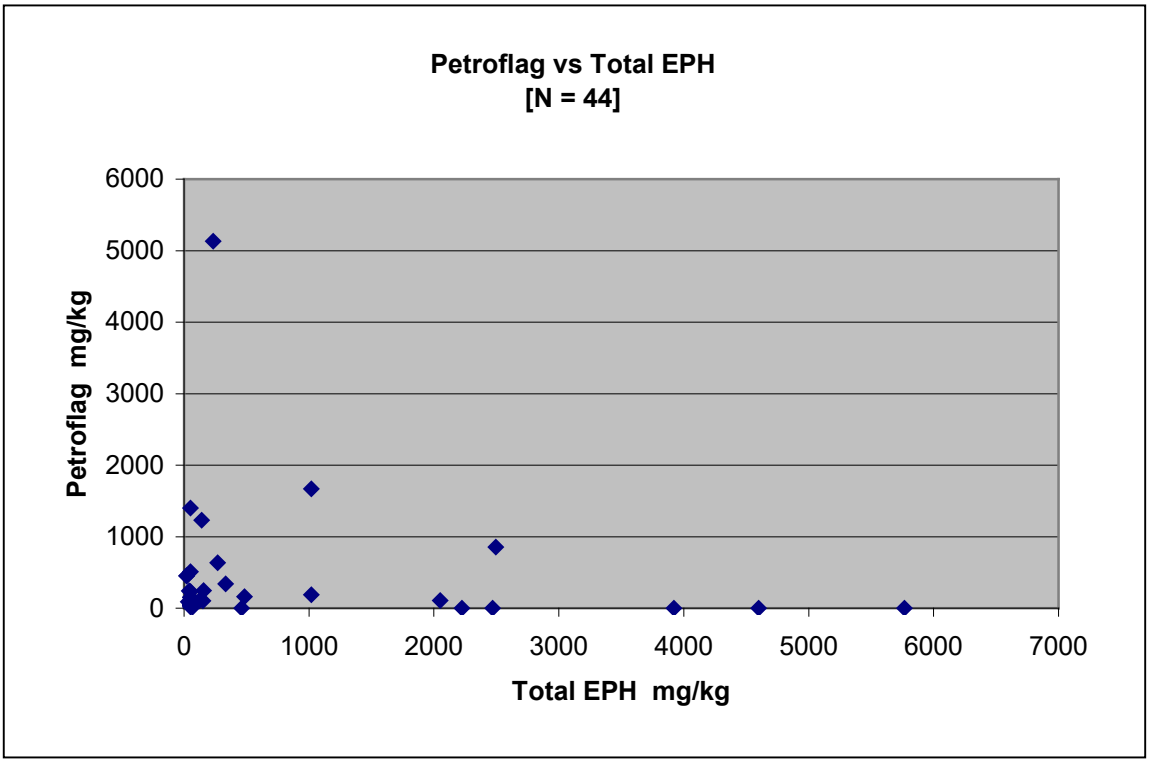


Figure 8 – Naphthalene via VPH and EPH Test Methods



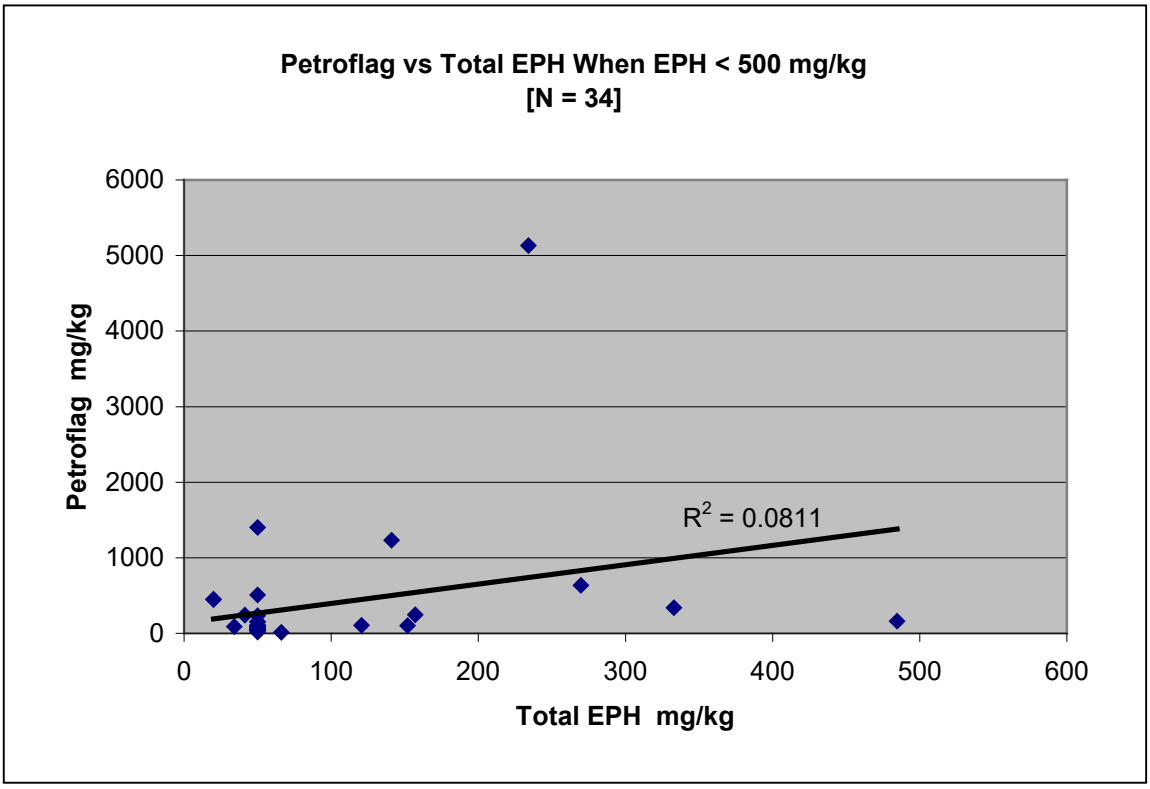


Figure 9 – Petroflag vs. Total EPH

Table 1 – Sites Evaluated								
#	Town	Street	RTN	Consultant	# EPH Samples	Other Samples[1]		
						VPH	HS	PF
1	Amesbury	6 Fern Avenue	3-23,733	ENPRO	85	✓	✓	
2	Amesbury	65 Market St	3-23,110	Simmons/ENPRO	6		✓	
3	Andover	18 Lincoln Circle	3-26,240	Norfolk RAM Group	5		✓	
4	Arlington	73 Jason St	3-23,276	Cyn Env	13	✓		
5	Ashland	14 Brook St	3-25543	Norfolk RAM Group	21		✓	
6	Ashland	19-21 Tilton Ave	3-23,910	TEC Envi	7	✓	✓	
7	Beverly	5 Cornell Rd	3-23,584	Boston Env	4	✓	✓	
8	Boston/Mat	4 Violante St	3-23,421	Hydro Env Tech	3	✓	✓	
9	Boston/SB	116 Dorchester St	3-23,369	Clean Harbors	4		✓	
10	Chelsea	226 Washington St	3-23,403	Clean Harbors	4		✓	
11	Framingham	220 Edmands Rd	3-25,846	Loitherstein Env	34	✓	✓	
12	Framingham	3 Myrna Rd	3-24,156	Bois Consulting	16	✓	✓	
13	Gloucester	5 Sawyer Ave	3-23,843	Loitherstein Env	18	✓	✓	
14	Lowell	99 11th Street	3-22,992	ENPRO	8	✓	✓	✓
15	Lynn	96 Alley St	3-22,454	Response Env	24		✓	
16	Marblehead	36 Glendale Rd	3-25,436	ENPRO	9	✓	✓	
17	Marblehead	Nanepashemet St	3-24,505	Exeter Env	17	✓	✓	
18	Needham	23 Fay Lane	3-23,613	Resource Controls	12	✓	✓	✓
19	Newbury	70 Cottage Road	3-23,102	Stonehill Env	5		✓	
20	Newbury	88 Main Street	3-23,343	ENPRO	15		✓	✓
21	Newburyport	63 High Street	3-25,459	Lessard Env	28	✓	✓	
22	Peabody	42 Oak Street	3-24,734	Boston Env	4	✓	✓	
23	Saugus	324 Lynn Fells Pk	3-24,301	Clean Soils	36		✓	✓
				Total EPH Samples	378			

[1] HS = Headspace (PID) data; PF = Petroflag data (Usually not as many as the number of EPH samples)

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
