APPENDIX A
EX-SITU REMEDIATION TECHNIQUES

APPENDIX A: EX SITU REMEDIATION TECHNIQUES

DEFINING EX-SITU REMEDIATION

Ex-situ remedial techniques aim to remove contaminated mass from media using a variety of technique that all include at a minimum physical soil manipulation. During this initial process, soil is broken down into agglomerates resulting in a significant increase in surface area, encouraging contaminant partitioning from soil to air. The volatilization rate, or emission flux, is dependent on a chemical concentration gradient between the soil and ambient air, the diffusive resistance within the soil matrix, and on convective mass transfer rates in the air adjacent to the soil (Devaull, 2001). To further encourage contaminant breakdown and liberation often multiple techniques are used (i.e. excavation and exposure, in conjunction with chemical reduction/oxidation). Techniques that are employed onsite and do not require the transport of soil will eliminate transport emissions and but include the equipment and process emission from onsite activities.

Excavation & Exposure

The excavation and removal of contaminated soils is necessary for all ex-situ remedial techniques. The impacted medium is physically extracted and either transported to the process unit (assumed on-site), treated, and the treated soil may be used as fill at the site. Soils are treated aboveground, and this technique is sometimes referred to as land farming. Soil handling generally involved in this process, influencing volatility, includes dumping, grading, sizing and feeding soil into treatment processes. Procedural elements of this process will also influence the volatility, like the duration and vigorousness of the soil handling, rate of excavation, the dumping drop height, the shape of the piles, and the size of the equipment used (smaller bucket size will increase surface area exposure). The main emission points for soil disturbance includes exposed wastes in pits or trenches, material as it is physically processed (i.e. dumped from the excavation bucket or passed through an aeration auger) and soil storage units or biopiles (US EPA, 1997). Often soil may be physically aerated through tilling, or auguring to improve aeration and volatilization. Importantly, contaminants are also exposed to ultra-violet light enhancing contaminant transformation. Particulate emissions will be higher depending on the aggressiveness of the physical treatment process.

Volatilization through Soil Manipulation

Physical soil manipulation and processing to encourage contaminant volatilization by increasing the total exposed area of the soil often uses mechanical processors to pulverise and aerate the soil material. One mechanical processor commonly applied is an allu bucket, which usually contains an internal rotating drum, or some form of an internal crushing/screening system, generally controlled by the operator. This physical processing pulverizes the soil matrix, removing any hardened soil aggregates, and separates any large rocks, roots or other large items of organic matter. This pulverized soil is then passes through the screen and released some distance to the ground, generally 2-5 meters or the height of the bucket.

As the soil is released to the ground, which aerates the soil and encourages volatilization, the soil volume also dries and warms to ambient air temperatures. The drying and warming of the soil, in addition to the reduced aggregate size and increased surface area, encourage contaminant volatilization reducing contaminant concentrations in the soil. Little information is available on allu processing efficiencies, however, the

required number of soil passes through the allu bucket to volatilize a sufficient mass of contaminant will depend on the soil moisture content, the amount of organic carbon present in the soil, the ambient air temperatures and the initial contaminant concentrations.

Biological Treatment

This treatment technique refers to a broad range of technologies such as bio-treatment cells, soil piles, composting, and prepared treatment beds. These treatments usually involve placing excavated soil into above ground enclosures or spreading it over treatment beds that may include aeration of leachate systems. These systems allow for increased control on environmental factors influencing biodegradation processes and rates. Often in addition to the physical treatment design (i.e. treatment cells) the addition of oxygen, nutrients, water or microorganisms may be done to enhance the breakdown of contaminants. Active aeration, also using tilling, dumping, auguring, or even forced air flow with fans improves soil aeration and contact between the microorganisms and the contaminants; nutrients, microorganisms or soil amendments are routinely added at this time. Emission points are similar to excavation and removal and generally regarded as area emissions, but the main emission points would include exposed waste in excavation pit or pile and material as it is dumped from the excavation bucket (US EPA, 1997). Emissions tend to increase with an increase in surface turbulence due to wind or mechanical agitation. Temperature affects emissions through its influence on microbial activity, as well as increasing chemical volatility. Microbial degradation of contaminants to encourage volatile losses takes more time than exposure alone.

Chemical Reduction/Oxidation

As with the other ex-situ techniques, this soil treatment technique involves the extraction of contaminated material and the addition of reducing/oxidizing agents to chemically reduce contaminant concentrations and create more stable, less mobile or inert compounds, as well as stimulating aerobic microbial degradation through the presence of oxygen released during decomposition (Goi et al., 2009). Commonly used reducing agents are hydrogen peroxide, hypochlorites, chlorine, and chlorine dioxide (Environment Canada, 2002). This technique will generally require less soil disturbance than excavation and exposure alone and will therefore be expected to have less particulate matter emissions.

Thermal Desorption

Low and high temperature thermal desorption involves exposing the excavated material to heat, encouraging the volatilization of water and organic contaminants. Low temperature thermal desorption utilizes temperatures from 95 – 315 ºC, while high temperature thermal desorption applies temperatures ranging from 315 – 540 ºC, and these higher temperatures facilitate the removal of less volatile compounds. Both treatments control the residence time of heat application, designed to volatilize selected contaminants but not oxidize them, and not incinerate the soil. These techniques, in comparison to the other ex-situ techniques reviewed, would require fuel addition to generate the required desorption temperatures creating additional site emissions, in addition to the excavation equipment emissions and soil volatile losses.

APPENDIX B
REVIEW OF EMISSIONS MODELS

Appendix B:
Review of Emissions Models

MODELS TO ESTIMATE AIR CONCENTRATIONS FROM CONTAMINANT PARTITIONING

Models based on contaminant partitioning and diffusion are appropriate for estimating the emissions of VOCs from stationary soil. This would include emissions from excavations and from stockpiled contaminated soils.

Jury Model

The original Jury model was published in 1983 and updated with a simplified equation in 1990. It is used to calculate volatilization losses for both infinite and finite sources. In general, both versions of the model describe the vapour-phase diffusion of the contaminants to the soil surface and loss by volatilization to the atmosphere, establishing the relationship between vapour and solute diffusion and adsorption by defining total phase concentration partitioning as it relates to the effective diffusion coefficient. Each model predicts an exponential decay curve over time once equilibrium is achieved; determined by the rate at which contaminants diffuse upward. The simplified equation applies the following assumptions (US EPA, 1996b):

- uniform soil properties,
- instantaneous linear adsorption,
- linear liquid-vapour partitioning
- soil concentration is below saturation limit,
- no stagnant air layer, or boundary layer thickness,
- no water evaporation or leaching,
- no chemical reactions, including biodegradation or photolysis, and
- diffusion occurs simultaneously across the upper boundary and the lower boundary.

The model is therefore limited to surface contamination extending to a known depth and does not account for subsurface contamination covered by a layer of clean soil. Both models do not account for the high initial rate of volatilization before equilibrium is attained and will tend to under-predict emissions during this period (Environmental Quality Management, 1995). The model does also not consider mass flow of contaminants due to water movement in the soil profile, or the volatilization rate of saturated soils or non-aqueous phase liquids.

US EPA commissioned a study to validate the relative accuracy of the Jury volatilization models using experimental emission flux data (Environmental Quality Management, 1995). From the results of this study, it was concluded that for the compounds included in the experimental data, both models showed good agreement with measured data given the conditions of each test. Each model demonstrated a high agreement with bench-scale measured values, and to a lesser extent the infinite source model showed reasonable agreement with pilot-scale data, and overall these models are expected

make reasonable estimates of loss through volatilization at the soil surface given the boundary conditions of each model.

The simplified finite source model as implemented by US EPA (1996b, 2002) is shown below. The apparent diffusivity is calculated first, followed by contaminant flux. Finally, once the contaminant flux is calculated a volatilization factor is calculated. US EPA has created a publically available model largely based on the Jury model called EMSOFT which could be used to calculate volatilization factors.

$$J_s = C_o\left(\frac{D_A}{\pi t}\right)^{\frac{1}{2}}\left[1-\exp\left(\frac{-d_s{}^2}{4D_A t}\right)\right]$$

where:

J_s = contaminant flux at ground surface (g/cm^{2}sec)
C_o = uniform contaminant concentration at t=0 (g/cm^3)
D_A = apparent diffusivity (cm^2/s)
d_s = depth of uniform soil contamination at t=0 (cm)
t = time (seconds)

$$D_A = \frac{\left[\frac{\theta_a{}^{10/3} D_i H' + \theta_w{}^{10/3} D_w}{n^2}\right]}{\left(\rho_b K_d + \theta_w + \theta_a H'\right)}$$

where:

D_A = apparent diffusivity (cm^2/s)
θ_a = air filled porosity
n = total soil porosity
θ_w = water-filled soil porosity
D_w = diffusivity in water (cm^2/s)
D_i = diffusivity in air (cm^2/sec)
H' = dimensionless Henry's Law constant
ρ_b = soil dry bulk density (g/cm^3)
K_d = soil-water partition coefficient (cm^3/g)

$$VF = \left(\frac{Q}{C}\right)\times\left(\frac{C_o}{\rho_b}\right)\times\left(\frac{1}{J_s}\right)\times 10^{-4}$$

where:

VF = volatilization factor (m^3/kg)
J_s = contaminant flux at ground surface (g/cm^{2}sec)
C_o = uniform contaminant concentration at t=0 (g/cm^3)

ρ_b = soil dry bulk density (g/cm^3)

$\frac{Q}{C}$ = inverse concentration factor for air dispersion (g/m^2 per kg/m^3). If an area emission rate of 1 g/m^{2}s is assumed, then (Js x 10^{-4} cm^2/m^2) = 1, and the equation simplifies to simply the inverse of the maximum contaminant air concentration (kg/m^3).

American Society for Testing and Material Model

The American society for Testing and Materials (ASTM, 2004) has published equations to develop risk based screening levels for contaminant volatilization from soil and migration to air. Two separate scenarios can be modelled with these equations: one assuming contamination is exposed to air, and the second assuming that there is clean soil overlying the contamination. Both scenarios require calculation of a dispersion factor for air. Separate approaches are used to calculate a volatilization factor from soil to air depending on whether contamination is directly exposed to air.

The surface soil model includes the following assumptions:

- The contaminant is uniformly distributed in the affected soils.
- Partitioning between sorbed, dissolved and vapour phases is based on linear equilibrium partitioning.
- The chemical diffuses through the surficial soil layer.
- There is no biodegradation or other loss of the chemical.
- Vapours are well mixed in the atmosphere as modelled by a box model.
- If the time-averaged flux exceeds what would occur if the entire mass of contaminant was volatilized over the averaging time, then the volatilization factor can be determined using a mass balance relationship instead.

Depth to source can be adjusted to reflect the depth from the base of the excavation to the source. Alternatively, when groundwater is pooled in the trench a volatilization factor can be calculated accounting for loss from groundwater instead of soil. Risk-based screening levels from soil can be calculated using the volatilization factor and a target concentration in air.

$$DF_{amb} = \frac{U_{Air} \times W \times \delta_{Air}}{A}$$

where:

DF_{amb} = dispersion factor for ambient air from trench surface (cm/s)

U_{Air} = ambient air velocity in mixing zone (cm/s)

W = width of source-zone area (cm)

δ_{Air} = mixing zone height (cm)

A = source-zone area (cm^2)

$$D_{eff-vadose} = D_{air} \times \left(\frac{\theta_{air}^{3.33}}{n^2} \right) + D_{water} \times \left(\frac{\theta_{water}^{3.33}}{H_{eff} \times n^2} \right)$$

where:

$D_{eff-vadose}$ = dispersion factor for ambient air from trench surface (cm^2/s)
D_{air} = molecular diffusion coefficient in air (cm^2/s)
D_{water} = molecular diffusion coefficient in water (cm^2/s)
H_{eff} = effective Henry's Law coefficient (dimensionless)
θ_{air} = volumetric air content of soil (dimensionless)
θ_{water} = volumetric water content of soil (dimensionless)
n = total soil porosity (dimensionless)

VF_{ss} = the lower of $VF_{ss,1}$ or $VF_{ss,2}$:

$$VF_{ss,1} = \frac{\rho_b}{DF_{amb}} \sqrt{\frac{4 \times DF_{eff-vadose} \times H_{eff}}{\pi \times t \times 31536000\ sy^{-1} \times K_d \times \rho_b}}$$

$$VF_{ss,2} = \frac{\rho_b \times L_{ss}}{DF_{amb} \times t \times 3153600 \text{sec}/\ yr}$$

where:

VF_{ss} = volatilization factor, surficial soil to ambient outdoor air (g/cm^3)
DF_{amb} = dispersion factor for ambient air (cm/sec)
ρ_b = soil bulk density (g/cm^3)
L_{ss} = thickness of surficial soils (cm)
t = average time for surface emission vapour flux (yrs)
$D_{eff-vadose}$ = dispersion factor for ambient air from trench surface (cm^2/s)
H_{eff} = effective Henry's Law coefficient (dimensionless)
K_d = soil to water partition coefficient (cm^3/g)

$$VF_{sub} = \frac{1}{\left(1 + \frac{DF_{amb} \times L_s}{D_{eff-vadose}} \right) \times \frac{K_d}{H_{eff}}}$$

where:

VF_{sub} = volatilization factor, subsurface soil to ambient outdoor air (g/cm^3)
DF_{amb} = dispersion factor for ambient air (cm/sec)
$D_{eff-vadose}$ = dispersion factor for ambient air from trench surface (cm^2/s)

H_{eff} = effective Henry's Law coefficient (dimensionless)

L_s = depth to subsurface soils (cm)

K_d = soil to water partition coefficient (cm^3/g)

$$RBSL_s = \frac{RBSL_{air}}{VF} \times 10^{-3}$$

where:

$RBSL_s$ = risk-based screening level for soil (mg/kg)

$RBSL_{air}$ = risk-based screening level for air inhalation (mg/m^3)

VF = volatilization factor, soil to ambient air (g/cm^3)

Note: the VF used in the above equation will correlate to either the subsoil or surface soil volatilization; only one will be used to calculate the risk-based soil screening level.

