

# **IN-SITU BIOREMEDIATION EVALUATION USING THE WATERLOO EMITTER™**

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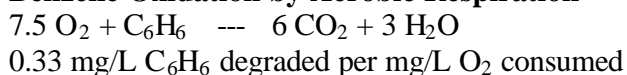
## **INTRODUCTION**

Subsurface hydrocarbon impacts from releases of petroleum products are oxidatively degraded by microbes found naturally in soil and groundwater. Significant research and a number of case studies have identified natural reduction/oxidation (redox) mechanisms associated with hydrocarbon mass transformation or “degradation” (Nyer and Duffin 1997). Since the mid 1990s, Natural Attenuation studies and protocols have established methods of determining the degradation processes active in reducing subsurface soil and groundwater fuel hydrocarbon (Benzene, Toluene, Ethylbenzene and Xylenes, BTEX) concentrations as part of Natural Attenuation assessments (Wiedemeier et al. 1995, ATSM 1998).

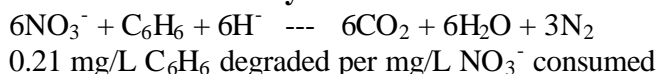
Natural Attenuation is defined by the US EPA as “the biodegradation, dispersion, dilution, sorption, volatilization, and/or chemical and biochemical stabilization of contaminants to effectively reduce contaminant toxicity, mobility, or volume to levels that are protective of human health and the ecosystem”. Biodegradation is the primary mechanism for attenuating biodegradable contaminants and bioremediation is the biochemical reactions related to Natural Attenuation (Wiedemeier et al. 1995).

Natural Attenuation protocols and studies have identified the key biodegradation mechanisms (redox reactions) commonly associated with hydrocarbon bioremediation as the following (Wiedemeier et al. 1995):

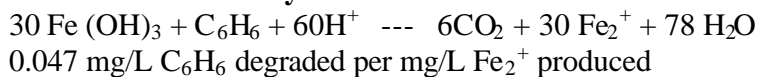
### **Benzene Oxidation by Aerobic Respiration**



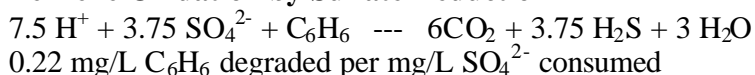
### **Benzene Oxidation by Nitrate Reduction**



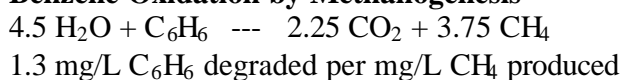
### **Benzene Oxidation by Iron Reduction**



### **Benzene Oxidation by Sulfate Reduction**



### **Benzene Oxidation by Methanogenesis**



The above equations are similarly applied to Toluene, Ethylbenzene and Xylenes resulting in Total BTEX average utilization factors or rate constants (mass of hydrocarbon degraded per unit mass of electron acceptor consumed) of 0.32 (aerobic respiration), 0.21 (denitrification) 0.05 (Iron reduction) 0.21 (sulfate reduction) and 1.28 (methanogenesis).

Using the above utilization factors the “biodegradation capacity” or Expressed Assimilative Capacity (EAC) can be estimated based on the amount of electron acceptor consumed or redox product produced (Wiedimer et al. 1995). The EAC is calculated based on observed concentration changes for electron acceptors or metabolic products as presented below:

$$EAC = UF \{ C_b - C_p \}$$

EAC – Expressed Assimilative Capacity for an electron acceptor (mg HC/L), amount of hydrocarbon degraded based on amount of electron acceptor consumed or redox product produced.

UF – utilization factor for electron acceptor (unitless)

$C_b$  – background concentration of electron acceptor (mg/L)

$C_p$  – concentration of electron acceptor in plume (mg/L)

Methods to facilitate biodegradation processes have been advanced with the increased understanding of the redox mechanisms. Understanding of the effectiveness of increased oxygen levels or addition of nutrients has significantly progressed since the mid 1990s. Several case studies have demonstrated that delivery of air, oxygen or nutrients into hydrocarbon-impacted aquifers has increased the rate of hydrocarbon biodegradation through changes in the oxidative level of activity.

This paper presents the methods used to establish current biodegradation processes occurring at a site located in Northeast Alberta, evaluation of the effectiveness of increasing dissolved oxygen concentrations in biodegradation of BTEX using the relatively new Waterloo Emitter™ insitu-bioremediation technology and thirdly presents key design requirements and operation protocols for monitoring and optimizing biomass accumulation in a field trial consisting of a “fence” of Waterloo Emitters™.