1_BF-2	253	830	180	490	3.2	8.9	0.92	1.6	1515
1_B-3	241	690	170	390	2.7	7.3	0.6	1.4	1262
1_B-8	155	30	30	110	0.43	1.7	0.15	0.38	173
1_B-10	6.1	30							55
1_B-11	0	30							56
1_B-4	76	30							140
1_B-6	130	670	200	500	2.7	12	0.84	2.6	1388
1_B-6	130	220	60	210	0.9	4.2	0.34	0.93	496
1_BF-6	0	30							59
1_S-3	1.9	30							50
1_S-4	4.6	30							50
1_S-8	0	30							50
1_S-9	10	30							50
1_S-17	3.1	30							50
1_S-19	0	30							50
1_S-20	3.1	30							50
1_S-27	0	30							50
1_TP S-1	302	1400	330	700	3.9	15	1.2	2.5	2453
1_S-43	7.1	30							50
1_S-44	20	30							50
1_S-51	20	30							50
1_S-52	65	30							50
1_S-53	100	30							50
1_S-58	14	30							50
1_S-59	135	160	55	76	0.15	1.7	0.15	0.5	294
1_S-61	6.2	30							50
1_S-62	12	30							50
1_S-65	23	30							50
1_S-66	3	30							50

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
1_S-67	0	30							50
1_S-74	0.8	30							50
1_S-78	0	30							50
1_SP-BTM#1	0	30							50
1_S83SPSW#1	3.4	30							50
1_S86SPSW#2	0	30							50
1_S90SPSW#3	62	180	30	30	0.15	0.15	0.15	0.15	241
1_S91SPSW#4	125	230	61	130	0.55	1.7	0.15	0.46	424
1_S92SPBTM2	0	30							50
1_S-108	160	860	230	520	2.9	9.9	0.71	1.7	1625
1_S-106	0.3	30							50
1_S-109	1.7	30							50
1_S105SPSW4	508	760	220	450	0.61	2.9	0.49	1.7	1436
1_S-101	0	30						0.43	50
1_S103SPBTM 3	0	30							50
1_TP-101	167	140	30	76	0.15	1.2	0.15	0.15	248
1_S-112A	0	30							50
1_S-113A	0	30							50
1_S-115A	4	30							50
1_S-117A	11	30							50
1_S119SPSW7	0	30							50
1_S117BTM4	0	30							50
1_S118SPSW6	20	220	30	120	0.52	1.4	0.15	0.31	372
1_S-115B	0	30							50
1_B-101B	0	30							50
1_B-102	0	30							50
1_B-103	0	30							50
1_S-122	5	30							50
1_S-120	0.6	30							50