This model assumes that vapour concentrations remain constant over the duration of exposure and all inhaled chemicals are absorbed. The calculation of the diffusion coefficient from the vadose zone assumes homogeneous soil layers. These equations published by ASTM (2004) are part of a body of equations used to develop risk-based screening levels and generally have a high level of regulatory acceptance. The application of these equations to a trench exposure scenario can be done through the manipulation of model inputs to reflect the source area and mixing zone of the trench, but are essentially applied without change.

The basis of the equations is not thoroughly documented. There is a reference to the US EPA (1988) Superfund Exposure Assessment Manual, but the specific equations published by ASTM (2004) do not appear to be in that document.

RTI Land Treatment Emission Model

The US EPA has published a model estimating emissions from the application of contaminated material onto land surfaces and during land treatment, developed by Clark Allen and referred to as the RTI model. The model, considered to be best suited for waste-piles by the US EPA due to a sound scientific basis, reasonable available input data, consideration of evaporative loses and diffusion through air-filled pore spaces. When contaminated soil is disturbed, volatile compounds have the potential for partitioning into four different phases: a vapour phase, an oil phase where volatiles are dissolved in the oil, a water phase where volatiles are dissolved in the soil moisture, and a soil phase where volatile material is absorbed by organic carbon within the soil (US EPA, 1994).

The RTI model is based on Fick's second law of diffusion (concentration depletion is proportional to the curvature of the concentration gradient). Multiple solutions are available for various time intervals in both approaches considering short, or long term emission lengths. When material containing volatile organics is applied onto or tilled into soil, the maximum rate of air emissions will occur immediately after application, and the highest exposure concentration is predicted during this period.

The two approaches are given to calculate short-term emission, first to calculate an instantaneous emission rate, and second to calculate the fraction of total emissions at a given time. Both of these approaches assume that emissions from the surface of the soil are limited by the diffusion of vapours though the pore spaces in the soil and further assumes that an equilibrium concentration of organic vapours exists at all times within pore spaces.

Short-term instantaneous emission rate equation:

$$E = \frac{M_o}{l}\left(\frac{1}{\frac{q_a}{K_{ea}k_G} + \left(\frac{pt}{D_e K_{ea}}\right)^{0.5}}\right)$$

Where:

E	=	emission rate of compound (g/cm^2/s)
M_o	=	initial loading of compound present (g/cm^3)
l	=	depth to which compound is found in soil (cm)
θ_a	=	air-filled porosity (unitless)
K_{eq}	=	equilibrium coefficient of compound in the soil (unitless)
k_g	=	gas phase mass transfer coefficient (cm/sec)
D_e	=	effective diffusion coefficient of compound in soil (cm^2/s)
t	=	time after initial disturbance (s)

Using:

$$K_{eq} = \frac{H_c}{Rt}10^6 \frac{q_a}{Waste_{fraction}}$$

Where:

H_c	=	Henry's Law constant for constituent (atm cm^3/g mol)
R	=	Ideal gas constant (82.1 atm cm^3/g mol k)
t	=	temperature of vapour in soil, (K)
θ_a	=	air-filled porosity (unitless)
$Waste_{fraction}$	=	volume fraction of compound in contaminated soil volume

$$k_G = 4.82(10^{-3})U^{0.78}\left(\frac{U_a}{D_a^2}\right)^{-0.67} de^{-0.11}$$

Where:

k_G	=	gas phase mass transfer coefficient (cm/sec)
U	=	wind speed (m/s)
de	=	effective diameter of land treatment area (m)
U_a	=	viscosity of air (g/cm s)
D_a	=	density of air (g/cm^3)

Fraction of emitted mass at short times:

$$F_{at} = \left(\frac{K_{eq} D_e t}{\rho l^2} \right) 2 \left(1 - \frac{1}{3} \frac{t}{t_b} \right)$$

Where:

F_{at}	=	fraction of constituent emitted to the air at time t (unitless)
K_{eq}	=	equilibrium coefficient of compound in the soil (unitless)
k_g	=	gas phase mass transfer coefficient (cm/sec)
D_e	=	effective diffusion coefficient of compound in soil (cm^2/s)
t	=	time after initial disturbance (s)
t_b	=	time constant for biological decay of constituent (unitless)

Evaluation

The Jury model (either the original version, the US EPA implementation or the Ontario implementation) and the ASTM model can address the expected scenarios for worst-case exposures to a worker at an ex-situ exposure situation. These allow for the consideration of a soil source and allow for an excavation directly in contact with contamination. The Jury model and ASTM model both have at least some degree of regulatory acceptance and review. Model field-testing has also been conducted by the US EPA to validate the relative accuracy of the Jury model; concluding sufficient agreement between the model and measured soil flux for compounds testing and has been applied to predict exposure concentrations herein. The Jury model first calculates a soil flux or rate of contaminant volatilization per unit of soil and time. This soil flux rate can then be used to calculate an air concentration as a function of time, with the concentration in air decreasing as contaminant mass is removed from soil.

The Jury model also importantly considers the loss of contaminant mass from the source over time, allowing the more accurate estimation of long-term exposures applicable to life cycle assessment considerations. Overall, based on its regulatory acceptance, field validation, and ability to predict emissions from both soil piles and excavations, the Jury model is recommended for the estimation of VOC emissions from soil piles and excavations.

ESTIMATING EX-SITU SOIL HANDLING EMISSIONS

Calculation of Emission Rates

In addition to estimating overall volatile exposures from the contaminant source, as explored above, estimating the emissions as a result of soil processing is also important to remedial exposure and life cycle emission quantification. Excavation and removal of soils contaminated with volatile compounds will increase the air exchange with soil-pore gas and the atmosphere, increasing emissions. The magnitude volatile emissions are

predicted to be a function of activity intensity, porosity and moisture content of the soil, as well as the initial concentration of VOCs.

Limited guidance is available related to the emissions from ex-situ soil processing specifically. US EPA has published related guidance on estimating air impacts during the excavation of contaminated soil (US EPA, 1992a), which outlines the calculation of an average long-term emission rate. This rate calculation uses the equation:

$$ER_{Long-term} = \frac{S_v \times C \times b \times 1}{t_R}$$

where:

$ER_{Long-term}$ = long-term emission rate (g/s)
S_v = volume of soil moved (m^3)
C = average contaminant concentration in soil (µg/g)
B = bulk density (g/cm^3)
1 = constant ($g/10^6$ µg x 10^6 cm^3/m^3)
t_r = duration of allu bucket operation (s)

This equation calculates a total emission potential as a function of remedial activity time, assuming that soil contamination is homogeneous and that volatilization of contaminants occurs at a constant rate. As this equation considers entire contaminant loss over time it is also referred to as the calculation of a long-term emission rate. While this model was not necessarily developed to predict worst case exposures, as the contaminant volatilization losses are distributed evenly over the activity time, it can quantify overall volatile losses from soil processing. This equation was applied using average soil concentrations to calculate long-term life cycle emission rates per compound from soil processing.

A short-term emission rate using the above equation can also be calculated. This modified equation removes the concentration deemed acceptable by an appropriate soil quality guideline for the subject site, calculated as:

$$ER_{Short-term1} = \frac{(C - SQG) S_v \times b \times 1}{t_R}$$

where:

SQG = soil quality guideline (µg/g)

Short-term emission rates during ex-situ soil processing, particularly at the start of soil processing, are predicted to be higher than long-term rates, which are a function of the entire processing time. Higher emission rates, resulting in higher air concentrations, are more appropriate for the calculation of worst-case worker exposure during soil treatment. Soil processing with an allu bucket was explored; this particular technique compared to other ex-situ techniques may result higher exposures due to increased aeration as soil is passed through the allu bucket and dropped to the ground. The calculation of an emission rate from soil pore space that is emitted to the atmosphere during an excavation was used (US EPA, 1992). To account for soil processing times, an allu

processing rate, which was assumed to be 25% slower than excavation rate to account for soil pulverizing and dropping, was adopted. The ExC, soil-gas to atmosphere exchange rate, was also adjusted to a value of 1, which conservatively assumes that allu treatment releases the entire fraction in pore space to the atmosphere. The above equation is based on the assumption that soil gas is saturated for each compound, and therefore may over-predict the emission rate.

$$ER_{Short-term2} = \frac{P \times MW \times 10^6 \times q_a \times Q \times ExC}{R \times T}$$

where:

$ER_{Short-term2}$ = short-term emission rate (g/s)
P = chemical specific vapour pressure (mm Hg)
MW = molecular weight of compound emitted (g/g-mol)
Θ_a = soil air-filled porosity (cm^3/cm^3)
Q = allu processing rate (m^3/s)
ExC = soil-gas to atmosphere exchange rate (m^3/sec)
R = gas constant (mmHg-cm^3/g-mol°K)
T = temperature (°K)

The calculation of an emission rate considering soil concentration and partitioning to soil vapour was also explored to compare the emission rates with the above equation. Soil vapour was calculated using the following equation (CCME, 2006):

$$C_{Vapour} = \frac{H' \times C_{Soil} \times r_b}{q_w + K_d \times r_b + H' \times q_a}$$

where:

C_{Vapour} = soil vapour concentration (g/cm^3)
H' = henry's law constant (unitless)
C_{Soil} = soil concentration (g/g)
ρ_b = soil dry bulk density (g/cm^3)
Kd = soil-water partition coefficient (cm^3/g)
Θ_a = soil air-filled porosity (cm^3/cm^3)

Soil vapour, as calculated above was then substituted into a modified version of the equation for the calculation of short emissions ($ER_{Short-term}$). The equation was adjusted to remove the consideration of soil vapour based on vapour pressure, and include the calculated soil vapour concentration based on soil partitioning. This modified equation calculated and short-term emission rate based on soil partitioning as:

$$ER_{Short-term3} = C_{Vapour} \times 10^6 \times q_a \times Q \times ExC$$

where:

$ER_{Short-term3}$ = short-term emission rate (g/s)

C_{Vapour} = soil vapour concentration (g/cm^3)
Θ_a = soil air-filled porosity (cm^3/cm^3)
Q = allu processing rate (m^3/s)
ExC = soil-gas to atmosphere exchange rate (m^3/sec)

Estimation of Ambient Air Concentrations

Ambient air, or outdoor air concentrations, that a worker may be exposed to during ex-situ soil processing can be estimated by applying a box model to estimate outdoor air concentrations. Conceptually, the emitting source will contribute emissions to a defined box area, at the rate defined by the emission rate, with pollutants removed from this theoretical box by wind. To estimate emission to a worker, the box was defined as the length of the emitting source and the height of the allu bucket. Wind speed will act as a lateral dispersion force. This box model is predicted to conservatively estimate ambient air concentrations, as it does not account for dispersion influences and applies conservative limits on the box area. Ambient air concentrations were calculated as:

$$C_{Air\_ST} = \frac{ER_{Short-term} \times 1000}{U \times Allu_h \times L}$$

where:

$C_{Air\text{-}ST}$ = short-term air concentrations (mg/m^3)
$ER_{Short\text{-}term}$ = short-term emission rate (g/s)
U = wind speed (m/s)
$Allu_h$ = height of allu bucket (m)
L = source length (m)

Long-term ex-situ air concentrations can be estimated for the life cycle assessment substituting the long-term emission rate in place of the short-term emission rate.

Evaluation

The calculation of a short-term emission rate reflective of more realistic worker exposures is based on an emission rate that considers an allu processing time ($ER_{Short\text{-}term2}$). This short-term emission rate may over-predict the emission rate, as it assumes vapour saturation in soil pore spaces. Soil vapours are not expected to be saturated during soil handling operations at most sites when contaminant concentrations in soil are below saturation limits, and therefore the partitioning version is likely more appropriate than assuming saturated vapours. Where soil concentrations are high enough to result in saturated soil pore space, the partitioning relationship will result in saturated vapours. The predicted emission rates from the calculation of $ER_{Short\text{-}term3}$ considering soil partitioning and $ER_{Short\text{-}term1}$ considering soil quality guideline remediation levels should be compared, with the highest value used for exposure calculations.

The calculation of this short-term emission rate assumes that remedial activity using an allu soil treatment method will occur up to the guideline value only.

MODELS TO ESTIMATE LANDFILL EMISSIONS

Landfill emission models, commonly used in greenhouse gas accounting were reviewed. However, most of these models are based on the annual reporting requirements for municipal landfills and do not consider the total contaminant lifetime emissions but rather emissions as a function of time.

Models used for the estimation of landfill gas emissions typically focus on the generation of methane through biodegradation of the initial waste substrate. This process occurs at a rate described by Monod's equation:

$$\frac{dC}{dt} = \frac{KxC}{K_c + C}$$

where:
C = concentration of substrate at time t
x = concentration of micro-organisms
K = maximum rate of substrate utilization
K_c = substrate concentration when rate is half of maximum rate

Zero order models assume generated landfill gas is constant and does not consider age or type of waste, first order models consider the depletion of carbon in the waste over time and are affected by waste characteristics, and second order models also consider different reaction rates of a number of degradation reactions (Kamalan, 2011).

Zero Order Models

Zero order models are straight forward and require minimal input regarding temporal changes to the landfill material, and are most appropriate for substrates with very high concentrations of contaminants and consistent communities. Examples of zero order models include EPER Germany, SWANA, and IPCC. The generic form of a zero order model is:

$$Q = M \times R$$

where:
Q = methane generation rate (mass/time)
M = mass of waste (mass)
R = carbon to methane conversion rate (1/time)

Models may also account for various inefficiencies in the biodegradation process with additional factors for carbon content, landfill gas recovery, lag time in methane generation etc. as appropriate.