## **CASE STUDY**

### **Site History**

The study site is located in a small town in Northeast Alberta. The retail service station had operated for greater than 30 years and was decommissioned and closed in the fall of 2002. The facilities at the time of decommissioning consisted of a retail service station building, one waste oil fiberglass underground storage tank (UST), a tank nest with three fiberglass USTs (two containing gasoline and one for storage of diesel) and two pump islands. The facility locations had not changed in the 30-year history; however, the underground storage tanks (USTs) were replaced in 1993 from steel to fiberglass.

At the completion of the decommissioning, the site was assessed to characterize the extent and degree of hydrocarbon impact present. Figure 1 presents the location of the

facilities and the location of the testpits, boreholes and monitor wells installed as part of the site assessment work.

### **Stratigraphy**

The stratigraphy at the site consists of 2 m to 3 m of glacial clay till (74% clay and silt) overlying a relatively clean (less than 5% clay and silt) sand. The grain size distribution of the sand unit consists of 55% fine and 40% medium grain sizes and is uniform graded.

### **Hydrogeology**

The sand aquifer is confined during groundwater highs and unconfined during groundwater lows. Groundwater levels typically range from 2.2 m below surface to 3.5 m below surface. Seasonal groundwater level fluctuations are approximately 0.5 m; however, extensive seasonal data has not been collected to date. Field slug tests indicate a hydraulic conductivity of between  $1 \times 10^{-4}$  m/s to  $5 \times 10^{-5}$  m/s. Groundwater flow is in a northeast direction at a gradient of approximately 0.002 m/m to 0.003 m/m. Using a porosity of 30% groundwater flow velocities likely range from approximately 11 m/year to 32 m/year.

## **HYDROCARBON IMPACT**

### **Residual**

Residual hydrocarbon impact (BTEX and F1 and F2) in soil was identified in the vicinity of the former tank nest and pump islands from surface to a depth of approximately 4 m (approximately 1 m into the sand unit).

Figure 1 presents the extent of the residual hydrocarbon impact. Total BTEX concentrations in soil range from 100 µg/g to 200 µg/g near the pump islands to 20 µg/g down gradient of the pump islands. F1 and F2 concentrations range from 2200 µg/g near the pump islands to between 200 µg/g and 20 µg/g down gradient of the pump islands (Table 1).

Figure 2 presents the BTEX soil concentrations along the approximate center axis of the residual phase hydrocarbon plume from upgradient BH107 to down gradient locations BH104 and BH205/BH206. Concentrations within the residual phase plume are represented by TP108, TP109, BH3, BH202 and BH9.

### **Light Non-Aqueous Phase Liquids (LNAPL)**

Light Non-Aqueous Phase Liquids (LNAPL) have historically been detected in vapour extraction wells near the former pump islands. LNAPL has not been measured in other monitor wells installed at the site with the exception of a hydrocarbon sheen observed on groundwater collected from BH104.

### **Dissolved**

Dissolved phase hydrocarbon impact was identified on site associated with the residual phase plume and extending northeast off site towards residential developments. Stacked piezometers identified the highest dissolved phase hydrocarbon concentrations were within the upper 2 m of the sand unit and significantly decreased below a depth of 2 m

within the sand. Figure 1 presents the approximate extent of the dissolved phase impact based on the most recent groundwater sampling program conducted in July 2004.

Figure 3 presents the Total BTEX concentrations and Figure 4 presents the F2 concentrations along the approximate center axis of the dissolved phase hydrocarbon plume from upgradient BH107 to down gradient location BH205/BH206. Concentrations within the dissolved phase plume are represented by BH201B, BH202B, BH9 and BH104 (Table 2).

### **REMEDIAL/RISK MANAGEMENT OPTIONS EVALUATION**

The site hydrogeology and the extent of residual and dissolved phase impacts were considered in the evaluation of remedial/risk management options. The options evaluated included excavation and disposal, dual phase extraction, air sparging and *in-situ* bioremediation. From an economic and practical perspective excavation into the confined sand aquifer was not considered feasible. Dual Phase extraction and air sparging were not considered feasible from an economic perspective (treatment costs) and vapour migration control issue, respectively. The risk management option of reducing dissolved phase migration off site through *in-situ* bioremediation to reduce potential risks associated with the down gradient residential developments warranted further evaluation and potential field testing.