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
1_S-123	31	490	120	250	0.46	2.8	0.15	0.88	864
1_S-121	29	190	30	110	0.3	1.4	0.15	0.49	332
1_S-124	0.6	30							50
1_S-125	0.6	30							50
1_S-126	1.5	30							50
1_S-129	55	680	130	330	1	4.2	0.39	1.1	1147
1_S-130	0.4	30							50
1_S-131	0.4	30							50
1_S-132	0	30							50
1_S-139	0	30							50
1_S-140	0	30							50
1_S-151	0	30							50
1_S-153	40	30							50
1_S-154	0	30							50
1_S156SPSW104	72	170	30	110	0.15	1.4	0.15	0.33	312
1_S-157	1	30							50
1_S-158	4	30							50
1_S-159	2	30							50
1_S-160	6	30							50
1_S-161	0.7	30							50
1_D-1	0	30							50
1_D-2	0	30							50
1_D-3	0	30							50
1_D-4	4	30							50
1_D-8	3	30							50
1_D-11	0	30							50
1_D-12	30	210	30	110	0.15	0.9	0.15	0.15	351
10_S-5	38	27,000	7300	8900	NA				43200
10_SS-1	5				0.3	0.3			50

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
10_SS-2	7				NA				50
10_SS-3	0.5	250	60	130	NA				440
11_S-1	20	2000	680	1900	3.1	34	7.7	9	4634
11_S-2	391	670	180	630	2.6	17	2.9	3.8	1506
11_S-3	5				0.1	0.1			50
11_S-4	4				0.1	0.1			50
11_S-5	4	1200	340	900	5.6	28	4	4.9	2483
11_S-6	7				0.1	0.1			50
11_S-7	5				0.1	0.1			50
11_S-8	5				0.1	0.1			50
11_S-9	10				0.1	0.1			50
11_S-10	37				0.1	0.1			50
11_S-11	8				0.1	0.1			50
11_S-12	223	2500	660	2200	9.6	60	7.7	8.2	5446
11_S-12A	11	38	42	45	0.1	0.1			125
11_S-13	7				0.1	0.1			50
11_S-14	182	190	57	130	0.3	3.3	0.3	0.3	381
11_CHIM S-1	6				0.2	0.2			50
11_CHIM S-2	0				0.2	0.2			50
11_S-1	0				0.2	0.2			50
11_S-2	92	3600	1100	2100	2.8	14	1.3	2.9	6821
11_S-3	7				0.2	0.2			50
11_S-4	134	57	15	52	0.2	0.52			125
11_S-5	15	300	90	290	0.73	6.5	1.3	1.6	690
11_S-6	0				0.2	0.2			50
11_S-7	0				0.2	0.2			50
11_S-8	0				0.2	0.2			50
11_S-9	0				0.2	0.2			50
11_S-10	0				0.2	0.2			50

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
11_S-11	0				0.2	0.2			50
11_S-12	0				0.2	0.2			50
11_S-13	0				0.2	0.2			50
11_S-14	0				0.2	0.2			50
11_S-15	0				0.2	0.2			50
11_BOT N	0				0.2	0.2			50
11_BOT S	0				0.2	0.2			50
12_IB-01 8-10'	79	159	51	121	0.2	1.4	0.2	0.57	333
12_IB-02 0-2'	0				0.2	0.2			50
12_IB-02 6-8	9				0.2	0.2			50
12_IB-03 6-8'	2				0.2	0.2			50
12_IB-04 6-8'	115				0.2	0.2			50
12_SB-01 0-5'	0				0.2	0.2			50
12_SB-01 5-10'	0				0.2	0.2			50
12_SB-02 5-10'	0				0.2	0.2			50
12_SB-03 5-10'	0				0.2	0.2			50
12_SS-01 6'	175	870	204	1150	6.2	38		2.7	2271
12_SS-03 6'	200	5130	1100	3680	18.6	112			10041
12_SS-04 6.5'	26				0.2	0.2			50
12_SS-101 7'	151	3000	698	2520	16.1	71.7	8.6	8.7	6323
12_SS-102 7'	129	510	121	425	2.6	10.1	1.4	1.5	1072
12_SS-103 7'	157	2080	465	1670	11.3	44.9	5.7	6.4	4283
12_SS-104	114	186	48.8	133	0.47	2.37		0.5	371
13_S-38	1.4				0.3	0.3			50
13_S-39	8.2				0.3	0.3			50
13_S-40	2.3				0.3	0.3			50
13_S-47	2.9				0.3	0.3			50
13_S-51	0				0.3	0.3			50
13_S-54	3				0.3	0.3			50

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
13_S-74	8.4	570	220	270	0.3	0.3			1061
13_S-45	20				0.3	0.3			50
13_S-46	29	4100	1300	2900	4	39	5.2	0.3	8349
13_S-58	130	4200	1500	2600	8.1	40	1.6	9.6	8359
13_S-59	2.7				0.3	0.3			50
13_S-73	5.7	180	130	120	0.3	0.3			431
13_S-76	0.8	75	53	69	0.3	0.3			198
13_S-77	66	3000	1100	1600	1.3	6.2	3.8	4.8	5716
13_S-78	31	1700	940	1400	0.79	10	2.8	4	4058
13_S-79	2				0.3	0.3			50
13_S-80	5	230	120	150	0.3	1.1			501
13_S-81	35	5100	1700	1800	1.2	46	6.9	9.3	8663
14_B1/S-1	8								50
14_B2/S-2	256	90	25	25	0.15	0.55	0.15	0.15	141
14_B3/S2	285	1400	160	630	6	25	1	1.9	2224
14_B4/S1	15				0.15	0.15			50
14_SW-1	5				0.15	0.15			50
14_SW-2	5				0.15	0.15			50
14_PB-4	9				0.15	0.15			50
14_PB-5/SW-5	15				0.15	0.15			50
15_Base-1	8.2	210	154	146	0.7	3.7	0.39	1.1	516
15_Base-2	0				0.2	0.2			50
15_Westwall-1	0				0.2	0.2			50
15_S-2	14.3	38	15	15	0.2	0.2			50
15_S-3	71	1100	420	1034	0.2	5.5	1.7	4.9	50
15_S-5	2.8				0.2	0.2			50
15_S-6	10.6				0.2	0.2			50
15_Cell 3 base	0				0.2	0.2			50
15_cell 3 WW	6.2	64	15	51	0.2	0.2		0.3	131