First Order Models

First order models are the most common landfill emission models as they can consider the effect of biodegradation reducing the overall carbon content in the waste material. These models are more appropriate for contaminated material with a lower concentration of organic material and, much like zero order models, assume a constant microbial community. Examples of first order models include: SWANA, TNO, LandGEM, GasSim, Afvalzord, EPER France, Mexico FLG, and LFGGEN. The generic form of a first order model is:

$$Q = M \times R \times e^{-kt}$$

where:
Q = methane generation rate (mass/time)
M = mass of waste (mass)
R = carbon to methane reaction rate (1/time)
k = degradation rate constant (1/time)
t = time

A common feature of these models is the use of broad waste categories to describe the carbon content in the initial material and generic descriptors of landfill conditions accounting for moisture and biodegradation rates.

US EPA Model (LandGEM)

The US EPA has included a first order model for determining methane emissions from municipal solid waste landfills in the *Mandatory Reporting of Greenhouse Gases; Final Rule* (2009). This is intended as a tool to determine yearly greenhouse gas emissions, but could easily be modified to calculate total emissions.

The formula used is as follows:

$$G_{CH4} = \sum_{x=S}^{T-1} \left[W_x L_{0,x} \left(e^{-k(T-x-1)} - e^{-k(T-x)} \right) \right]$$

where:
G_{CH4} = methane generation rate (mass methane/time)
x = year in which waste was disposed
S = start year of calculation
T = reporting year for which emissions are calculated
W_x = quantity of waste disposed of (mass waste)
L_0 = methane generation potential (mass methane/mass waste)
k = rate constant (1/time)

Methane generation potential is the mass of methane generated from a specified mass of waste and is calculated as follows:

$$L_0 = MCF \times DOC \times DOC_F \times F \times (16/12)$$

where:

L_0 = methane generation potential (mass methane/mass waste)
MCF = methane correction factor (unitless, default value is 1)
DOC = degradable organic carbon (mass carbon/mass waste)
DOC_F = fraction of DOC dissimilated (unitless, default value is 0.5)
F = fraction of methane in landfill gas (unitless, default value is 0.5)

Further calculations are available to account for methane recovery units and oxidation of methane in cover material. The adjustment for oxidation is done using the following formula:

$$Q = G_{CH4} \times (1 - OX)$$

where:
Q = adjusted methane generation rate (mass methane/time)
G_{CH4} = methane generation rate (mass methane/time)
OX = oxidation fraction (unitless, default value is 0.1)

Default values are provided for all necessary parameters, with additional values for the degradable organic carbon and methane generation rate constants that are based on waste composition. As this model is intended for municipal landfills no values have been provided specifically for contaminated soils. This model is publically available as a spreadsheet tool.

CCME Biosolids Emission Estimation Model

The Canadian Council of Ministers of the Environment (CCME) recently published an updated version of the Biosolids emission estimation model, intended for the calculation of greenhouse gases generated from the transformation of biosolid contained carbon disposed of in municipal landfills. This model, although it does not consider petroleum waste specifically, considers the disposal of organic carbon mass applying conversion and uncertainty factors to the generation of carbon dioxide and methane. The default inputs referenced in this model as well as the general approach were reviewed and thought to be appropriate based on the current publically recognized inputs and national scope of the publication.

Within the references and assumptions sheet of this spreadsheet tool, inputs used for the landfill disposal scenario are listed including the proposed fraction of methane in landfill gas (50%), a methane correction factor for semi-aerobic landfills (50%) and a model correction factor of (90%) to account for model uncertainties, which were applied. While this scenario is intended to consider an anaerobic landfill scenario, the landfill will transition from aerobic to anaerobic and this correction factor of 50% for semi-aerobic landfills was thought appropriate. Conversion factors converting carbon to methane or carbon dioxide were also applied of 1.3 and 3.667 respectively.

While this model considers the organic carbon present in the soil as available for decomposition this was not considered as this organic carbon will too eventually break down in the ex-situ scenario and introduced unnecessary error and uncertainty.

Landfill methane emissions were calculated using the following formula:

$$CH_4 emissions = C_{mass} \times Fraction_{CH_4} \times Fraction_{uncertainty} \times Correction_{CH_4} \times CF$$

where:

Cmass	= total mass of carbon from contaminants
Fraction $_{CH4}$	= fraction of methane in landfill gas
Fraction$_{uncertainty}$	= model correction factor to account for uncertainties
CF	= conversion factor, carbon to methane
Correction$_{CH4}$	= Methane correction factor, to account for uncertainties in landfill conversion from aerobic to anaerobic gas generation

Once the predicted methane emissions were calculated with the equation above, the remaining carbon that was calculated remaining in the landfill and not converted to methane was assumed to be eventually emitted to the atmosphere as carbon dioxide and accounted for as such.

Evaluation

The CCME Biosolids Emission Estimation model was selected to calculate greenhouse gas emission from landfill disposal. This model was published by a Canadian regulatory agency, applied the most current application accepted model correction factors from the International Panel on Climate Change, was macro in focus and is not limited to a specific time period. This model is considered appropriate for the life cycle assessment that did not consider the influences of time, but rather considered the contaminant life cycle, which was assumed completed during the emission of contaminant breakdown products carbon dioxide and methane.

MODELLING PARTICULATE EMISSIONS

For the purposes of this life cycle assessment, particulate emissions from vehicular road traffic, non-road equipment processes such as excavation as well as particulate emissions from combustion by-products are required. There are a number of applicable established emission models published by both by regulatory agencies, and industry for activity specific emission calculations.

Particulate Emissions from Combustion Engines

For non-road engines used during remedial activities, including bulldozers, excavators, backhoes, and generators it can often be difficult to attempt emission estimations partly because the power output of these engines is a function of the fuel used and thus emissions. Emission factors applied in the calculation of exhaust emissions are frequently used.

The NONROAD model applies an emission factor that is a function of horse power use per hour, assuming a constant power output and the emissions calculation is a function of time (rather than fuel use). The NONROAD model does not consider Canadian fuel characteristics and because of the constant power output that is assumed may not be applicable to remedial situations which encompass variable horse power outputs.

More recently, studies have been conducted to measure non-road equipment emissions in the field and generate equipment specific emission factors and fuel usage based on equipment model and specific soil handling activity; data are presented in both fuel and time-based emission rates (Frey et al., 2010). Fuel-based emission rates tend to have less variability and higher certainty than time-based emission rates. Therefore, the development of emission inventories based on quantifying fuel consumed, rather than time of operation, is preferred where possible (Frey et al., 2010). The results from these field measurements indicate that the results are highly dependent on the type of soil handling activity that is being performed, and may be a preferred method for emissions estimations in ex-situ situations. Alternatively for vehicular road traffic, it may be more applicable to apply an emission factor based on distance travelled for vehicular road traffic, rather than a fuel use alone because of the dependence on distance travelled on particulate matter generation and that generally engine power output is more consistent for highway travel.

GHGenius Model

In Canada, the GHGenius model has been developed for Natural Resources Canada, capable of analyzing emissions from conventional internal combustion engines for light duty vehicles, and class 3 - 8 heavy-duty trucks for both diesel and gasoline combustions. This comprehensive model considers many aspects of life-cycle emissions relating to vehicle operation, fuel dispensing, distribution and storage and considers all criteria air contaminants, greenhouse gases, particulate matter emissions, and non-methane organic compounds, and can be applied to an individual vehicle perspective. This model is based on an algorithm from a US EPA model, MOBILE 6.2, subsequently adapted to Canadian vehicles and environment by Environment Canada, and appears to be the most current model for calculating in-use emission from light and heavy duty motor vehicles considering Canadian fuel composition, climatic conditions, and road types. Data are obtained from Canadian sources including Statistics Canada, Natural Resources Canada, Environment Canada and the National Energy Board; Canadian Association of Petroleum Producers (CAPP) and the Canadian Gas Association (CGA) have also been used as sources of data. This model is publically available at www.ghgenius.ca

The usable portion of this comprehensive model includes the light-duty and heavy-duty emissions in g/km for diesel and gasoline engines, under the exhaust emission tab, as well as the Emissions Factors by device under Tab ‘n’. Using distance travelled to estimate emissions may not accurately estimate emissions during remedial activities as equipment is often running but not travelling, and stationary equipment is therefore not considered. An estimation of emissions based on fuel input may be more appropriate, which can be seen in Table 5. The US EPA (1996a) AP-42 Emission Factors document establishes emissions factors for diesel and gasoline engines in both power output and fuel input (lb/mm Btu), similar to the emission factors produced by the GHGenius model. Based on the consideration of Canadian fuel characteristics and the variety of equipment

considered in the GHGenius model this spreadsheet tool was used in the calculation of emissions from all associated equipment. Fuel usage by equipment model and type was taken from Frey et al., 2007 and 2010, which is referenced in the model.

This model was also used to estimate other criteria air contaminants other than particulate matter including N_20, NO_x, SO_x, volatile organic compounds, CH_4, CO and CO_2. The same process where fuel usage by equipment type was applied to the emissions factors provided by the GHGenius model for Canadian fuel specifications was used.

Equipment Process Particulate Matter Emission Modelling

Few models are available for the estimation of particulate emissions specifically from remedial processes and many of the applicable available models do not consider the adsorbent properties of petroleum hydrocarbons influencing particulate emissions during soil disturbance and processing. US EPA, Environment Canada and the Ontario Ministry of Environment all use a set of applicable equations for various remedial processes based on the publically available US EPA methods. To estimate equipment emissions of particulate from various soil handling processe are generally accepted as the definitive source of construction related particulate emissions, and have been applied for applications in this report.

Particulate emissions from all transfer operations (i.e. adding to or removing from piles, conveyor belts, truck dumping etc.), US EPA (1993):

$$E = \frac{k(0.0016)M\left(\frac{U}{2.2}\right)^{1..3}}{\left(\frac{q_w}{2}\right)^{1.4}}$$

Where:
E = emissions (g)
k = particle size multiplier (unitless)
M = mass of waste handled (Kg)
U = mean wind speed (m/sec)
Θ_w = soil moisture content (%)
0.0016 = empirical constant (g/kg)
2.2 = empirical constant (m/sec)

Particulate emissions during mixing and tilling (waste incorporation and cultivation), US EPA (1993):

$$E = k\left(0.00538\right)SA \times 10^{-4}\left(s\right)^{0.6}$$

Were:

E = emissions (g)
k = particle size multiplier
10^{-4} = conversion factor (hectare/m^2)
SA = area treated (m^2)
s = percent silt content (%)
0.00538 = empirical constant (g/hectare)

Percent silt content was estimated from typical soil texture composition in glacial till, which generally comprises sand, clay and till representing a one third portion each. Based on this a default silt content was estimated to be 30%, however, site specific information related to soil texture would help to more accurately define this proportion and is recommended where available.

Particulate emissions during soil being spread by a bulldozer or any other tractor with a blade can be calculated as a function of time with the following equation, US EPA (1993):

$$ER_{PM10} = \frac{0.094 \times s^{1.5}}{q_w^{1.4}}$$

Where:
ER_{PM10} = PM_{10} emission rate (g/sec)
s = percent silt content (%)
Θ_w = percent moisture content (%)
0.094 = empirical constant (g/sec)

In addition to these equations, there is also published guidance on emission factors from area sources that may be applicable if the requirements for field data cannot be met and default input variables seem inappropriate. Published applicable emissions factors are available for activities relevant to this study such as: loading of excavated material into trucks, truck dumping, truck transport, debris and soil handling, soil haulage, scrapers unloading topsoil, and vehicular traffic (US EPA, 1995).

Vehicular Transport Particulate Emission Modelling

Dust emissions for both paved and unpaved roads vary with the weight of the vehicle, and the silt content (or silt loading content in paved roads); unpaved road dust emissions will also be dependent on the vehicle speed, the number of vehicle wheels, and in Canada the number of days where dust can be liberated (no snow cover). Environment Canada has published guidance on estimating road dust from industrial unpaved surfaced, adopted from US EPA (2010), with an adjustment for snow covered days, no guidance is provided for particulate emissions from paved road traffic. Ontario (1999) has published guidance on particulate emissions from vehicular traffic on paved roads, which is adopted from US EPA (2010). Particulate emissions from paved roads are due to direct emissions from vehicles in the form of exhaust, brake wear, tire emissions, and resuspension of loose material on the road surface.

Particulate emissions from resuspension of loose material on the road surface due to vehicle traffic on a dry paved road, US EPA (2010). Note that in the equation below, the weight is modified by a factor of 2.72 instead of 3 to allow for metric vehicle weights, as per Environment Canada (2009) guidance:

$$EF_{Paved1} = k\left(\frac{sL}{2}\right)^{0.98} \times \left(\frac{W}{2.72}\right)^{0.53} \times \left(\frac{S}{30}\right)^{0.16}$$

The above equation is an update, and Ontario (1999) modified an older equation to reflect snow and precipitation influences:

$$EF_{Paved2} = k\left(\frac{sL}{2}\right)^{0.65} \times \left(\frac{W}{2.72}\right)^{1.5} \times \left(\frac{365-p}{365}\right)$$

The new US EPA equation could be updated to include precipitation influences becoming:

$$EF_{Paved3} = k\left(\frac{sL}{2}\right)^{0.98} \times \left(\frac{W}{2.72}\right)^{0.53} \times \left(\frac{s}{30}\right)^{0.16} \times \left(\frac{365-p}{365}\right)$$

Where:

EF	= particulate emission factor (g/vehicle km travelled)
k	= particle size multiplier (g/vehicle km travelled)
sL	= road surface silt surface loading (g/m^2)
S	= average speed of vehicle (km/hr)
s	= percent silt content of road surface (%)
W	= mean vehicle weight (tonnes, metric)
w	= mean number of wheels per vehicle
S	= average speed (km/hr)
p	= number of days with <0.01 inches precipitation

Days with <0.01 precipitation are assumed to have no particulate emissions from the resuspension of particles. Based on this the US EPA, 2010, equation maybe the most applicable given the recent update to equation factors and the total calculation of emissions.

Particulate emissions from vehicular traffic can also be estimated using Environment Canada's, NPRI (National Pollutant Release Inventory) Toolbox, guidance on estimating road dust emissions from industrial unpaved sources. While models are available from the US EPA and the Ontario MOE, a trial run of these models produced emissions considerably higher than the model from the NPRI toolbox and was deemed inappropriate with our data inputs. Considering that the Environment Canada model is currently used to calculate national industrially relevant reportable emissions, it was applied here to calculate vehicular traffic particulate emissions.