One *in-situ* bioremediation technology considered in the remedial options evaluation was the Waterloo Emitter™ technology, which has been developed, patented and now marketed by the University of Waterloo (Waterloo Ont. Canada). The Waterloo Emitter™ utilizes a diffusive device (silicon or LPDE tubing) for controlled and uniform delivery of dissolved oxygen to the groundwater. The Waterloo Emitter™ is essentially a coil of polymeric tubing that is pressurized to create a concentration gradient driving dissolved oxygen into the groundwater flowing past the device in accordance to Fick's first law of diffusion (Waterloo Emitter™ web page 2004). The Waterloo Emitter™ was selected for further analysis for the following reasons:

- a potentially effective method of delivering high concentrations of dissolved oxygen into the aquifer to increase biodegradation rates; and
- the technology is relatively simple with potentially low maintenance requirements.

### **WATERLOO EMITTER™ EVALUATION**

The approach used to evaluate the Waterloo Emitter™ technology included assessment of field parameters, conducting a geochemical laboratory testing program and modelling of the current biodegradation capacity and potential biodegradation capacity as a result of increased dissolved oxygen levels using the US EPA model BIOSCREEN. Additionally, a preliminary assessment of the potential for biological plugging was conducted.

#### **Field and Laboratory Program**

The field program consisted of measuring Dissolved Oxygen (DO), pH, Temperature, Reduction/Oxidation potential and conductivity (EC) in select monitor wells on and off site with the use of a HYDROLAB Surveyor 4 down hole probe.

The laboratory testing program for geochemical (excluding BTEX and F1 and F2) parameters included submission of groundwater samples from upgradient (BH107), within (BH201A and B, BH9, BH202A and B, BH104), downgradient (BH205 and BH206) and cross gradient (BH103 and BH105) of the dissolved phase plume.

#### **Microbiological Protocol Development Program.**

As part of the site characterization and Waterloo Emitter™ technology evaluation, the initial microbiological protocol selected was based on the determination of the activity levels for heterotrophic bacteria using the HAB-BART™ system (Droycon Bioconcepts Inc. Regina, SK, Canada). This system allows for both the quantification of the size of the active population and the differentiation into aerobic and anaerobic groups (Cullimore, 1999). To undertake the test, a HAB-BART tester was used with incubation at  $28 \pm 1^\circ\text{C}$  in a reader that detects the development of reductive conditions in the initially oxidative test and assigns a time lag measured in seconds. This time lag is then extrapolated to give a population (predicted active cells or p.a.c./ml) and also indicates whether the bacterial activity is primarily aerobic or anaerobic. Environment Canada's Environmental Technology Verification (ETV) provided certification of the claims ascribed by the manufacturer (Anonymous 2003).

Groundwater samples for the microbiological evaluation were collected from upgradient (BH107), within (BH201A and B, BH9, BH202A and B, BH104), downgradient (BH205 and BH206) and cross gradient (BH103 and BH105) of the dissolved phase plume. The samples were collected without monitor well purging and minimal well disturbance with the use of disposal bailers. These initial trials were established to develop microbiological protocols for monitoring any positive impacts (increased rates of biodegradation) and potential negative impacts (plugging within the treatment zone).

#### **Modelling**

The US EPA model BIOSCREEN was used as a screening tool to simulate the natural attenuation of dissolved BTEX constituents at the site and to evaluate the potential for enhancing bioremediation by increasing dissolved oxygen concentrations within the aquifer. BIOSCREEN is an analytical model that allows comparison of non-degraded solute transport with transport that includes either first order decay or "instantaneous" biodegradation reactions. Modelling was conducted using site-specific data collected for hydrogeologic parameters and industry-accepted default parameter values. Calibration and sensitivity analysis was conducted for benzene concentrations in down gradient wells located along the plume centerline. The instantaneous biodegradation option was subsequently used to assess the effect of increasing dissolved oxygen levels in the source zone on benzene concentrations at BH104, the nearest down gradient monitoring point.

### **RESULTS**

#### **Field and Laboratory Results**

Table 2 presents the field parameters and laboratory geochemical testing results from monitor wells and groundwater samples collected along the approximate centerline up-gradient, within, down gradient and cross-gradient of the dissolved phase plume.