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
15_S-7	3.7				0.2	0.2			50
15_S-8	42	701	268	179	0.7	4.8	0.6	1.9	1156
15_S-9	42	2040	749	602	5.3	17.8	2.1	6.5	3423
15_S-10	7.6				0.2	0.2			50
15_S-11	3.6	41.9	15	15	0.2	0.2		0.2	73
15_MW-1 6-8'	0	389	129	278	0.2	2.7	0.4	1.6	801
15_MW-1 8-10'	0				0.2	0.2			50
15_MW-2 0-8'	0				0.2	0.2			50
15_MW-2 8-12'	0				0.2	0.2			50
15_MW-2 12-16'	0				0.2	0.2			50
15_MW-3 6-9'	0				0.2	0.2			50
15_MW-2 5-10'	0				0.2	0.2			50
15_MW-2 10-15	0				0.2	0.2			50
15_MW-3 5-10'	0				0.2	0.2			50
15_MW-3 10-15'	0				0.2	0.2			50
16_B-6	30	12	5	5	0.05	0.05			20
16_S-3									20
16_S-4									20
16_S-7		390	100	240	0.18	1.7	0.25	1.2	733
16_S-8		24	5	5	0.05	0.12			34
16_S-10		31	5	5	0.05	0.31			41
16_S-11		120	30	5	0.25	1.4	0.05	0.39	157
16_S-12		1300	310	860	4.4	17	0.78	3.3	2495
16_S-13B		190	46	78	0.26	1.8	0.11	0.45	317
17_BAS-1	2	10	30	50	0.1	0.05	0.2	2.8	93
17_BAS-2	2	10	40	90	0.2	0.1	0.6	8.9	150
17_BAS-3	3	10	10	30	0.05	0.05	0.05	0.6	51

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
17_BAS-4	3	15	50	40	0.05	0.05	0.05	0.6	106
17_BAS-5	3	30	100	170	0.1	0.05	0.1	4.5	305
17_BAS-6	3				0.05	0.95			50
17_BAS-7	2	10	40	60	0.1	0.05	0.2	3.7	114
17_BAS-8	3				0.05	0.05			50
17_BAS-9	4				0.05	0.05			50
17_SD-1	3	10	120	60	0.1	0.05	0.1	2.2	192
17_SD-2	3	10	30	30	0.05	0.05	0.05	1.1	71
17_SD-3	6	50	70	110	0.2	0.2	0.05	3.3	234
17_VD-1	3	10	50	100	0.8	0.3	0.3	5.3	167
17_VD-2	4	10	50	70	0.1	0.05	0.05	1.5	132
17_VD-3	3				0.05	0.05			50
17_VD-4	6	30	110	110	0.2	0.1	0.2	3.4	254
17_VD-5	3				0.05	0.05			50
18_S-17	0				0.3	0.3			50
18_S-18	0				0.3	0.3			50
18_S-19	0				0.3	0.3			50
18_S-20	10	110	52	72					234
18_S-31	0								50
18_S-32	0				0.3	0.3			50
18_S-33	0				0.3	0.3			50
18_S-34	0				0.3	0.3			50
18_S-35	0	47	39	34	0.3	0.3			121
18_S-36	0	240	91	150	0.3	3.3			485
18_S-37	0	490	190	330	0.8	6.6	1.3		1019
18_S-38	0				0.3	0.3			50
19_S-6	0				0.03	0.03			50
19_S-7	5	10	5	6	0.03	0.03			50
19_S-13	2.5				0.03	0.03			50

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
19_S-19	0				0.03	0.03			50
19_S-15	16	40	5	24	0.03	0.13		0.07	85
2_SES1	42	3200	1600	1700	0.87	17	4	3.5	6525
2_SES2	44	3400	1500	1400	0.63	7.7	2.8	1.3	6312
2_SES3	46	3500	1500	1800	3.3	22	4.2	7.5	6837
2_SES4	38	2900	1200	1400	5	27	3.7	7.2	5543
2_SES5	44	3300	1300	1500	0.84	5.4	1.6	1.1	6109
2_SES6	36	1600	770	900	0.25	4	0.25	1.1	3276
20_SW-1	9				0.15	0.34			50
20_SW-2	8	160	50	120	0.35	1.9	0.15	0.5	333
20_SW-3	4				0.15	0.15			50
20_PB-1	6				0.15	0.15			50
20_PB-2	23				0.15	0.15			50
20_FSW S-2	7	220	68	170	0.15	1.2	0.15	0.68	460
20_MSW S-1	1.6				0.15	0.15			50
20_FRPB S-1	5.2	130	50	89	0.15	0.15		0.41	270
20_SW-4	19	2600	560	1400	4	27	3.2	6.2	4600
20_SW-5	27	1700	410	340	1.4	12	2	4.2	2470
20_SW-6	27	2200	490	1200	3.9	19	2.5	4.9	3920
20_PB-3	4				0.15	0.15			50
20_CW-1	2				0.15	0.15			50
20_CW-2	24	3300	730	1700	3.7	22	3.3	7.1	5766
20_CW-3	5				0.15	0.15			50
21_S-1	83	206	95.8	224	0.07	1.33	0.07	1	528
21_S-3	8				0.07	0.07			50
21_S-5	323	2110	871	1950	6.32	25.6	1.89	7.2	4972
21_S-7	343	478	198	523	0.7	4.5	0.3	1.6	1206
21_LEI-4	5	82.1	30	76	0.07	0.7	0.07	0.18	189
21_LEI-1	30				0.07	0.07			50