Particulate emissions from vehicular traffic on unpaved industrial surfaces, Environment Canada, (2009):

$$EF_{Unpaved} = k \times \left(\frac{s}{12}\right)^{a} \times \left(\frac{W}{2.72}\right)^{b}$$

$$VKT = Total\ count\ of\ vehicle\ passes \times Length\ of\ Unpaved\ Road \times Operating\ Days$$

$$E_x = VKT \times EF_{Unpaved} \times ADJ$$

Where:

EF	= emission factor (g/vehicle km travelled)
k	= particle size multiplier (g/vehicle km travelled)
a, b	= numerical constant dependent on road dust particle size
s	= percent silt content of road surface (%)
W	= mean vehicle weight (tonnes, metric)
w	= mean number of wheels per vehicle
S	= average speed (km/hr)
p	= number of days with <0.01 inches precipitation
VKT	= total vehicle km travelled
ADJ	= Adjustment factor for precipitation, snow cover and frozen days (p + Snow Covered + Frozen Days)
E_x	= Particulate emissions (kg)

Modified by the Ontario Ministry of Environment (1999), accounting for number of wheels and speed:

$$EF_{Unpaved} = k \times 1.7 \times \left(\frac{s}{12}\right) \times \left(\frac{S}{48}\right) \times \left(\frac{W}{2.7}\right)^{0.7} \times \left(\frac{w}{4}\right)^{0.5} \frac{(365-p)}{365}$$

Evaluation

The models provided for particulate emissions from soil processing (US EPA, 1993) were adopted for the life cycle assessment with the rationale that currently they are really the only accepted published models for such calculations.

Both the GHGenius model and the particulate emissions from vehicular traffic model published by Environment Canada were adopted for their Canadian focus and national applicability. However, the vehicular emission models from the US EPA and the Ontario Ministry of Environment were also calculated to give context to the choice. While the basic approach is the same between the US EPA model and the Environment Canada model, the Environment Canada model applies numerical constants to the calculation dependent on road dust particle size. Environment Canada also provides useful

guidance on appropriate default values for unpaved silt road content, and further recommends the use of Environment Canada's Climate Data Online, although weather is not predicted to be an important consideration for the life-cycle assessment as most remedial activities are conducted during dry conditions. The US EPA model only calculated one number for particulate emissions (PM_{10}) and did not consider smaller particulate emission ($PM_{2.5}$), which is defined as a criteria air contaminant and was therefore not considered further. The Ontario model was published 10 years prior to the Environment Canada model, with no real change and calculated numbers are considerably higher than both the US EPA and Environment Canada model. Due to these consideration the Environment Canada particulate emissions from vehicular traffic model was selected.

The GHGenius model was used to estimate equipment emissions from engine combustion applying an emission factor. This model applied Canadian fuel specifications and applied data from Statistics Canada Data. This model was developed in consultation with Natural Resources Canada, Environment Canada and the National Energy Board; Canadian Association of Petroleum Producers (CAPP) and the Canadian Gas Association (CGA) and due to the regulatory agency consideration, the industry inclusion and Canadian focus this model was selected as appropriate for life-cycle considerations.

APPENDIX C
AMBIENT AIR QUALITY OBJECTIVES AND OCCUPATIONAL EXPOSURE LIMITS

APPENDIX C
AMBIENT AIR QUALITY OBJECTIVES AND OCCUPATIONAL EXPOSURE LIMITS

C.1 INTRODUCTION

Ambient air exposure may result in unacceptable human health risks for occupationally exposed individuals during both ex-situ remediation and landfill disposal of contaminated soil. The largest releases of landfill gas to ambient air occur when a permeable landfill cover is used, or when an impermeable cover has been breached. Onsite human exposure occurs as a function of the actual landfill gas emission rates, while offsite exposure occurs through atmospheric dispersion of emissions.

Two main types of exposure limits in ambient air are briefly summarized here:

- Ambient air quality objectives, which are maximum concentrations in ambient air deemed acceptable by regulatory agencies, most often expressed as a 1-hour average concentration but sometimes as 15-minute, 24-hour or annual average.
- Occupational exposure limits, which are used to evaluate risks to onsite workers; normally specified as either an 8-hour average concentration or a short-term exposure limit.

In addition to these limits, tolerable concentrations and risk-specific concentrations, which are health-based limits established for long-term (chronic) exposure, may also be applicable in some cases. In general these limits would only be applied for long-term exposure or in the absence of ambient air quality objectives, however.

C.2 AMBIENT AIR QUALITY OBJECTIVES

Within Canada, many of the provinces (Alberta, Quebec, Ontario, Newfoundland and Labrador, Nova Scotia, and Nunavut) have published provincial ambient air quality objectives or standards, while other provinces (Manitoba, Yukon, Saskatchewan, the Northwest Territories, and Prince Edward Island) rely on national air ambient air quality objectives published by the Government of Canada. The number of compounds included in the ambient air objectives varies significantly by jurisdiction, and the most comprehensive documents are provided by Alberta Environment, the Ontario Ministry of Environment, and the Quebec Ministère du Développement durable, de l'Environnement et des Parcs. National AAQOs published by Health Canada are available for carbon monoxide, ground-level ozone, and particulate matter.

Alberta Environment has adopted AAQO that are protective of the environment and human health. The AAQO are used as measures of air quality, as well as for planning and management of emissions from industrial facilities.

C.3 OCCUPATIONAL EXPOSURE LIMITS

Occupation exposure limits differ from ambient air objectives in both intent and application. Occupational exposure limits are considered to be acceptable for repeated exposure of workers using a well-defined exposure term, whereas ambient air quality objectives are intended to be protective of sensitive receptors in the general population under continuous exposure. Many of the provinces have based their occupational exposure limits on threshold limit values for atmospheric contaminants published by the American Conference of Governmental Industrial Hygienists (ACGIH). These values are not standards or objectives but refer to airborne concentrations of substances under which '*it is believed that nearly all workers may be repeatedly exposed day after day without adverse health effects*' (ACGIH, 1994), referred to as threshold limit values (TLV). The ACGIH also notes that it may often be economically or technically infeasible to meet some TLVs under certain conditions. The basis of the published TLVs includes peer reviewed scientific literature as a primary source, with reviewed articles and unpublished studies as secondary sources (ACHIH, 2006). TLVs are generally expressed as an average concentration per cubic metre of air measured over a specified exposure period, and are not derived for continuous exposure situations or other exposure durations. TLVs are not intended for use as ambient air objectives, but in many cases the data reviewed to develop the TLV have been used as a starting point to from which to derive provincial ambient air objectives.

The Canadian Centre for Occupational Health and Safety (CCOHS) has published chemical profiles for 27 compounds, many of which have air exposure limits based on toxicological responses derived by other organizations. The CCHOS air exposure limits are based solely on human health endpoints and do not consider environmental effects of the chemicals. These values can also be used as a starting point to develop occupational exposure limits in the absence of published guidelines. The basis for occupational exposure limits in various provinces are described in Table C.1.

Table C.1. Basis of Provincial Occupational Exposure Limits

Alberta	Occupational exposure limits (OELs) are under the Occupational Health and Safety Act, Chemical Hazard Regulation, which requires the employer to ensure that workers are not exposed above the limits.
British Columbia	The Industrial Health and Safety Regulations set legal requirements for most of British Columbia industry, which refer to the current schedule of TLVs for atmospheric contaminants published by the American Conference of Governmental Industrial Hygienists (ACGIH).
Manitoba	The Department of Environment and Workplace Safety and Health is responsible for legislation and its administration concerning the OELs. The guidelines currently used to interpret risk to health are the ACGIH TLVs with the exception that carcinogens are given a zero exposure level “so far as is reasonably practicable”.
New Brunswick	The applicable standards are those published in the latest ACGIH issue and, in case of an infraction, it is the issue in publication at the time of infraction that dictates compliance.
Northwest Territories	The Northwest Territories Safety Division of the Justice and Service Department regulates workplace safety for non-federal employees under the latest edition of the ACGIH TLVs.
Nova Scotia	The list of OELs is the same as that of the ACGIH as published in 1976 and its subsequent amendments and revisions.
Ontario	Regulations for a number of hazardous substances are enforced under the Occupational Health and Safety Act, published each in a separate booklet that includes the permissible exposure level and codes for respiratory equipment, techniques for measuring airborne concentrations and medical surveillance approaches.
Quebec	Permissible exposure levels are similar to the ACGIH TLVs and compliance with the permissible exposure levels for workplace air contaminants is required.

Taken from ILO, 2007

In Alberta an 8-hour OEL refers to the maximum concentration, averaged over an eight hours exposure period, which a sample (obtained over a period of 60 minutes) cannot exceed. The 15-minute OEL, or short-term exposure limit, cannot be exceeded over any 15-minute period. Elevated short-term exposure cannot occur more than 4 times per 8 hour shift. It may be possible to extend the OEL to a 10-hour, or extended work shift, depending on the contaminant and associated health effects.

C.3 ALBERTA AIR CONCENTRATION LIMITS

Alberta ambient air quality objectives and occupational exposure limits for key compounds are summarized in Table C.2 below.

Table C.2. Alberta Ambient Air Quality Objectives and Occupational Exposure Limits (mg/m^3)

Chemical	Ambient Air Quality Objective[a]	Occupational Exposure Limit[b]
Benzene	0.003 (1-hour average)	1.6 (8-hour average) 8 (15-minute OEL)
Toluene	1.88 (1-hour average) 0.4 (24-hour average)	188 (8-hour average)
Ethylbenzene	2 (1-hour average)	434 (8-hour average) 543 (15-minute OEL)
Xylenes	2.3 (1-hour average) 0.7 (24-hour average)	434 (8-hour average) 651 (15-minute OEL)
n-Hexane	21 (1-hour average) 7 (24-hour average)	176 (8-hour average)

a – Alberta Ambient Air Quality Objectives
b – Alberta Occupational Health and Safety Code (2009)

APPENDIX D
RECOMMENDED MODELLING APPROACH AND EQUATIONS

APPENDIX D: RECOMMENDED MODELLING APPROACH AND EQUATIONS

D.1 INTRODUCTION

This appendix presents the details of the equations used to facilitate a comparison between emissions of concern through contaminant disposal in a landfill, or contaminant removal through *ex situ* remediation. Emissions of concern included the emission of greenhouse gases, volatile organic compounds, particulate matter, NO_x, and SO_x, from remedial activities. This life cycle comparison considered emissions from the various component processes involved including equipment combustion and process emissions, as well as the direct emissions from release or transformation of contaminants. Details of the models and input parameters used to estimate emissions are presented in the sections below, and the default model input parameters applied can be seen in Table D-1.

D.2 GREENHOUSE GASE EMISSIONS FROM SOURCE CONTAMINANTS

The available carbon, eventually assumed released to the atmosphere was calculated by first estimating the mass of carbon bound within the contaminant, and was calculated as follows:

$$Carbon_{Mass} = \frac{(Carbon_{fraction} \times Soil_{Mass} \times Soil_{Concentration})}{10^6}$$

Where:

$Carbon_{Mass}$ = Mass of carbon emitted from contaminant in soil (Tonnes)
$Carbon_{fraction}$ = Relative mass portion of carbon (fraction)
$Soil_{Mass}$ = Mass of contaminated soil (kg)
$Soil_{Concentration}$ = Maximum measured soil concentration of compound (mg/kg)
10^6 = Unit conversion factor

Where:

$$Soil_{Mass} = (\rho b \times 1000) \times Soil_{volume}$$

$Soil_{Mass}$ = Mass of contaminated soil (kg)
ρ_b = Fine-grained, dry soil bulk density (g/cm^3)
$Soil_{Volume}$ = Volume of contaminated soil (m^3)

Where:

$$Carbon_{fraction} = \frac{(MW_{carbon} \times Carbon_{count})}{MW_{contaminant}}$$

$Carbon_{Fraction}$ = Relative mass portion of carbon (fraction)
MW_{carbon} = Molecular weight of carbon (g/mol)
$Carbon_{count}$ = Number of carbon molecules in compound (g/mol)
$MW_{Contaminant}$ = Molecular weight of compound (g/mol)

From this mass of carbon, that is assumed to be released as carbon dioxide in both *ex situ* and landfill disposal remedial scenarios, the mass of carbon dioxide was calculated. In the landfill scenario the entire calculated mass of carbon is assumed to be transferred

$$CO_{2Mass} = \frac{Carbon_{mass}}{0.2727}$$

Where:

$CO_{2\ Mass}$ = Mass of carbon dioxide emitted (Tonnes)
$Carbon_{Fraction}$ = Mass of carbon emitted from contaminant in soil (Tonnes)
0.2727 = Mass percentage of carbon in carbon dioxide

D.3 GREENHOUSE GASES FROM LANDFILL EMISSIONS

Landfill methane emissions were calculated using the following formula:

$$CH_4 emissions = Carbon_{mass} \times Fraction_{CH_4} \times Fraction_{uncerta\,\mathrm{int}\,y} \times Correction_{CH_4} \times CF$$

where:

CH_4emissions = total mass of methane emitted (tonnes)
$Carbon_{Mass}$ = total mass of carbon from contaminants (tonnes)
Fraction $_{CH4}$ = fraction of methane in landfill gas
$Fraction_{uncertainty}$ = model correction factor to account for uncertainties
CF = conversion factor, carbon to methane (1.34)
$Correction_{CH4}$ = methane correction factor, to account for uncertainties in landfill conversion from aerobic to anaerobic gas generation

Once the predicted methane emissions were calculated with the equation above, the remaining carbon from contaminants which was not converted to methane was assumed to be eventually emitted to the atmosphere as carbon dioxide and accounted for as such.