Background concentrations are represented by BH107 (upgradient), BH105 (cross gradient) and the extreme down gradient well BH205. Dissolved oxygen levels were depressed in BH107 and BH205; however, the cross gradient well indicated a DO of 3.7 mg/L. Redox potential in all background wells ranged from 156mV to 187 mV. Dissolved  $\text{NO}_3^-$  concentrations in the background wells ranged from 0.3 mg/L to 2.1 mg/L.  $\text{Fe}_2^+$  concentrations in the background wells were relatively low and ranged from 0.01 mg/L to 0.02 mg/L. Dissolved  $\text{SO}_4^{2-}$  concentrations in the background wells ranged from 20 mg/L to 30 mg/L.  $\text{CH}_4$  concentrations in the background wells ranged from 0.0002 mg/L to 0.0011 mg/L.

Although BH107 is upgradient of the site and indicated non detectable concentrations of dissolved hydrocarbons, given the commercial/industrial setting upgradient of BH107 some of the commercial/industrial activities may have influenced the observed field and geochemical concentrations measured in BH107. Monitor wells BH105 and BH205 may be more representative of background conditions. Additional future monitoring and testing will assist in confirmation of these results.

Within the plume DO levels ranged from 0.28 mg/L to 0.93 mg/L. Redox potential levels within the plume were all below 90 mV and ranged from 60 mV to 86 mV.  $\text{NO}_3^-$  concentrations were below the detection limit of 0.2 mg/L.  $\text{Fe}_2^+$  concentrations were elevated and ranged from 1.35 mg/L to 5.54 mg/L.  $\text{CH}_4$  concentrations within the plume ranged from 0.00084 mg/L to 0.016 mg/L.

Comparing the field and geochemical data collected from within the plume to background wells the following lines of evidence for biodegradation mechanisms occurring at the site include:

- Depressed DO levels within the plume especially when compared to BH105 (cross gradient)
- Depressed  $\text{NO}_3^-$  concentrations within the plume compared to all three background wells
- Elevated  $\text{Fe}_2^+$  concentrations within the plume compared to all three background wells
- Depressed  $\text{SO}_4^{2-}$  levels within the plume (only BH104) compared to all three background wells
- Relatively elevated  $\text{CH}_4$  levels within the plume compared to BH105 (cross gradient and BH205 (down gradient)).

### **Expressed Assimilative Capacity**

The Expressed Assimilative Capacity (EAC) with respect to biodegradation and redox reactions was calculated as presented in Table 3. The EAC estimates were based on background concentrations represented by BH105 and plume concentrations in BH9 where potential *in-situ* bioremediation enhancement technologies would be installed.

The results indicate the EAC or “biodegradation capacity” is approximately 1.6 mg/L while the total BTEX concentration at BH9 is approximately 14.4 mg/L. Based on the EAC and Total BTEX concentrations there currently is insufficient “biodegradation capacity” available within the site boundaries for bioremediation of BTEX concentrations

to below established risk management target concentrations. Total BTEX concentrations in off site monitor well BH104 are 30.8 mg/L with Benzene being the primary contaminant of concern with respect to the vapour inhalation pathway.

### **Evaluation of Increased Dissolved Oxygen Levels**

To increase the EAC on site, injection of dissolved oxygen in the vicinity of BH9 and BH202 (to increase aquifer DO concentrations) would potentially simulate biological activity and thus increase *in-situ* bioremediation of BTEX levels potentially below risk management target concentrations at the site down gradient boundaries.

Preliminary estimates based on the theoretical amount of dissolved oxygen (DO) emitted within a well installed with a Waterloo Emitter™ using different well diameters, diffusive tubing materials and operating pressures, suggest that DO levels as high as 20 to 30 mg/L are possible (Waterloo Emitter™ web page 2004). The theoretical increase in EAC (0.32 mg/L of hydrocarbons per mg/L of DO) of such a well would be approximately 6 mg/L to 10 mg/L based on minimal initial DO concentrations. Based on the theoretical estimates, installation of a “fence” of Waterloo Emitter™ wells across the dissolved phase plume at the property boundary in the vicinity of BH9 and BH202 would potentially reduce dissolved phase migration of hydrocarbons off site below risk management target concentrations.

Limited case studies were available in the literature using the of Waterloo Emitter™ technology and there appears to be no long term monitoring performance data in literature searched by the authors. Key design requirements for installation of a “fence” of Waterloo Emitter™ wells include; installation well diameter and completion details, well spacing and the potential for long term maintenance issues associated with biological plugging.