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
21_LEI-2	53	288	89	262	0.6	3	0.2	1	644
21_LEI-3	56				0.07	0.07			50
21_LEI-5	0				0.07	0.07			50
21_LEI-6	0				0.07	0.07			50
21_AP-3 15-20'	183	3630	1030	1660	2.1	14.8	2.3	6	6345
21_AP-3 35-40'	1.7				0.07	0.07			50
21_AP-4	208	256	76.9	169	0.07	0.9	0.07	0.47	503
21_AP-6	0				0.07	0.07			50
21_SB-1	0				0.07	0.07			50
21_SB-2	3.6				0.07	0.07			50
21_LEI-7	1.1				0.07	0.07			50
21_LEI-8	0.3				0.07	0.07			50
21_LEI-9	0				0.07	0.07			50
21_LEI-10	0				0.07	0.07			50
21_LEI-11	118	425	194	318	0.7	3.3	0.23	0.9	942
21_LEI-12 30-32'	26	807	381	461	0.07				1649
21_LEI-12 40-42	0				0.07	0.07			50
21_SW-1	112	1120	460	673	0.4	4.7	0.8	1.46	2260
21_SW-2	10	39	15	41	0.07	0.07	0.07	0.07	95
21_SW-3	15	92	35	99	0.07	0.07	0.07	0.07	226
21_SW-4	17	84	16	83	0.07	0.07	0.07	0.07	183
21_BOTTOM	28	116	44	128	0.07	0.07	0.07	0.07	288
22_101	52	750	426	916	3.3	10.4	3.9	5.5	2115
22_103	54	1570	859	1780	6.9	24.7	8.2	11.4	4260
22_Under Chim	50	2940	2170	3340	15	68	0.1	23.7	8557
22_Floor shallow	30	179	117	39	0.1	0.1			335

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
23_SG-2	3.4				0.2	0.2			50
23_PX1	0.8				0.2	0.2			50
23_PX2	1.2				0.2	0.2			50
23_PX3	1.3				0.2	0.2			50
23_PX4	2.7				0.2	0.2			50
23_PX5	10.2				0.2	0.2			50
23_PX6	11.4				0.2	0.2			50
23_PX7	12.8				0.2	0.2			50
23_PX8	0.2				0.2	0.2			50
23_PX9	0.7				0.2	0.2			50
23_PX10	28.6	168	66	77	0.2	0.2			311
23_PX11	0.8				0.2	0.2			50
23_PX12	0				0.2	0.2			50
23_PX14	13.2				0.2	0.2			50
23_PX15	0.5				0.2	0.2			50
23_PX16	25.8				0.2	0.2			50
23_PX17	12.3				0.2	0.2			50
23_PX18	2.7				0.2	0.2			50
23_PX19	2.6				0.2	0.2			50
23_PX20	0.5				0.2	0.2			50
23_PX21	2.7				0.2	0.2			50
23_PX22	0.3				0.2	0.2			50
23_PX23	5.1				0.2	0.2			50
23_PX24	14.2				0.2	0.2			50
23_PX25	0.2				0.2	0.2			50
23_PX26	3.1				0.2	0.2			50
23_PX27	75.2	867	203	437	1.2	8.55	1.1	1.6	1519
23_PX28	3.8				0.2	0.2			50
23_PX29	39	594	165	453	1.2	2.5	0.92	0.7	1217

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
23_PX30	3				0.2	0.2			50
23_PX31	0				0.2	0.2			50
23_PX32	0.2				0.2	0.2			50
23_PX33	4.1				0.2	0.2			50
23_PX36	51	1020	316	713	0.2	0.2			2049
23_PX40	1.9	25	22	86	14.6	3.51	0.02	1	152
23_PX41	0.2	23	12	31	0.2	0.2			66
3_S-123	8	15	15	15	0.2	0.2	0.2	0.2	50
3_S-45	5	15	32	33	0.2	0.2	0.2	0.2	50
3_S-689	6	15	15	15	0.2	0.2	0.2	0.2	50
3_S-710	6	15	15	15	0.2	0.2	0.2	0.2	50
3_S-1112	11	15	15	15	0.2	0.2	0.2	0.2	50
4_GP-100		11000	4900	3600	0.2	4.1	1.2	16	19522
4_GP-101		13000	3400	7000	15	58	6	27	23506
4_GP-105		420	140	170	0.2	0.3			731
4_GP-106		480	140	190	0.2	0.6			811
4_GP-107		27000	8100	3500	7	33	2.9	19	38662
4_Comp A		5500	1900	3600	1.2	6.6	1.5	3.1	11012
4_Comp B		1800	490	1200	0.8	5.5	1.4	4	3502
4_Comp C		2400	680	1400	1.6	13	1.4	5.2	4501
4_Grab 1		6200	1600	3500	0.3	1.8	1.8	5.6	11310
4_Comp 2,3,4		3900	990	2200	0.3	4.2	1.9	7.4	7104
4_Grab 5		1300	410	760	0.2	0.3			2471
4_Comp 1		1300	490	780	0.2	0.3			2571
4_Comp 2		1600	540	1200	0.2	0.3			3341
5_B-5	90	494	202	241	0.32	1.9	0.16	0.6	940
5_B-6	14				0.1	0.1			50
5_B-8	160	434	191	292	0.23	2	0.2	0.9	920
5_B-10	134	8220	3260	3140	12.5	56	5.4	18	14712