D.4 CALCULATION OF VOLATILE EXPOSURE AND EMISSIONS

D.4.1 Exposure from Contaminant Source After Disturbance

A variation of the Jury model was used to estimate air concentrations of volatiles potentially released during remedial activities. The US EPA version of the Jury model (1990) is shown below, calculating a contaminant flux at ground surface using a calculated effective diffusivity.

$$J_s = C_o\left(\frac{D_{Eff}}{\pi t}\right)^{\frac{1}{2}}\left[1-\exp\left(\frac{-d_s^2}{4D_{Eff}t}\right)\right]$$

where:

J_s = contaminant flux at ground surface (g/cm^2/s)
C_o = uniform contaminant concentration at t=0 (g/cm^3)
D_{Eff} = effective diffusivity (cm^2/s)
d_s = depth of uniform soil contamination from surface at t=0 (cm)
t = time (seconds)

$$D_{Eff} = \frac{\left[\frac{\theta_a^{10/3}D_{air}H' + \theta_w^{10/3}D_w}{n^2}\right]}{\left(\rho_b K_{oc} F_{oc} + \theta_w + \theta_a H'\right)}$$

where:

D_{eff} = effective diffusivity (cm^2/s)
θ_a = air filled porosity
n = total soil porosity
θ_w = water-filled soil porosity
D_w = diffusivity in water (cm^2/s)
D_{air} = diffusivity in air (cm^2/s)
H' = dimensionless Henry's Law constant
ρ_b = soil dry bulk density (g/cm^3)
K_{oc} = organic carbon coefficient (cm^3/g)
f_{oc} = fraction of organic carbon

To calculate a concentration in air, a box model was considered in the following equation to

conservatively estimate concentrations of volatile losses above the soil disturbance in a defined volume. Theoretically, the box works as follows, emissions are assumed to volatilize directly into a defined volume of air, this volume experiences air exchanges, which are analogous to mixing through wind influences. The use of a box model approach is conservative and the defined box volume will directly influence outcome numbers. Therefore, a realistic volume that is appropriately conservative without inflating the exposure numbers is the goal when defining the box volume. The first eight minutes were omitted from the eight-hour average as considerable uncertainty is predicted during this initial disturbance, however volatilization losses during the first 8 minutes are considered in the 15-minute exposure.

An instantaneous rate calculated using a modified equation from the Jury model, (US EPA, 1990) to omit considerations related to air exposure in a trench was conducted as follows:

$$C_{air} = \frac{J_s 10^6 A_c}{(U \times Box_h \times L)}$$

where:

C_{air} = concentration in air (µg/m^3)
J_s = contaminant flux at ground surface (g/cm^2/s)
A_c = contaminated area (cm^2)
U = average wind speed (m/s)
Box_h = height of assumed box (m)
L = length of site perpendicular to wind direction (m)

D.4.2 Exposure During Ex-Situ Allu Bucket Soil Processing

The approach for deriving an allu soil processing emission rate was to calculate two separate emission rate and adopt the highest, one rate based on soil partitioning and the other based on contaminant mass lost distributed over the allue processing time. The later calculates the contaminant emission rate, or a short-term emission rate, from soil processing using an allu bucket a function of the soil volume, concentration less the soil quality guideline and the bulk density was distributed over the Allu processing time. This equation assumes that the entire mass of contaminants, less the contaminant mass remaining in soil at the guideline concentration, is volatilized at a constant rate during the course of Allu bucket operation. The maximum contaminant concentration was be used to determine the short-term emission rate.

$$ER_{Short-term1} = \frac{(C - SQG) S_v \times \mathrm{b} \times 1}{t_R}$$

where:

$ER_{Short-term1}$ = long-term emission rate (g/s)
SQG = soil quality guideline (µg/g)
S_v = volume of soil moved (m^3)

C = average contaminant concentration in soil (µg/g)
B = bulk density (g/cm^3)
1 = constant (g/10^6 µg x 10^6 cm^3/m^3)
t_r = duration of allu bucket operation (s)

A short-term emission rate calculated based on soil partitioning was also calculated, and the lower of this and $ER_{Short\text{-}term1}$ was adopted. A soil gas concentration was used to calculate the emission rate based on soil partitioning and calculated with the equation:

$$C_{Vapour} = \frac{H' \times C_{Soil} \times \rho_b}{\theta_w + K_d \times \rho_b + H' \times \theta_a}$$

where:

C_{Vapour} = soil vapour concentration (g/cm^3)
H' = henry's law constant (unitless)
C_{Soil} = soil concentration (g/g)
ρ_b = soil dry bulk density (g/cm^3)
Kd = soil-water partition coefficient (cm^3/g)
Θ_a = soil air-filled porosity (cm^3/cm^3)

This calculated soil vapour was then applied in the equation to calculate a short-term emission rate based on soil partition, calculated as:

$$ER_{Short-term2} = C_{Vapour} \times 10^6 \times \theta_a \times Q \times ExC$$

where:

$ER_{Short\text{-}term3}$ = short-term emission rate (g/s)
C_{Vapour} = soil vapour concentration (g/cm^3)
Θ_a = soil air-filled porosity (cm^3/cm^3)
Q = allu processing rate (m^3/s)
ExC = soil-gas to atmosphere exchange rate (m^3/sec)

The higher of the two calculated short-term emission rates is then applied to calculate a short-term ex-situ air concentration as calculated below.

Using the contaminant short-term emission rate ex-situ air concentration can be calculated. The emission rate is assumed to be occurring across the site simultaneously into the defined area of the source contaminant length and allu bucket height and dispersed with wind.

$$C_{air\_ST} = \frac{ER \times 1000 mg/g}{U \times L \times Allu_h}$$

C_{air_ST} = short-term ex-situ air concentration (mg/m^3)
$ER_{Short\text{-}term}$ = short-term contaminant emission rate (g/s)
U = average wind speed (m/s)

L = site length perpendicular to wind direction (m)
$Allu_h$ = height of Allu bucket during operation (m)

A long-term emission rate, applicable to life-cycle assessment considerations applied the same equation but instead considered that the entire contaminant mass would be emitted. This calculation used average soil concentrations and did not consider soil quality guideline levels.

$$ER_{Long-term} = \frac{S_v \times C \times b \times 1}{t_R}$$

where:

$ER_{Long-term}$ = long-term emission rate (g/s)
S_v = volume of soil moved (m^3)
C = average contaminant concentration in soil (µg/g)
B = bulk density (g/cm^3)
1 = constant ($g/10^6$ µg x 10^6 cm^3/m^3)
t_r = duration of allu bucket operation (s)

Long-term ex-situ air concentrations from soil processing with an Allu bucket apply the same equation to calculate the short-term ex-situ air concentration with a direct substitution of the long-term emission rate for the short-term emission rate, all other inputs remain the same.

D.4.3 Exposure Reduction from Biofilters

The presence of a biofilter does not change any of the fundamental assumptions regarding the previous calculations of exposure concentration. The only change is a contaminant removal efficiency factor, the proportion of contaminants removed by the biofilter, which is applied directly to the long-term air concentration for ex-situ exposure.

$$C_{air\_BF} = C_{air} \times (1 - BEF)$$

where:

C_{air} = concentration in air ($\mu g/m^3$)
C_{air_BF} = concentration in air with biofilter ($\mu g/m^3$)
BEF = Biofilter efficiency factor (unitless)

D.5 CALCULATION OF PARTICULATE EMISSIONS

D.5.1 Particulate Emissions Generated from Vehicle Traffic

Environment Canada's NPRI (National Pollutant Release Inventory) Toolbox guidance on estimating road dust emissions from industrial unpaved sources was applied.

Particulate emissions from vehicular traffic on unpaved industrial surfaces, Environment Canada, (2009):

$$EF_{Unpaved} = k \times \left(\frac{s}{12}\right)^{a} \times \left(\frac{W}{2.72}\right)^{b}$$

Where:

EF = emission factor (g/vehicle km travelled)
k = particle size multiplier (g/vehicle km travelled)
s = percent silt content of road surface (%)
W = mean vehicle weight (tonnes, metric)
a = numerical constant (see Table 1)
b = numerical constant (see Table 1)

Once an emission factor has been calculated this can be applied to the total number of vehicle kilometers travelled, for this scenario it was assumed that no remedial transport activities would take place during the winter or during rain events and no dust control methods would be applied.

$$E_x = VKT \times EF$$

where:

E_x = Particulate emissions (kg)
VKT = total vehicle kilometers travelled (km)
EF = emission factor (g/vehicle km travelled)

D.5.2 Particulate Emissions Generated from Equipment Processes

Particulate emissions from all transfer operations (i.e. adding to or removing from piles, conveyor belts, truck dumping etc.), were calculated using US EPA (1993) as follows:

$$E = \frac{K(0.0016)M\left(\frac{U}{2.2}\right)^{1..3}}{\left(\frac{\theta_w}{2}\right)^{1.4}}$$

Where:

E = emissions (g)
K = particle size multiplier (unitless)
M = mass of waste handled (kg)

U = mean wind speed (m/s)
Θ_w = soil moisture content (%)
0.0016 = empirical constant (g/kg)
2.2 = empirical constant (m/s)

Particulate emissions during soil being spread by a bulldozer or any other tractor with a blade can be calculated as a function of time with the following equation from US EPA (1993):

$$ER = \frac{0.094 \times s^{1.5}}{q_w^{1.4}}$$

Where:

ER = PM_{10} emission rate (g/s)
s = percent silt content (%)
Θ_w = percent moisture content (%)
0.094 = empirical constant (g/s)

Percent silt content was estimated from soil texture mapping in Alberta (Alberta Agriculture, 2005). The methodology to determine an appropriate silt default value for Alberta is as follows. The textural class grouping that covers the largest area of the province is the medium textural class. Within this textural class silt content is estimated to represent approximately 6.5%, not considering silty-loam or silty-clay loam. The silt textural class contains silt ranging in content from 70 - 100%. Based on this the silt content was estimated to be 6.5%, which conservatively assumes 100% silt content in the silt textural class, but does not consider potential silt contributions in other textural classes.

D.5.3 Particulate Emissions Generated from Engine Combustion

Particulates are also generated as a combustion by-product and were calculated using emission factors published by the GHGenius model, applied with fuel usage based on equipment type published in Frey et al. (2010). The calculation is as a follows:

$$EQ = \frac{EF \times F}{E_1 \times H}$$

where:

EQ = particulate emissions from engine combustion (g)

EF = equipment specific particulate emission factor based on fuel use (g/GJ)
F = equipment specific fuel use (L/hr)
H = hours of equipment operation (hr)
E_1 = petro-diesel required to generate 1 GJ energy (L/GJ)

Hours of equipment use were estimated based on professional experience.

D.6 CALCULATION OF COMBUSTION RELATED VOLATILE EMISSIONS

Equipment engine emissions of volatiles were also estimated using emission factors from the GHGenius model and applied with fuel use, the calculation is as follows:

$$E_{Engine} = \frac{F \times H \times EF \times E_2}{1000}$$

where:

E_{Engine} = emissions of criteria air contaminants as engine combustion products (kg)
F = equipment specific fuel use (L/hr)
H = hours of equipment operation (hr)
EF = equipment specific criteria air contaminant emission factor based on fuel use (g/GJ)
E_2 = energy released per liter of petro-diesel (GJ/L)

D.7 INPUT PARAMETERS

Default input parameters that were used specifically for model related inputs, not necessarily site dependent can be found in Table D-1 below.

TABLE D-1
DEFAULT MODEL INPUTS

Vehicular Traffic and Equipment Process Particulate Emissions									
Parameter	**Symbol**	**Units**	**$PM_{2.5}$**	**PM_{10}**	**TPM**	**References / Notes**			
Particle size multiplier - unpaved	k	kg/VKT	0.042	0.42	1.38	Environment Canada, 2009			
Numerical constant	a	unitless	0.9	0.9	0.7				
Numerical constant	b	unitless	0.45	0.45	0.45				
Particle size multiplier - soil handling	K	dimensionless	0.11	0.35	-	US EPA, 1993			
Parameter			**Default**	**Range**					
Mean wind speed	U	m/sec	4			Environment Canada, 2008			
Soil silt content	s	%	30			Estimated based on glacial till texture portioning.			
Surface road material silt content	S	%	6.65	3.2	12.9	US EPA, 2006 (see below)			
Mean vehicle weight	W	Tonnes	23			Maximum Alberta commerical weight 53.5 tonnes, 23 is the max for a tridem axle, more probable.			
Silt Content (%) in Surface Materal, Industrial Unpaved Roads									
Industry	**Road Use**	**N**	**Mean**	**Range**					
Municipal solid waste landfills	Disposal routes	20	6.4	2.2	21	US EPA, 2006 Table 13.2.2-1			
Construction Sites	Scraper routes	20	8.5	0.56	23				
Western Surface coal mining	Plant road	2	5.1	4.9	5.3				
Sand and gravel processing	Plant road	3	4.8	4.1	6				
Taconite mining and processing	Service road	8	4.3	2.4	7.1				
Taconite mining and processing	Haul road	12	5.8	3.9	9.7				
Stone quarrying and processing	Plant road	10	10	2.4	16				
Stone quarrying and processing	Haul road	20	8.3	5	15				
Mean silt content	All	-	6.65	3.18	12.89	Adopted as default			
Combustion Engine Particulate Emissions									
Energy content in petro-diesel	E1	L/GJ	25.6			GHGenius			
Energy content in petro-diesel	E2	GJ/L	0.039						
Wheeled loader	EF1	g/GJ	42.27						
Off-road trucks	EF2	g/GJ	41.29						
Tractor	EF3	g/GJ	97.27						
Industrial Engine	EF4	g/GJ	80.10						
Mass excavation using an excavator	F1	L/hr	7.19			Frey et al., 2010			
Material handling using a front-end loader	F2	L/hr	4.67						
Power generation using a generator	F3	L/hr	4.54						
Contaminated soil transport (km)	F4	L/hr	7.57						
Combustion Engine Criteria Air Contaminant Emissions[a]			**CH_4**	**CO**	**N_20**	**NO_x (NO_2)**	**SO_x (SO_2)**	**CO_2**	**VOC**
Wheeled loader	EF5	g/GJ fuel used	1.38	138.58	28.60	223.30	6.54	68,158	27.02
Off-road trucks	EF6	g/GJ fuel used	1.38	79.46	28.60	280.42	6.54	68,253	27.02
Tractor	EF7	g/GJ fuel used	1.20	194.02	28.60	359.59	6.54	67,849	48.46
Industrial engine	EF8	g/GJ fuel used	4.15	199.55	28.60	439.41	6.54	67,889	45.74

a - Emission factors taken from GHGenius model

APPENDIX E
EXAMPLE SITE CALCULATIONS

APPENDIX E: EXAMPLE SITE CALCULATIONS

E.1 APPROACH

An example site and scenario was created to test the modeling approach for both an ex situ remediation, with and without a biofilter, and a landfill disposal scenario. While based on data from a real site where ambient air quality monitoring was conducted during ex situ remediation, for purposes of this report the site is not identified or considered to be at a specific location. This example site reflects soil hydrocarbon concentrations thought to be applicable to a range of contaminated sites, and many of the assumptions are attempted to be as widely applicable as possible. For the evaluation of landfill disposal, the site is assumed to be located approximately 100 km from the nearest appropriate landfill disposal facility, connected by gravel roads. Approximately 800 m^3 of contaminated soil are estimated to be present onsite, based on an affected area of 400 m^2 to a depth of 2 m. Soils were assumed to have the same characteristics as a fine-grained soil as define by the Canadian Council of Ministers for the Environment (CCME, 2006).