### **HAB-BART Results**

Table 2 and Figure 5 presents the results of the field HAB-BART program. The HAB populations are plotted in Figure 5 in units of log p.a.c./ml. Given the limited microbiological data there appears to be a significant correlation between the size of the HAB population and the presence of the various fractions of hydrocarbons. The HAB BART results showed aerobic activity along most of the plume centerline with anaerobic activity occurring only in BH107 upgradient from the plume. There was a very distinct gradient of HAB populations along the plume centre line with the highest populations being recorded in BH202B of 1,600,000 p.a.c./mL. For the F2 (>C<sub>10</sub> – C<sub>16</sub>) concentrations presented in Figure 2, it was found that chain lengths of hydrocarbon polymers varied in concentration where the HAB population was most active. This would indicate that degradation of the longer chained hydrocarbons was also occurring. Based on the preliminary HAB-BART results, increased biodegradation rates would be possible if a predominately aerobic environment is maintained where heterotrophic bacteria become dominant.

It should be noted that as the oxidation zone expands increasing biomass accumulation could generate biological plugging in which occlusive materials such as slimes and encrustations fill voids in the aquifer reducing hydraulic flow down gradient of the

emitters beyond the application “fence”. HAB-BART testing protocols to monitor biomass accumulation were established to further evaluate this potential after installation of the emitters.

### **BIOSCREEN Modelling Results**

Model calibration results provided strong evidence for the occurrence of biodegradation, as physical attenuation processes (e.g. dispersion, sorption) alone could not account for the reduced benzene concentrations observed at the leading edge of the plume near BH205/BH206.

Comparison of first order biodegradation with instantaneous reactions indicated that results based on first order biodegradation rates more closely coincided with the benzene concentrations observed down gradient. However, while the instantaneous option underestimated benzene decay at BH205/BH206, first order simulations overestimated benzene degradation near the source area. A sensitivity analysis indicated that first order reactions were most sensitive to the biodegradation rate while the instantaneous model was most sensitive to the source zone hydrocarbon mass estimate.

To predict the effect of increasing dissolved oxygen levels on benzene concentrations the instantaneous aerobic model in BIOSCREEN was applied. By applying the net changes in benzene concentrations determined from the instantaneous model to the original benzene concentrations predicted by the first order model, reasonable estimates were derived for down gradient benzene concentrations through time. The following conclusions were subsequently inferred from the modelling results:

- Biodegradation of hydrocarbons at the site appears to be most closely approximated by first order degradation rates. Modelling indicates that the dissolved plume is likely already at steady-state conditions (not expanding);
- Any reductions observed on benzene concentrations in monitoring well BH104 will likely occur between 0.5 and 1.5 years after oxygen delivery is initiated;
- Based on current plume conditions, regulatory compliance occurs approximately 40 metres down gradient from the site. If dissolved oxygen levels of approximately 25 to 30 mg/L can be generated by the Waterloo Emitter™ fence, regulatory compliance for benzene in well BH104 located about 10 metres from the site could occur in approximately 10 to 20 years.

### **PROPOSED FIELD PILOT TEST PROTOCOLS**

To minimize potential long term biological plugging activities often associated with oxygen release technologies such as the Waterloo Emitter™ technology, the following protocols will be followed for the field installations: (1) pure oxygen and not air will be used as air contains nutrient sources that would increase the potential for biofouling on the surface of the emitter diffusive tubing, (2) any nutrient supplementation to be applied would be conducted at the edge of the plume to “entice” biomass growth away from the emitter “fence”, (3) 150 mm diameter well screens will be used for 100 mm diameter emitters, (4) operation of the system on a continuous basis to limit movement of the biomass towards the emitter wells, and (5) BART testing consisting of HAB, SRB (sulphate reducing bacteria), DN (denitrifying bacteria) and IRB (iron related bacteria) at locations where redox fronts are expected to form in a stable manner will be conducted.

The field installation of the emitter “fence” will consist of two rows of 5 emitter wells spaced on 3 m centers. The second row of emitters will be off set 1.5 m providing an effective spacing between emitters of 1.5 m. The emitter “fence” is to be installed in the vicinity of BH9 and BH202 perpendicular to groundwater flow in the fall of 2004.