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
5_B-10	38	254	110	163	0.1	0.6	0.16	0.53	528
5_B-12	154	1960	821	722	1.1	7.7	0.67	2.4	3515
5_Basement	7.2	286	215	261	0.1	0.1	0.1	0.1	762
5_C-1	3.9	10			0.1	0.1			50
5_C-2	1.9	10			0.1	0.1			50
5_C-3	26.8	40.3	25	45	0.1	0.1			111
5_C-4	0.4	10			0.1	0.1			50
5_C-5	0.6	10			0.1	0.1			50
5_C-6	83.5	641	323	578	1.6	7.7	5.7	1.5	1559
5_C-7	3.4	10			0.1	0.1			50
5_C-8	8.4	10			0.1	0.1			50
5_C-9	0.8	10			0.1	0.1			50
5_C-10	0.5	10			0.1	0.1			50
5_C-11	1.3	10			0.1	0.1			50
5_C-12	0.2	10			0.1	0.1			50
5_C-13	0.1	10			0.1	0.1			50
5_C-14	3.8	10			0.1	0.1			50
6_Comp 1	512	1600	510	1400	0.1	7.3	0.8	4.4	3523
6_Comp 2	140	3200	920	2400	0.4	14	2	6.6	6543
6_Comp 3	160	1100	370	870	0.4	3.1	0.5	1.7	2346
6_Comp 4	240	2600	600	2300	7.3	39	1.9	7.9	5556
6_Comp5	250	3100	640	1900	5.1	27	1.6	6.2	5680
6_SS4	21	10	10	10	0.1	0.1	0.1	0.1	50
6_SS6	567	5300	1200	5000	14	68	3.4	13	11598
7_102	25	25.5	12	12	0.3	0.3			60
7_104	0.4				0.3	0.3			50
7_205	8				0.3	0.3			50
7_303	1.8				0.3	0.3			50
8_HB-1	224	3900	1200	2400	4.8	57	5.5	11	7578

Table 2 – EPH Data – all values mg/kg									
Sample[1]	PID[2] Headsp	C9-C18[3] Aliphatics	C19-C36[3] Aliphatics	C11-C22[3] Aromatics	Fuel Oil Target PAH Analytes[4]				Total EPH[5]
					Naph	2-Mnaph	Acen	Phen	
8_HB-2	214	3100	1200	1500	7.8	49	9.8	7.5	5874
8_HB-4	131	980	330	700	2.3	17	1.1	2.2	2033
9_TP-1	50	140	65	240	0.3	2.1	0.3	1.7	449
9_TP-2A	35	55	60	140	0.3	1.7	3.2	14	274
9_TP-3	26	180	65	140	0.3	2.9	0.3	1.3	390
9_TP-8A	98	1400	330	1100	9.7	46	0.25	9.5	2895

NOTES:

1 Sample prefix number corresponds to site ID number in Table 1.

2 Assumes reported headspace data was obtained via MassDEP Jar Headspace procedure with properly cleaned and calibrated PID unit.

3 Blank cell is less than Reporting Limit. For C9-C18 Aliphatic Hydrocarbons, a value was entered that was ½ of the Reporting Limit, in order to facilitate data correlation efforts for this fraction. Often times, it was necessary to infer this value, since tabulations in site reports were not clear. Inferred values generally 10 to 30 mg/kg.

4 Blank cell is less than Reporting Limit. For naph (naphthalene) and 2-mnap (2-Methylnaphthalene), a value was sometimes entered that was ½ of the Reporting Limit, in order to facilitate data correlation efforts for this fraction. Often times, it was necessary to infer this value, since tabulations in site reports were not clear. Inferred values generally 0.1 to 0.3 mg/kg.

5 Total EPH was summation of all hydrocarbons ranges and Target Analytes. For "Not Detected" data points, a value was entered that was ½ of the Reporting Limit, in order to facilitate data correlation efforts for this fraction. Often times, it was necessary to infer this value, since tabulations in site reports were not clear. Inferred values generally 20 to 50 mg/kg.

Table 3 – VPH Data – all values in mg/kg											
Sample[1]	PID[2] Hdspace	C5-C8[3] Aliphatics	C9-C12[3] Aliphatics	C9-C10[3] Aromatics	VPH Target Analytes[4]						Total VPH[5]
					MtBE	Ben	Tol	EB	xyls	naph	
1_D-11	0	1.5								0.15	1
1_D-12	30	8.3	79	66						0.3	154
1_D-4	4	1.5	0.9							0.15	3
1_D-8	3	1.5	1.7	0.4						0.15	4
1_S-108	160	26	140	150			0.27	0.61	0.7	3	321
1_S-121	29	6.1	70	34				0.09		0.85	111
1_S-122	5	1.5	5.2	2.2						0.15	9
1_S-123	31	40	240	170						3.1	453
1_S-129	55	1.5	150	100						1.9	253
1_S-130	0.4	1.5	0.9	0.4						0.15	3
1_S-131	0.4	1.5								0.15	1
1_S-140	0	1.5								0.15	1
1_S-153	40	1.5	3.8	0.4						0.15	6
1_S156SPSW104	72	6.4	83	34						0.28	124
1_S-159	2	1.5								0.15	1
1_S-160	6	1.5								0.15	1
1_S-161	0.7	1.5								0.15	1
1_S90SPSW3	62	2.9	24	26						0.15	53
1_S91SPSW4	125	8.5	150	65				0.13	0.11	1	225
1_S92SPBTM2	0	1.5								0.15	1

Table 3 – VPH Data – all values in mg/kg											
Sample[1]	PID[2] Hdspace	C5-C8[3] Aliphatics	C9-C12[3] Aliphatics	C9-C10[3] Aromatics	VPH Target Analytes[4]						Total VPH[5]
					MtBE	Ben	Tol	EB	xyls	naph	
11_BOT N	0									0.3	2
11_BOT S	0									0.3	2
11_CHIM S-1	6									0.3	2
11_CHIM S-2	0									0.3	2
11_S-1	20	1	41	93						4.6	140
11_S-1	0									0.3	2
11_S-10	37									0.3	2
11_S-10	0									0.3	2
11_S-11	8									0.3	2
11_S-11	0									0.3	2
11_S-12	223	49	240	450						16	755
11_S-12	0									0.3	2
11_S-12A	11									0.3	4
11_S-13	7									0.3	2
11_S-13	0									0.3	2
11_S-14	182	7	32	51			0.43		2.1	1.2	94
11_S-14	0									0.3	2
11_S-15	0									0.3	2
11_S-2	391	5.7	78	170						8.2	262
11_S-2	92	8.8	85	220	0.13	0.13	0.86	0.14	0.14	5.6	321