All site-related assumptions and equipment operational hours for each scenario are presented in Table E-1. The equipment assumed to be present during soil processing for both ex situ and landfill disposal, with respective emission factors and default model inputs are presented in Table E-2. Chemical-specific parameters used for the calculations are provided in Table E-3. Contaminant concentrations in soil are provided in Table E-4; the average concentrations were used to calculate lifecycle emissions of greenhouse gases, and maximum soil concentrations were used to calculate worst-case volatile exposures onsite.

For the ex situ remediation scenario, it was assumed that the contaminated soil volume, 800 m^2, would be first excavated using a backhoe, then passed through an allu bucket twice before being placed back into the excavation pit and leveled using a front-end loader to resemble pre-disturbance surface conditions. If a biofilter was used, it was assumed to be present over excavated material. For the landfill disposal scenario, it was assumed this same volume of soil would be excavated using a backhoe and placed directly into a haul truck for transport to a landfill disposal facility. Once at the landfill, it was assumed this soil volume would be incorporated into the landfill cell using a backhoe. Both scenarios were assumed to use a site generator.

Workers in both the landfill and ex situ scenario are predicted to be exposed to worst case air concentrations during the initial soil excavation; however, the ex situ worker may receive an increased relative exposure as this worker is predicted to be exposed longer.

E.2 WORKED EXAMPLE CALCULATIONS

Worked example calculations for greenhouse gas emissions, criteria air contaminants including particulates and volatile exposure can be found below.

E.2.1 Greenhouse Gas Emissions from Source contaminants - Benzene

$$Soil_{Mass} = \rho b \times Soil_{volume}$$

$$Soil_{Mass} = 1.4\frac{g}{cm^3} \times 1000 \times 800 m^3 = 1120000 kg$$

Where:

$Soil_{Mass}$ = Mass of contaminated soil (kg)
ρ_b = Fine-grained, dry soil bulk density (g/cm^3)
$Soil_{Volume}$ = Volume of contaminated soil (m^3)

$$Carbon_{fraction} = \frac{(MW_{carbon} \times Carbon_{count})}{MW_{contaminant}}$$

$$Carbon_{fraction} = \frac{(12.0107 g/mol \times 6)}{78.1 g/mol} = 0.92$$

$Carbon_{Fraction}$ = Relative mass portion of carbon (fraction)
MW_{carbon} = Molecular weight of carbon (g/mol)
$Carbon_{count}$ = Number of carbon molecules in compound (g/mol)
$MW_{Contaminant}$ = Molecular weight of benzene (g/mol)

$$Carbon_{Mass} = \frac{(Carbon_{fraction} \times Soil_{Mass} \times Soil_{Concentration})}{10^6}$$

$$Carbon_{Mass} = \frac{(0.92 \times 1120000 kg \times 0.49 mg/kg)}{10^6} = 0.51 Tonnes$$

Where:

$Carbon_{Mass}$ = Mass of carbon emitted from contaminant in soil (Tonnes)
$Carbon_{fraction}$ = Relative mass portion of carbon (fraction)
$Soil_{Mass}$ = Mass of contaminated soil (kg)
$Soil_{Concentration}$ = Maximum measured soil concentration of benzene (mg/kg)
10^6 = Conversion factor

$$CO_{2Mass} = \frac{Carbon_{mass}}{0.2727}$$

$$CO_{2Mass} = \frac{0.51 tonnes}{0.2727} = 1.9 tonnes$$

Where:

$CO_{2\ Mass}$	= Mass of carbon dioxide emitted from benzene in soil (Tonnes)
$Carbon_{Fraction}$	= Mass of carbon emitted from benzene in soil (Tonnes)
0.2727	= Mass percentage of carbon in carbon dioxide

E.2.2 Greenhouse Gases from Landfill Emissions

Using the equation to calculate $Carbon_{Mass}$ for benzene shown above, the carbon mass for all contaminants was estimated and summed, giving 1556 tonnes. Landfill methane emissions were then calculated using the following formula:

$$CH_4 emissions = Carbon_{mass} \times Fraction_{CH_4} \times Fraction_{uncertainty} \times Correction_{CH_4} \times CF$$

$$CH_4 emissions = 1556 tonnes \times 0.5 \times 0.9 \times 0.5 \times 1.3 = 445 tonnes$$

where:

$Carbon_{Mass\_total}$	= total mass of carbon from contaminants (Tonnes)
Fraction $_{CH4}$	= fraction of methane in landfill gas
$Fraction_{uncertainty}$	= model correction factor to account for uncertainties
CF	= conversion factor, carbon to methane
$Correction_{CH4}$	= Methane correction factor, to account for uncertainties in landfill conversion from aerobic to anaerobic gas generation

E.2.3 Calculation of Volatile Emissions from Source- Benzene

$$D_{Eff} = \frac{\left[\frac{\theta_a^{10/3} D_{air} H' + \theta_w^{10/3} D_w}{n^2}\right]}{\left(\rho_b K_{oc} F_{oc} + \theta_w + \theta_a H'\right)}$$

$$D_{Eff} = \frac{\left[\frac{0.302^{10/3} 0.088 \times 0.225 + 0.168^{10/3} \times 0.0000098}{0.47^2}\right]}{\left(1.4 \times 79.4 \times 0.005 + 0.168 + 0.302 \times 0.225\right)} = 0.0021 cm^2 / s$$

where:

D_{eff} = effective diffusivity (cm^2/s)
θ_a = air filled porosity (cm^3/cm^3)
n = total soil porosity (cm^3/cm^3)
θ_w = water-filled soil porosity (cm^3/cm^3)
D_w = diffusivity in water (cm^2/s)
D_{air} = diffusivity in air (cm^2/s)
H' = dimensionless Henry's Law constant (unitless)
ρ_b = soil dry bulk density (g/cm^3)
K_{oc} = organic carbon coefficient (cm^3/g)
f_{oc} = fraction of organic carbon

$$J_s = C_o\left(\frac{D_{Eff}}{\pi t}\right)^{\frac{1}{2}}\left[1-\exp\left(\frac{-d_s^2}{4D_{Eff}t}\right)\right]$$

Instantaneous contaminant flux at 1 second after disturbance:

$$J_s = 6.88\times10^{-7}\left(\frac{0.0021}{3.14\times1}\right)^{\frac{1}{2}}\left[1-\exp\left(\frac{-200^2}{4\times0.0021\times1}\right)\right] = 1.78\times10^{-8}\,\mathrm{g/cm^2 s}$$

where:

J_s = contaminant flux at ground surface (g/cm^2s)
C_o = uniform contaminant concentration at t=0 (g/cm^3)
D_{Eff} = effective diffusivity (cm^2/s)
d_s = thickness of uniform soil contamination at t=0 (cm)
t = time (seconds)

$$C_{air} = \frac{J_s 10^6 A_c}{(U\times Box_h \times L)}$$

Instantaneous air concentration at 1 second after disturbance:

$$C_{air} = \frac{1.78\times10^{-8}\, g/cm^2 s \times 10^6\, \mu g/g \times 4000000 cm^2}{4m/s \times 2m \times 20m} = 4.45\times10^2\, ug/m^3$$

where:

C_{air} = concentration in air (µg/m^3)
J_s = contaminant flux at ground surface (g/cm^{2}s)
A_c = contaminated area (cm^2)
U = average wind speed (m/s)
Box_h = height of assumed box (m)
L = length of site perpendicular to wind direction (m)

E.2.4 Calculation of Volatile Emissions from Ex-Situ Soil Treatment with an Allu Bucket

Two emission rates were calculated as, shown for benzene:

$$ER_{Short-term1} = \frac{(C - SQG) S_v \times \mathrm{b} \times 1}{t_R}$$

$$ER_{Short-term1} = \frac{(0.49 mg/kg - 0.046 mg/kg) 800 m^3 \times 1.4 g/cm^3 \times 1}{7.1 h \times 3600 s/h} = 0.139 g/s$$

where:

$ER_{Short\text{-}term1}$ = long-term emission rate (g/s)
SQG = soil quality guideline (µg/g)
S_v = volume of soil moved (m^3)
C = average contaminant concentration in soil (µg/g)
B = bulk density (g/cm^3)
1 = constant (g/10^6 µg x 10^6 cm^3/m^3)
t_r = duration of allu bucket operation (s)

$$C_{Vapour} = \frac{H' \times C_{Soil} \times \mathrm{r}_b}{\mathrm{q}_w + K_d \times \mathrm{r}_b + H' \times \mathrm{q}_a}$$

$$C_{Vapour} = \frac{0.225 \times 0.00000317 g/g \times 1.4 g/cm^3}{0.168 + 0.397 cm^3/g \times 1.4 g/cm^3 + 0.225 \times 0.302} = 0.00000126 g/cm^3$$

where:

C_{Vapour} = soil vapour concentration (g/cm^3)
H' = henry's law constant (unitless)
C_{Soil} = soil concentration (g/g)
ρ_b = soil dry bulk density (g/cm^3)
Kd = soil-water partition coefficient (cm^3/g)
Θ_a = soil air-filled porosity (cm^3/cm^3)

$$ER_{Short-term2} = C_{Vapour} \times 10^6 \times q_a \times Q \times ExC$$

$$ER_{Short-term2} = 0.00000126 g/cm^3 \times 10^6 \times 0.302 \times 112.5 m^3/hr \times \frac{1hr}{3600s} \times 1 m^3/s = 0.0119 g/s$$

where:

$ER_{Short-term3}$ = short-term emission rate (g/s)
C_{Vapour} = soil vapour concentration (g/cm^3)
Θ_a = soil air-filled porosity (cm^3/cm^3)
Q = allu processing rate (m^3/s)
ExC = soil-gas to atmosphere exchange rate (m^3/sec)

Based on the above calculations two equations calculating short-term emission rates, the higher $ER_{Short-term1}$ was adopted and applied to calculate an outdoor air concentration from ex-situ Allu bucket soil processing, which was calculated as:

$$C_{air\_ex-situ\_ST} = \frac{ER_{Short-term1} \times 1000}{U \times L \times Allu_h}$$

$$C_{air\_ex-situ\_ST} = \frac{0.139 g/s \times 1000 mg/g}{4 m/s \times 20 m \times 2 m} = 0.868 mg/m^3$$

where:

$C_{air\_ex\text{-}situ\_ST}$ = short-term ex-situ air concentration (mg/m^3)
ER = short-term contaminant emission rate (g/s)
U = average wind speed (m/s)
L = site length perpendicular to wind direction (m)
$Allu_h$ = assumed box height, equal to height of Allu bucket during operation (m)

A long-term emission rate was also calculated, more appropriate for life-cycle considerations and was calculated as:

$$ER_{Long-term} = \frac{S_v \times C \times \mathrm{b} \times 1}{t_R}$$

$$ER_{Short-term1} = \frac{0.49mg/kg \times 800m^3 \times 1.4g/cm^3 \times 1}{7.1h \times 3600s/h} = 0.0215g/s$$

where:

$ER_{Long\text{-}term}$ = long-term emission rate (g/s)
S_v = volume of soil moved (m^3)
C = average contaminant concentration in soil (µg/g)
B = bulk density (g/cm^3)
1 = constant (g/10^6 µg x 10^6 cm^3/m^3)
t_r = duration of allu bucket operation (s)

The calculation of outdoor air considering long-term soil emissions:

$$C_{air\_ex-situ\_LT} = \frac{ER_{Long-term} \times 1000}{U \times L \times Allu_h}$$

$$C_{air\_ex-situ\_LT} = \frac{0.0215g/s \times 1000mg/g}{4m/s \times 20m \times 2m} = 0.134mg/m^3$$

where:

$C_{air\_ex\text{-}situ\_LT}$ = long-term ex-situ air concentration (mg/m^3)
ER = long-term contaminant emission rate (g/s)
U = average wind speed (m/s)
L = site length perpendicular to wind direction (m)
$Allu_h$ = assumed box height, equal to height of Allu bucket during operation (m)

For the biofilter case, the long-term air concentration was modified using a biofilter efficiency factor, using the following calculation:

$$C_{air\_BF} = C_{air\_ex-situ\_LT} \times (1 - BEF)$$

$$C_{air\_BF} = 0.134 mg/m^3 \times (1 - 0.6) = 0.054 mg/m^3$$

where:

$C_{air\_ex\text{-}situ\_LT}$ = long-term ex-situ air concentration (mg/m^3)
C_{air_BF} = long-term ex-situ air concentration with a biofilter (mg/m^3)
BEF = Biofilter efficiency factor (BEF)

E.2.5 Calculation of Particulate Emissions

E.2.5.1 Particulate Emissions Generated from Vehicle Traffic

$$EF_{Unpaved} = k \times \left(\frac{s}{12}\right)^a \times \left(\frac{W}{2.72}\right)^b$$