### **SUMMARY**

Based on the site characterization data and preliminary analyses the Waterloo Emitter™ technology may be an effective method for the delivery of high concentrations of dissolved oxygen into the subsurface, thereby increasing aerobic bioremediation of dissolved hydrocarbons. Protocols for installation and operation of a “fence” of emitters were developed. Installation of the emitters will be completed in the fall of 2004.

### **ACKNOWLEDGEMENTS**

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Waterloo Emitter™ web page 2004. <http://www.waterlooemitter.com/>

<b>TABLE 1: SUMMARY OF SOIL ANALYTICAL RESULTS - HYDROCARBONS</b>									
Sample ID		BH107	TP108	TP109	BH3	BH202A	BH9	BH104	BH205
Date		23 Jul 2004	23 Jul 2004	23 Jul 2004	23 Jul 2004	23 Jul 2004	23 Jul 2004	23 Jul 2004	
Location	Units	Upgradient	Plume	Plume	Plume	Plume	Plume	Downgradient	Downgradient
Benzene	ug/g	<0.02	0.03	3.8	0.4	0.65	1.9	0.02	<0.04
Toluene	ug/g	<0.1	6.7	1.7	1.3	3.3	2.7	0.86	<0.1
Ethylbenzene	ug/g	<0.1	25	28	2.3	2.3	0.36	0.71	<0.1
Xylenes	ug/g	<0.1	170	74	13.8	13	1.8	6.4	<0.1
Total BTEX	ug/g	<0.1	201.73	107.5	17.8	19.25	6.76	7.99	<0.1
F1-BTEX (C6-C10)	ug/g	<10	720	1400	216	170	23	12	<10
F2 (>C10-C16)	ug/g	<10	640	860	53	83	<10	<10	<10
F3 (>C16 -C34)	ug/g	<10	15	20	-	12	-	<10	<10
F4 (>C34-C50)	ug/g	<10	<10	<10	-	<10	-	<10	<10

<b>TABLE 3: SUMMARY OF EXPRESSED ASSIMILATIVE CAPACITY (EAC)</b>						
Sample ID		BH9	BH105		BTEX	BTEX
Location	Units	Plume	Cross Gradient	Delta	Utilization	EAC
Date		EA Concentration	EA Concentration	EA Concentration	Factor	
aerobic respiration	mg/L	0.4	3.7	3.3	0.32	1.06
denitrification	mg/L	< 0.2	2.1	1.9	0.21	0.4
Iron reduction	mg/L	3.17	0.01	3.16	0.05	0.16
Sulfate reduction	mg/L	37	20	-	0.21	0
methanogenesis	mg/L	0.0018	0.0002	0.0016	1.28	0.002
EAC Total	mg/L					1.62
Total BTEX (BH9)	mg/L					14.4

**TABLE 2: SUMMARY OF FIELD PARAMETERS AND GROUNDWATER ANALYTICAL RESULTS**

Sample ID		BH107	BH201A	BH201B	BH202A	BH202B	BH9	BH104	BH105	BH205
Location	Units	Upgradient	Plume - deep	Plume - shallow	Plume - deep	Plume - shallow	Plume	Plume	Cross Gradient	Down Gradient
Date		23 Jul 2004	23 Jul 2004	23 Jul 2004	23 Jul 2004	23 Jul 2004	23 Jul 2004	23 Jul 2004	23 Jul 2004	24 Jul 2004
<b>HYDROCARBONS</b>										
Benzene	mg/L	< 0.0005	0.0342	0.214	0.278	0.189	6.05	8.24	0.0377	< 0.0005
Toluene	mg/L	< 0.0005	0.234	1.23	0.707	0.762	5.3	16.8	0.0017	< 0.0005
Ethylbenzene	mg/L	< 0.0005	0.0313	0.566	0.113	0.192	0.429	0.981	< 0.0005	< 0.0005
Xylenes	mg/L	< 0.0005	0.224	3.66	0.521	1.5	2.63	4.8	0.0022	< 0.0005
Total BTEX	mg/L	< 0.0005	0.5235	5.67	1.619	2.643	14.409	30.821	0.0416	< 0.0005
F1-BTEX (C6-C10)	mg/L	< 0.1	0.2	5.4	1.9	4.9	10.5	< 0.1	< 0.1	< 0.1
F2 (>C10-C16)	mg/L	< 0.1	0.2	2.2	0.8	2.4	1.6	2	< 0.1	< 0.1
<b>FIELD PARAMETERS</b>										
Dissolved Oxygen (deep)	mg/L	0.34	0.93	0.8	0.65	0.55	0.4	0.28	3.7	0.96
Redox Potential (deep)	mV	156	85	86	67	60	63	76	187	156
pH (deep)	pH units	7.86	7.72	7.85	8.04	8.01	7.91	7.88	7.66	7.86
Temperature (deep)	°C	5.74	6.17	5.49	6.63	5.64	5.89	5.92	6.7	6.23
<b>GEO-CHEMICAL PARAMETERS</b>										
Alkalinity Total	mg/L	466	585	580	492	530	543	604	608	510
Dissolved Nitrate	mg/L	0.6	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	2.1	0.3
Iron (total)	mg/L	0.491	5.837	13.24	9.871	13.22	19.28	16.42	0.125	0.358
Ferrous Iron	mg/L	0.02	1.35	5.54	2.35	3.31	3.17	4.2	0.01	0.02
Sulfate (dissolved)	mg/L	30	37	24	20	27	37	8	20	26
Methane	mg/L	0.0011	0.00084	0.00095	0.0072	0.016	0.0018	0.0064	0.0002	0.00085
Carbon Dioxide	mg/L	40.2	54.5	79.2	55.6	71.9	83.3	109	75.5	49.5
<b>BART SYSTEM</b>										
HAB Population	thousands (p.a.c./ml)	16	500	500	500	1600	25	40	2.5	20
Population Type		anaerobic	aerobic	aerobic	aerobic	aerobic	anaerobic	aerobic	aerobic	aerobic