Table 3 – VPH Data – all values in mg/kg											
Sample[1]	PID[2] Hdspace	C5-C8[3] Aliphatics	C9-C12[3] Aliphatics	C9-C10[3] Aromatics	VPH Target Analytes[4]						Total VPH[5]
					MtBE	Ben	Tol	EB	xyls	naph	
11_S-3	5	0.1	1.4	6.1						0.3	8
11_S-3	7									0.3	4
11_S-4	4									0.3	2
11_S-4	134	9.1	97	200						6.9	313
11_S-5	4									0.3	2
11_S-5	15	2.2	20	42						0.3	65
11_S-6	7									0.3	2
11_S-6	0									0.3	2
11_S-7	5									0.3	2
11_S-7	0									0.3	2
11_S-8	5									0.3	2
11_S-8	0									0.3	2
11_S-9	10									0.3	2
11_S-9	0									0.3	2
12_IB-01 8-10'	79	7	35.5	54							97
12_IB-02 0-2'	0										4
12_IB-02 6-8	9	1.5	8.6	4.6							15
12_IB-03 6-8'	2	1.5	5.4	1.5							8
12_IB-04 6-8'	115	1.5	3.8	1.5							7
12_SB-01 0-5'	0										4

Table 3 – VPH Data – all values in mg/kg											
Sample[1]	PID[2] Hdspace	C5-C8[3] Aliphatics	C9-C12[3] Aliphatics	C9-C10[3] Aromatics	VPH Target Analytes[4]						Total VPH[5]
					MtBE	Ben	Tol	EB	xyls	naph	
12_SB-01 5-10'	0										4
12_SB-02 5-10'	0										4
12_SB-03 5-10'	0										4
12_SS-01 6'	175	127	484	234							845
12_SS-03 6'	200	78.4	640	323						18.3	1060
12_SS-04 6.5'	26									0.2	4
12_SS-101 7'	151	158	1880	1110						43.6	3192
12_SS-102 7'	129	51.6	544	318						11.6	925
12_SS-103 7'	157	21.8	179	109						3.18	313
12_SS-104	114										4
13_S-45	20	1.2	1.2	4.7						0.6	8
13_S-46	29	60	205	540				4	10	12	831
13_S-47	2.9	0.6	1.2	3						0.6	5
13_S-58	130	77	160	575				4	16	11.5	844
13_S-59	2.7	1	1	4.2						0.6	7
13_S-77	66	21.5	39	245				3	2	14	325
13_S-81	35	9	56.5	360				1.7	4	20.5	452
14_B2/S-2	256	3.4	9.1	25	0.03	0.03	0.06	0.16	0.66	0.48	39
14_B3/S2	285	96	97	500	0.03	0.03	4.4	5.2	33	9.4	745
14_PB-4	9	1	1.5							0.03	2

Table 3 – VPH Data – all values in mg/kg											
Sample[1]	PID[2] Hdspace	C5-C8[3] Aliphatics	C9-C12[3] Aliphatics	C9-C10[3] Aromatics	VPH Target Analytes[4]						Total VPH[5]
					MtBE	Ben	Tol	EB	xyls	naph	
14_PB-5/SW-5	15	1	13	6.8						0.22	21
16_S-10		2.5	2.5	4.1						0.08	9
16_S-11		2.5	2.5	19						0.46	24
16_S-12		15	34	230						5.4	284
16_S-13B		2.5	9.3	76						2.2	90
16_S-3		2.5	2.5	2.5						0.05	5
16_S-4		2.5	2.5	2.5						0.05	5
16_S-7		10	16	170					2.5	3	202
16_S-8		2.5	2.5	2.5						0.1	5
17_BAS-4	3									0.3	20
17_BAS-7	2									0.3	20
17_BAS-9	4									0.3	20
17_SD-3	6	5	30	5						0.3	40
17_VD-2	4	5	56	11						0.4	72
17_VD-4	6									0.3	20
18_S-17	0									0.3	2
18_S-18	0									0.3	2
18_S-19	0									0.3	2
18_S-20	10	2	9	16							27
18_S-31	0									0.3	2

Table 3 – VPH Data – all values in mg/kg											
Sample[1]	PID[2] Hdspace	C5-C8[3] Aliphatics	C9-C12[3] Aliphatics	C9-C10[3] Aromatics	VPH Target Analytes[4]						Total VPH[5]
					MtBE	Ben	Tol	EB	xyls	naph	
18_S-32	0									0.3	2
18_S-33	0	0.5	3.4	6.4						0.3	11
18_S-34	0									0.3	2
18_S-35	0	0.5	1.9	3.7						0.3	6
18_S-36	0	0.5	1	2.4						0.3	4
18_S-37	0	1.6	9.5	29						1.3	41
18_S-38	0									0.3	2
21_AP-3 15-20'	183	58	325	307					9	21	720
21_AP-3 35-40'	1.7									0.02	2
21_AP-4	208	9	34	37					1.5	3.4	85
21_AP-6	0									0.02	2
21_BOTTOM	28	2	11	10						0.56	24
21_LEI-1	30	0.3	2	1						0.2	4
21_LEI-11	118	60	168	283					19	25	555
21_LEI-2	53	1	8	5						0.3	14
21_LEI-3	56	0.5	5	2						0.15	8
21_LEI-4	5	8	39	29					1	2	79
21_LEI-5	0									0.02	2
21_LEI-6	0									0.02	2
21_LEI-7	1.1	0.3	3	1						0.02	4