Fine-grained, particulate matter 2.5 micrometers or less:

$$EF_{Unpaved} = 0.042 kg/VKT \times \left(\frac{6.5}{12}\right)^{0.9} \times \left(\frac{23}{2.72}\right)^{0.45} = 0.0645 kg/VKT$$

Where:

EF = emission factor (kg/vehicle km travelled)
k = particle size multiplier (kg/vehicle km travelled)
s = percent silt content of road surface (%)
W = mean vehicle weight (tonnes, metric)
a = numerical constant
b = numerical constant

$$E_x = VKT \times EF$$

$$E_x = 125km \times 0.0645kg/km = 8.06kg$$

where:

E_x = Particulate emissions (kg)
VKT = total vehicle kilometers travelled (km)
EF = emission factor (kg/vehicle km travelled)

E.2.5.2 Particulate Emissions Generated from Equipment Processes

$$E = \frac{K(0.0016)M\left(\frac{U}{2.2}\right)^{1..3}}{\left(\frac{\theta_w}{2}\right)^{1.4}}$$

Emissions from all transfer operations PM2.5:

$$E = \frac{0.052(0.0016g/kg)1120000kg\left(\frac{4.4m/s}{2.2m/s}\right)^{1..3}}{\left(\frac{0.168}{2}\right)^{1.4}}$$

$$E = \frac{0.11(0.0016g/kg)1120000kg\left(\frac{4m/s}{2.2m/s}\right)^{1..3}}{\left(\frac{0.168}{2}\right)^{1.4}} = 13700g$$

Where:

E = emissions from soil transfer operations (g)

K = particle size multiplier (unitless)
M = mass of waste handled (kg)
U = mean wind speed (m/s)
Θ_w = soil moisture content (%)
0.0016 = empirical constant (g/kg)
2.2 = empirical constant (m/s)

$$ER = \frac{0.094 \times s^{1.5}}{q_w^{1.4}}$$

Emissions from soil spreading, PM10:

$$ER = \frac{0.094 g/s \times 0.30^{1.5}}{0.168^{1.4}} = 0.19 g/s$$

Where:

ER = PM_{10} emission rate (g/s)
s = percent silt content (%)
Θ_w = percent moisture content (%)
0.94 = empirical constant (g/s)

E.2.5.3 Particulate Emissions Generated from Engine Combustion

$$EQ = \frac{EF \times F}{E_1 \times H}$$

Excavator engine emissions during ex situ excavation and allu:

$$EQ = \frac{97.27 g/GJ \times 7.19 L/hr}{25.6 L/GJ \times 24 hr} = 655.7 g$$

where:

EQ = particulate emissions from engine combustion (g)
EF = equipment specific particulate emission factor based on fuel use (g/GJ)
F = equipment specific fuel use (L/hr)

H = hours of equipment operation (hr)
E_1 = petro-diesel required to generate 1 GJ energy (L/GJ)

E.2.6 Calculation of Combustion Related Volatile emissions

Equipment engine emissions of volatiles were also estimated using emission factors from the GHGenius model and applied with fuel use, the calculation is as follows:

$$E_{Engine} = \frac{F \times H \times EF \times E_2}{1000}$$

Excavator ex situ methane emissions:

$$E_{Engine} = \frac{7.19 L/hr \times 24 hr \times 1.2 g/GJ \times 0.039 GJ/L}{1000} = 0.008 kg$$

where:

E_{Engine} = emissions of criteria air contaminants as engine combustion products (kg)
F = equipment specific fuel use (L/hr)
H = hours of equipment operation (hr)
EF = equipment specific criteria air contaminant emission factor based on fuel use (g/GJ)
E_2 = energy released per liter of petro-diesel (GJ/L)

E.3 RESULTS

The results of the calculations are presented in Tables E-5 through E-9. Based on the calculations, more methane is produced in the landfill disposal scenario than in the *ex-situ* soil treatment scenario; landfill disposal is predicted to produce more particulate emissions, largely a result of distance to landfill, and landfill disposal is predicted to have higher criteria air contaminant emissions based on predicted higher equipment operational hours. Exposures from the soil source after disturbance, not considering soil processing, are very similar for both scenarios and highest immediately after soil disturbance. For this example site, the volatile exposures from ex-situ soil treatment with the allu bucket are not predicted to exceed occupational exposure limits, neither is exposure from the disturbed soil source for both the ex-situ or landfill disposal scenarios. Utilization of a biofilter is reduces long-term ex-situ exposure as a basic model assumption and always provides a reduction to long-term air concentration as long as the biofilter is operating. The use of a biofilter increased engine combustion emissions of criteria air contaminants, but the contribution of was equivalent to less than 1% of overall equipment emissions.

E.4 INDUSTRIAL HYGIENE ASSESSMENT

An industrial hygiene assessment was conducted at this example site, involving instantaneous spot measurements on equipment where workers would likely be exposed. Total volatile organic compounds ranged from 0.4 ppm to 24 ppm during the excavation, and no measurable concentrations of benzene were detected (<0.01 ppm). These results are below the modelled predicted exposures, suggesting that the modelling of volatile exposures is conservative and may over-predict exposures.

E.5 DISPERSION MODELLING AND PREDICTION OF OFFSITE CONCENTRATIONS

Parameters calculated by the emission model can be utilized as inputs for air dispersion modelling software, including models recommended by Alberta Environment such as AERSCREEN, CALPUFF, and AERMOD-PRIME. Use of these dispersion models allows for predictions of emission behaviour based on local topological and meteorological condition, as well as prediction of pollutant concentrations at critical receptor locations.

For demonstration purposes, results of the emission model from an allu bucket at the example site were used as inputs in the AERSCREEN dispersion model. This is a screening model that utilizes a generic set of site conditions and calculates a worst-case concentration at regular distance intervals from the site, as well as the maximum 1-hour, 3-hour, 8-hour, 24-hour, and scaled annual concentrations. The meteorological conditions that resulted in the maximum predicted concentrations at each distance are also determined and can potentially be used as a risk management tool. The required inputs included the rate of short-term benzene emissions from soil being processing using an Allu bucket (0.139 g/s, detailed in section 2.4), the volume of soil contained in the bucket (2 m^3), and the height Allu bucket emissions (2 m). Selected results are shown below:

Distance (m)	Maximum Predicted Benzene Concentration (mg/m^3)
3.2	5.2
50	1.6
100	0.93
250	0.42
500	0.21
1000	0.093
2000	0.038
5000	0.011

As this specific model is a screening tool, the results obtained are fairly generic. More detailed results can be obtained when refined dispersion models are utilized and additional site specific data is provided. Refined results could include determination of exposure concentrations, exceedances of short-term exposure limits at specific locations, maps of the emission plume, or

various other outputs. The required meteorological data sets to run refined models is publicly available, and detailed user guidance on running these models is provided by Alberta Environment and other regulatory organizations.

TABLE E.1
EXAMPLE SITE CHARACTERISTICS & PROCESS ASSUMPTIONS

Parameter	Symbol	Unit	Number	Reference
Volumetric air content or vapour-filled porostiy	θ_a	cm^3/cm^3	0.302	Fine-grained soil CCME (2006)
Volumetric water content or soil moisture content	θ_w	cm^3/cm^3	0.168	Fine-grained soil CCME (2006)
Total soil porosity	n	cm^3/cm^3	0.47	Fine-grained soil CCME (2006)
Soil dry bulk density	ρ_b	g/cm^3	1.4	Fine-grained soil CCME (2006)
Soil dry bulk density	ρ_b	kg/m^3	1400	Fine-grained soil CCME (2006)
Fraction of organic carbon	f_{oc}	unitless	0.005	Fine-grained soil CCME (2006)
Thickness of source soil	ds	cm	200	Assumed
Contaminated area	Ac	m^2	400	20 m by 20 m
Contaminated soil volume	V	m^3	800	site specific input
Mass of contaminated soil	Soil	kg	1120000	calculated
Contaminant thickness	Cd	cm	200	Assumed
Box defined area	Box_{area}	m^2	400	Assumed
Box defined height	Box_h	m	2	Assumed
Equipment Operational Inputs				
Process		**Unit**	**Operational Hours Ex Situ Scenario**	**Operational Hours Landfill Disposal Scenario**
Material Handling using a front end loader		hr	6	12
Mass excavation using a backhoe, including allu		hr	24	12
Power generation using a generator		hr	24	24
Contaminated soil transport (km)		km	25	125

TABLE E.2
MODEL INPUTS

Vehicular Traffic and Equipment Process Particulate Emissions						
Parameter	**Symbol**	**Units**	**$PM_{2.5}$**	**PM_{10}**	**TPM**	**References / Notes**
Particle size multiplier - unpaved	k	kg/VKT	0.042	0.42	1.38	Environment Canada, 2009
Numerical constant	a	unitless	0.9	0.9	0.7	
Numerical constant	b	unitless	0.45	0.45	0.45	
Particle size multiplier - soil handling	K	dimensionless	0.11	0.35	-	US EPA, 1993
Parameter			**Default**	**Range**		
Mean wind speed	U	m/sec	4			Environment Canada, 2008
Soil silt content	s	%	30			Estimated based on glacial till texture portioning.
Surface road material silt content	S	%	6.65	3.2	12.9	US EPA, 2006 (see below)
Mean vehicle weight	W	Tonnes	23			Maximum Alberta commerical weight 53.5 tonnes, 23 is the max for a tridem axle, more probable.
Silt Content (%) in Surface Materal, Industrial Unpaved Roads						
Industry	**Road Use**	**N**	**Mean**	**Range**		
Municipal solid waste landfills	Disposal routes	20	6.4	2.2	21	US EPA, 2006 Table 13.2.2-1
Construction Sites	Scraper routes	20	8.5	0.56	23	
Western Surface coal mining	Plant road	2	5.1	4.9	5.3	
Sand and gravel processing	Plant road	3	4.8	4.1	6	
Taconite mining and processing	Service road	8	4.3	2.4	7.1	
Taconite mining and processing	Haul road	12	5.8	3.9	9.7	
Stone quarrying and processing	Plant road	10	10	2.4	16	
Stone quarrying and processing	Haul road	20	8.3	5	15	
Mean silt content	All	-	6.65	3.18	12.89	Adopted as default
Combustion Engine Particulate Emissions						
Energy content in petro-diesel	E1	L/GJ	25.6			GHGenius
Energy content in petro-diesel	E2	GJ/L	0.039			
Wheeled loader	EF1	g/GJ	42.27			
Off-road trucks	EF2	g/GJ	41.29			
Tractor	EF3	g/GJ	97.27			
Industrial Engine	EF4	g/GJ	80.10			
Mass excavation using an excavator	F1	L/hr	7.19			Frey et al., 2010
Material handling using a front-end loader	F2	L/hr	4.67			
Power generation using a generator	F3	L/hr	4.54			
Contaminated soil transport (km)	F4	L/hr	7.57			
Combustion Engine Criteria Air Contaminant Emissions[a]			**CH_4**	**CO**	**N_20**	**NO_x (NO_2)**	**SO_x (SO_2)**	**CO_2**	**VOC**
Wheeled loader	EF5	g/GJ fuel used	1.38	138.58	28.60	223.30	6.54	68,158	27.02
Off-road trucks	EF6	g/GJ fuel used	1.38	79.46	28.60	280.42	6.54	68,253	27.02
Tractor	EF7	g/GJ fuel used	1.20	194.02	28.60	359.59	6.54	67,849	48.46
Industrial engine	EF8	g/GJ fuel used	4.15	199.55	28.60	439.41	6.54	67,889	45.74
Biofilter Inputs									
Biofilter Efficiency Factor	BEF	%	60			Meridian, 2012			

TABLE E.3
CHEMICAL PARAMETERS

Parameter Name	Symbol	Units	Benzene	Toluene	Ethyl-benzene	Xylenes	Aliphatic F1 (C_6-C_8)	Aliphatic F1 (C_8-C_{10})	Aromatic F1 (C_8-C_{10})	Aliphatic F2 (C_{10} - C_{12})	Aliphatic F2 (C_{12} - C_{16})	Aromatic F2 (C_{10} - C_{12})	Aromatic F2 (C_{12} - C_{16})	Source
Henry's Law constant	H_i	atm-m^3/mol	5.50E-03	6.71E-03	8.75E-03	7.30E-03	1.22E+00	1.96E+00	1.20E-02	2.94E+00	1.27E+01	3.40E-03	1.30E-03	Health Canada (2009)
Dimensionless Henry's Law constant	H'	unitless	2.25E-01	2.74E-01	3.58E-01	3.00E-01	5.00E+01	8.00E+01	4.80E-01	1.20E+02	5.20E+02	1.40E-01	5.30E-02	Health Canada (2009)
Diffusivity in water	D_w	cm^2/s	9.80E-06	8.60E-06	7.80E-06	7.80E-06	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	Health Canada (2009)
Diffusion coefficient in air	D_{air}	cm^2/s	8.80E-02	8.70E-02	7.50E-02	7.00E-02	5.00E-02	5.00E-02	5.00E-02	5.00E-02	5.00E-02	5.00E-02	5.00E-02	Health Canada (2009)
Molar mass of carbon in compound	Carbon Molar Mass	g/mol	72.0642	84.0749	96.0856	96.0856	108.0963	108.0963	108.0963	132.1177	168.1498	120.107	144.1284	Carbon count x Molar mass of carbon
Molecular weight of component i	MW_i	g/mol	7.81E+01	9.21E+01	1.06E+02	1.06E+02	1.00E+02	1.30E+02	1.20E+02	1.60E+02	2.00E+02	1.30E+02	1.50E+02	ORNL (2010) online RAIS database, Health Canada (2009b).
Relative mass portion of carbon	$Carbon_{Fraction}$	fraction	0.92	0.91	0.91	0.91	1.08	0.83	0.90	0.83	0.84	0.92	0.96	Calculated
Organic Carbon - Water Partition coefficient	K_{oc}	cm^3/g	7.94E+01	1.51E+02	2.95E+02	4.10E+02	3.98E+03	3.16E+04	1.58E+03	2.51E+05	5.01E+06	2.51E+03	5.01E+03	Health Canada (2009b)
log Octanol-water partition coefficient	log K_{ow}	unitless	2.13	2.69	3.13	3.12	4.11	5.21	3.69	6.3	7.95	3.93	4.29	Health Canada (2009b)
Fraction of Petroleum Hydrocarbon Subfraction in Soil	$F_{i(soil)}$	unitless					0.55	0.36	0.09	0.36	0.44	0.09	0.11	CCME, 2008
Maximum concentration of contaminant in soil	C_s	µg/g	3.22	0.09	227	246	1837	1202	301	16992	20768	4248	5192	Maximum value
Maximum concentration of contaminant in soil	C_o	g/cm^3	0.004508	0.000126	0.3178	0.3444	2.5718	1.68336	0.42084	23.7888	29.0752	5.9472	7.2688	Maximum value
Average concentration of contaminant in soil	C_s	µg/g	0.49	0.04	17	16	152.35	99.72	25	458	559.68	114.48	139.92	Average value
Average concentration of contaminant in soil	C_o	g/cm^3	0.000687831	0.000050225	0.0233977	0.022252588	0.21329	0.139608	0.034902	0.641088	0.783552	0.160272	0.195888	Average value

Notes Not accounting for petroleum hydrocarbon subfraction contributions from soil vapour or groundwater contributions.