Figure 2 Total BTEX Concentrations versus Location Along Plume Centre Line (Soil)

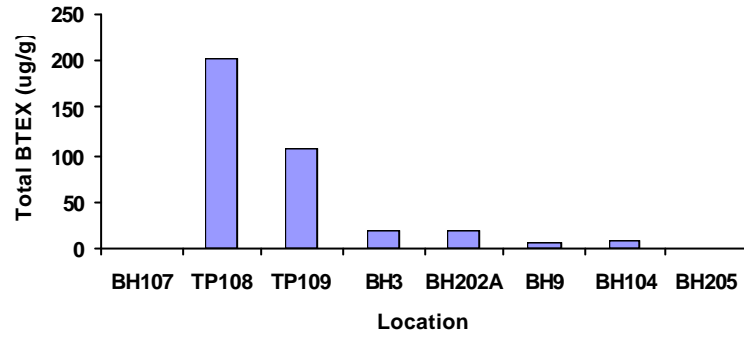


Figure 3 Total BTEX Concentrations versus Location Along Plume Centre Line (Groundwater)

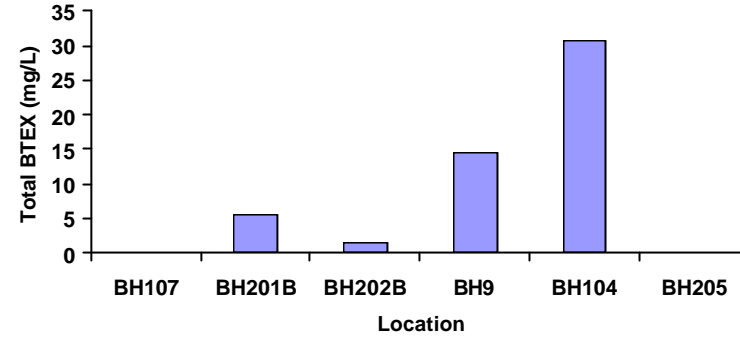


Figure 4 F2 Concentrations versus Location Along Plume Centre Line (Groundwater)

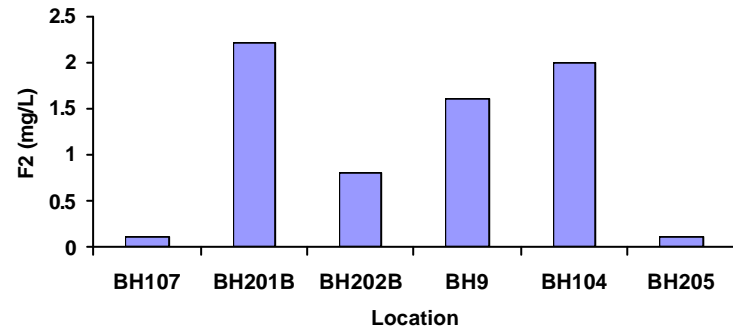


Figure 5 Log HAB Populations versus Location Along Plume Centre Line