Table 3 – VPH Data – all values in mg/kg											
Sample[1]	PID[2] Hdspace	C5-C8[3] Aliphatics	C9-C12[3] Aliphatics	C9-C10[3] Aromatics	VPH Target Analytes[4]						Total VPH[5]
					MtBE	Ben	Tol	EB	xyls	naph	
21_LEI-8	0.3									0.02	2
21_S-1	83	4.3	23	24						2.5	54
21_S-3	8									0.04	2
21_S-5	323	131	501	481					24	33	1170
21_S-7	343	65	227	206					14	14.4	526
21_SB-1	0									0.03	2
21_SB-2	3.6									0.02	2
21_SW-1	112	27	135	152					2	9.6	326
21_SW-2	10	0.6	3	4						0.2	8
21_SW-3	15	2	11	12						0.51	26
21_SW-4	17	1	7	9						0.38	17
22_101	52	156	503	505					27	46	1237
22_103	54	114	358	356					16	33	877
22_Floor shallow	30	52	144	278			2	2	13	12	503
22_Under Chim	50	200	517	1060		1	14		56	37	1885
4_Comp 1		1.1	36	5.5						0.1	43
4_Comp 2		1.1	19	5.6						0.1	26
4_Comp 2,3,4		37	220	110					0.71	0.1	368
4_Comp A		62	230	110					5.6	1.8	409
4_Comp B		54	210	140	0.05	0.12	1.3	1.9	14	2.9	424

Table 3 – VPH Data – all values in mg/kg											
Sample[1]	PID[2] Hdspace	C5-C8[3] Aliphatics	C9-C12[3] Aliphatics	C9-C10[3] Aromatics	VPH Target Analytes[4]						Total VPH[5]
					MtBE	Ben	Tol	EB	xyls	naph	
4_Comp C		45	220	150	0.05	0.11	0.31	0.99	9.2	2.9	429
4_GP-100		1.1	4.1	1.1						0.1	6
4_GP-101		59	800	430	2.6	0.3	12	14	77	24	1419
4_GP-105		6	72	11					1.5	0.1	91
4_GP-106		4	40	8.1	0.56				1.2	0.1	54
4_GP-107		41	390	300	0.56	0.18	1.5	5	30	20	788
4_Grab 1		21	220	82						0.32	323
4_Grab 5		1.1	46	1.1						0.1	48
6_Comp 1	512	2	230	84						2.8	319
6_Comp 2	140	2	170	90						1.3	263
6_Comp 3	160	2	130	77						1.8	211
6_Comp 4	240	18	540	270						21	849
6_Comp5	250	14	330	220						6.6	571
6_SS4	21	1	1	1						0.2	2
6_SS6	567	44	570	370						23	1007
7_102	25	10	10	10						0.3	20
7_104	0.4	10	10	10						0.3	20
7_205	8	10	10	10						0.3	20
7_303	1.8	10	10	10						0.3	20
8_HB-1	224	68	230	690	NA	NA	0.6	3.5	22	NA	1014

Table 3 – VPH Data – all values in mg/kg											
Sample[1]	PID[2] Hdspace	C5-C8[3] Aliphatics	C9-C12[3] Aliphatics	C9-C10[3] Aromatics	VPH Target Analytes[4]						Total VPH[5]
					MtBE	Ben	Tol	EB	xyls	naph	
8_HB-2	214	63	250	640	NA	NA	1.9	9.3	19	NA	983
8_HB-4	131	12	130	270	NA	NA	0.6	2	4.4	NA	419

NOTES:

1 Sample prefix number corresponds to site ID number in Table 1.

2 Assumes reported headspace data was obtained via MassDEP Jar Headspace procedure with properly cleaned and calibrated PID unit. Blank cell indicates that Headspace data was not reported.

3 Blank cell is less than Reporting Limit.

4 Blank cell is less than Reporting Limit. For naph (naphthalene), a value was sometimes entered that was ½ of the Reporting Limit, in order to facilitate data correlation efforts for this fraction. Often times, it was necessary to infer this value, since tabulations in site reports were not clear. Inferred values generally 0.02 to 0.3 mg/kg.

5 Total VPH was summation of all hydrocarbons ranges and Target Analytes. For "Not Detected" data points, a value was entered that was ½ of the Reporting Limit, in order to facilitate data correlation efforts for this fraction. Often times, it was necessary to infer this value, since tabulations in site reports were not clear. Inferred values generally 2 to 30 mg/kg.

Table 4 – Petroflag Data – all Data in mg/kg					
Sample[1]	Total EPH[2]	Petroflag	Sample[1]	Total EPH[2]	Petroflag
16_S-3	20	450	20_CW-3	50	154
16_S-4	20	450	23_PX38	50	18
16_S-8	34	90	23_PX39	50	51
16_S-10	41	240	23_PX41	66	13
14_B4/S1	50	33	18_S-35	121	105
14_PB-4	50	87	14_B2/S-2	141	1232
14_PB-5/SW-5	50	151	23_PX40	152	102
18_S-17	50	38	16_S-11	157	245
18_S-18	50	43	18_S-20	234	5130
18_S-19	50	104	20_FRPB S-1	270	634
18_S-31	50	79	20_SW-2	333	340
18_S-32	50	86	20_FSW S-2	460	>2000
18_S-33	50	107	18_S-36	485	159
18_S-34	50	67	23_PX37	1018	1667
18_S-38	50	44	18_S-37	1019	189
20_SW-1	50	232	23_PX36	2049	107
20_SW-3	50	94	14_B3/S2	2223.9	>4000
20_PB-1	50	105	20_SW-5	2470	>2000
20_PB-2	50	1402	16_S-12	2495	855
20_MSW S-1	50	509	20_SW-6	3920	>2000
20_PB-3	50	51	20_SW-4	4600	>2000
20_CW-1	50	74	20_CW-2	5766	>2000

NOTES:

1. Sample prefix number corresponds to site ID number in Table 1.
2. Total EPH was summation of all hydrocarbons ranges and Target Analytes. For "Not Detected" data points, a value was entered that was ½ of the Reporting Limit. Often times, it was necessary to infer this value, since tabulations in site reports were not clear. Inferred values generally 20 to 50 mg/kg.