TABLE E.4
EXAMPLE SOIL ANALYTICAL RESULTS

Depth (m)	Benzene mg/kg	Toluene mg/kg	Ethylbenzene mg/kg	Xylenes mg/kg	F1-BTEX mg/kg	F2 mg/kg	F3 mg/kg	F4 mg/kg
Maximum	**3.22**	**0.09**	**227**	**246**	**3340**	**47200**	**150000**	**19400**
Average	**0.49**	**0.04**	**17**	**16**	**277**	**1272**	**4029**	**1307**
0.6-1.0	0.004	<0.005	<0.010	<0.010	<4	174	921	414
5.75-6.0	<0.004	<0.005	<0.010	<0.010	<4	14	118	26
1.0-1.5	<0.004	<0.005	<0.010	<0.010	12	437	2480	1060
5.75-6.0	<0.004	<0.005	<0.010	<0.010	<4	27	168	29
1.0-1.5	<0.004	<0.005	<0.010	<0.010	<4	86	1150	502
2.75-3.0	<0.004	<0.005	<0.010	<0.010	<4	19	47	<20
0.6-1.0	<0.004	<0.005	<0.010	<0.010	<4	20	<30	<20
2.75-3.0	<0.004	<0.005	<0.010	<0.010	<4	<10	<30	<20
0.6-1.0	<0.004	<0.005	<0.010	<0.010	<4	120	845	392
2.75-3.0	<0.004	<0.005	<0.010	<0.010	<4	<10	40	<20
1.0-1.5	<0.004	<0.005	<0.010	<0.010	<4	132	591	248
4.25-4.5	<0.004	<0.005	<0.010	<0.010	<4	132	267	37
0.3-0.6	<0.004	<0.005	<0.010	<0.010	<4	128	993	492
2.75-3.0	<0.004	<0.005	<0.010	<0.010	<4	<10	40	<20
0-0.3	<0.004	<0.005	<0.010	<0.010	5	201	2000	1010
2.75-3.0	<0.004	<0.005	<0.010	<0.010	<4	14	<30	<20
1.5	0.24	< 0.02	0.80	1.80	458	< 10	47	71
1	< 0.02	< 0.02	< 0.02	< 0.02	< 0.1	< 10	356	266
1.0	< 0.02	< 0.02	< 0.02	< 0.02	< 0.1	< 10	< 10	< 10
1.0	1.79	< 0.02	2.47	8.38	145	< 10	< 10	< 10
1.4	< 0.02	< 0.02	< 0.02	< 0.02	< 0.1	< 10	< 10	< 10
1.5	< 0.02	< 0.02	< 0.02	0.03	7.8	47200	150000	19400
1.0	< 0.02	< 0.02	0.03	0.11	25.9	< 10	20	< 10
1.0	< 0.02	< 0.02	1.01	0.24	254	1620	1090	437
1.25-1.4	<0.004	<0.005	<0.010	<0.010	<4	164	1230	116
2.15-2.5	<0.004	<0.005	<0.010	<0.010	<4	25	119	<20
0.6-1.0	<0.004	<0.005	<0.010	<0.010	<4	19	95	<20
0.6-1.0	0.036	0.09	1.33	6.93	401	<10	<30	<20
1.0-1.5	0.009	0.061	0.389	1.58	262	3520	10200	3940
0-0.3	<0.004	0.017	<0.010	0.03	132	716	3390	1020
1.25-1.4	<0.004	<0.005	<0.010	<0.010	<4	20	217	22
3-3.2	<0.004	<0.005	<0.010	<0.010	<4	<10	<30	<20
0-0.3	0.006	<0.005	<0.010	<0.010	8	2320	9230	4770
0.3-0.6	0.711	<0.005	0.248	2.52	14	<10	<30	<20
0.8	< 0.02	< 0.02	< 0.02	< 0.02	< 0.1	< 10	< 10	< 10
0.6	< 0.02	< 0.02	0.03	0.17	7.5	228	3920	2940
0.6	< 0.02	< 0.02	< 0.02	< 0.02	< 0.1	< 10	< 10	< 10
0.6	< 0.02	< 0.02	< 0.02	< 0.02	< 0.1	17	517	875
0.3	< 0.02	< 0.02	< 0.02	< 0.02	0.5	53	992	925
1.5	< 0.02	< 0.02	< 0.02	< 0.02	< 0.1	< 10	< 10	< 10
0.30-0.60	<0.004	<0.005	<0.010	<0.010	<4	25	56	<20
4	<0.004	<0.005	<0.010	<0.010	<4	74	239	65
2	<0.004	<0.005	<0.010	<0.010	<4	65	165	35
2	<0.004	<0.005	<0.010	<0.010	<4	31	76	<20
0.50 - 0.75	<0.004	<0.005	<0.010	<0.010	<4	10	49	27
0.50 -0.75	<0.004	<0.005	<0.010	<0.010	<4	20	130	53
3.5	<0.004	<0.005	<0.010	<0.010	<4	13	60	21
1	<0.004	<0.005	<0.010	<0.010	<4	24	58	<20
2	<0.004	<0.005	<0.010	<0.010	<4	56	152	35
1.5	<0.004	<0.005	<0.010	<0.010	<4	55	131	31
2.5	<0.004	<0.005	<0.010	<0.010	<4	56	148	34
1.20-1.50	<0.004	<0.005	<0.010	<0.010	<4	56	124	27
0.35-0.50	<0.004	<0.005	<0.010	<0.010	<4	60	261	115
0.50-0.65	<0.004	<0.005	<0.010	<0.010	<4	120	280	26
0.5	<0.004	<0.005	<0.010	<0.010	<4	36	140	60
1	0.011	0.009	0.012	0.05	6	313	2160	701
1.5	<0.004	<0.005	<0.010	<0.010	<4	151	353	30
0.00-0.15	<0.004	<0.005	<0.010	<0.010	<4	635	5530	2180
1.5	<0.004	<0.005	<0.010	<0.010	0	55	151	23
1	<0.004	<0.005	<0.010	<0.010	<4	<10	<30	<20
1	<0.004	<0.005	<0.010	<0.010	<4	49	135	<20
0.8-1.0	0.244	0.062	0.482	1.41	256	6280	25100	10200
1.5	0.039	0.024	0.144	0.48	163	2620	9870	4020
1.8-2.0	<0.004	<0.005	<0.010	<0.010	52	745	2820	1140
2.5	<0.004	<0.005	<0.010	<0.010	<4	23	36	<20
0.15-0.30	3.22	0.015	227	246	3340	5690	8450	3840
0.5	0.01	<0.005	0.017	0.28	<4	42	61	<20
1.5	<0.004	<0.005	<0.010	0.03	<4	32	46	<20
0.5	0.067	0.009	0.015	0.17	<4	52	96	22
0.00-0.30	<0.004	<0.005	<0.010	<0.010	<4	22	82	41
0.40-0.70	<0.004	<0.005	<0.010	<0.010	<4	43	96	26
0.30-0.60	<0.004	<0.005	<0.010	<0.010	<4	33	51	<20
0.45-0.70	<0.004	<0.005	<0.010	<0.010	<4	68	705	662
0.70-1.00	<0.004	<0.005	<0.010	<0.010	<4	50	691	171
0.50-0.75	<0.004	<0.005	<0.010	<0.010	<4	18	206	173

TABLE E.5

MODELLING AVERAGE POTENTIAL VOLATILE EXPOSURE FROM EXCAVATION

Calculated Parameter	Symbol	Unit	Benzene	Toluene	Ethyl-benzene	Xylenes	Aliphatic F1 (C_6-C_8)	Aliphatic F1 (C_8-C_{10})	Aromatic F1 (C_8-C_{10})	Aliphatic F2 (C_{10} - C_{12})	Aliphatic F2 (C_{12} - C_{16})	Aromatic F2 (C_{10} - C_{12})	Aromatic F2 (C_{12} - C_{16})
Calculation of VOC Exposure and Emissions													
Effective Diffusion Coefficient	D_{eff}	cm^2/s	2.10E-03	1.53E-03	9.63E-04	5.64E-04	4.87E-03	1.37E-03	1.77E-04	2.81E-04	6.20E-05	3.31E-05	6.32E-06
Instantaneous soil flux	J_s	g/cm^2s	1.78E-08	1.11E-09	4.10E-07	2.98E-07	8.40E-06	2.91E-06	3.67E-13	8.49E-12	4.87E-12	7.28E-13	3.89E-13
Air Concentration (t=0)	Ca^c	$\mu g/m^3$	4.45E+02	2.77E+01	1.02E+04	7.45E+03	2.10E+05	7.28E+04	9.18E-03	2.12E-01	1.22E-01	1.82E-02	9.72E-03
Air concentration (t=15 minutes)	Ca	$\mu g/m^3$	1.60E+02	2.99E+01	2.11E+04	8.03E+03	2.26E+05	7.85E+04	9.89E-03	2.29E-01	1.31E-01	1.96E-02	1.05E-02
8-Hour Average Ambient Air Concentrations After Soil Disturbance													
Day 1	Ca	$\mu g/m^3$	4.77E+00	2.97E-01	1.49E+03	7.99E+01	2.25E+03	7.81E+02	9.84E-05	2.28E-03	1.31E-03	1.95E-04	1.04E-04
Day 2	Ca	$\mu g/m^3$	1.40E+00	8.75E-02	4.39E+02	2.35E+01	6.63E+02	2.30E+02	2.90E-05	6.70E-04	3.85E-04	5.75E-05	3.07E-05
Day 3	Ca	$\mu g/m^3$	1.03E+00	6.41E-02	3.22E+02	1.72E+01	4.86E+02	1.68E+02	2.12E-05	4.91E-04	2.82E-04	4.21E-05	2.25E-05
Day 4	Ca	$\mu g/m^3$	8.50E-01	5.30E-02	2.66E+02	1.43E+01	4.01E+02	1.39E+02	1.75E-05	4.06E-04	2.33E-04	3.48E-05	1.86E-05
Day 5	Ca	$\mu g/m^3$	7.41E-01	4.62E-02	2.32E+02	1.24E+01	3.49E+02	1.21E+02	1.53E-05	3.54E-04	2.03E-04	3.03E-05	1.62E-05
Regulatory Requirements													
Occupational Health and Safety Alberta													
8-hour Occupational Exposure Limit		ug/m^3	1597	188000	434000	434000							
15 Minute Short-term Exposure Limit		ug/m^3	7986		543000	651000							

Hours	Seconds	Calculated Parameter	Symbol	Unit	Benzene	Toluene	Ethyl-benzene	Xylenes	Aliphatic F1 (C_6-C_8)	Aliphatic F1 (C_8-C_{10})	Aromatic F1 (C_8-C_{10})	Aliphatic F2 (C_{10} - C_{12})	Aliphatic F2 (C_{12} - C_{16})	Aromatic F2 (C_{10} - C_{12})	Aromatic F2 (C_{12} - C_{16})
		Effective Diffusion Coefficient	D_{eff}	cm^2/s	2.10E-03	1.53E-03	9.63E-04	5.64E-04	4.87E-03	1.37E-03	1.77E-04	2.81E-04	6.20E-05	3.31E-05	6.32E-06
0.00	1	Instantaneous Soil flux	J_s	g/cm^2s	1.78E-08	1.11E-09	4.10E-07	2.98E-07	8.40E-06	2.91E-06	3.67E-13	8.49E-12	4.87E-12	7.28E-13	3.89E-13
0.13	480				8.12E-10	5.06E-11	2.54E-07	1.36E-08	3.83E-07	1.33E-07	1.68E-14	3.87E-13	2.22E-13	3.32E-14	1.77E-14
0.27	960				5.74E-10	3.58E-11	1.80E-07	9.62E-09	2.71E-07	9.40E-08	1.18E-14	2.74E-13	1.57E-13	2.35E-14	1.26E-14
149.60	538560				2.42E-11	1.51E-12	7.58E-09	4.06E-10	1.12E-08	3.97E-09	5.00E-16	1.16E-14	6.64E-15	9.92E-16	5.30E-16
149.73	539040				2.42E-11	1.51E-12	7.58E-09	4.06E-10	1.12E-08	3.97E-09	5.00E-16	1.16E-14	6.64E-15	9.92E-16	5.30E-16
149.87	539520				2.42E-11	1.51E-12	7.58E-09	4.06E-10	1.12E-08	3.97E-09	5.00E-16	1.16E-14	6.63E-15	9.91E-16	5.29E-16
150.00	540000				2.42E-11	1.51E-12	7.57E-09	4.06E-10	1.12E-08	3.96E-09	4.99E-16	1.16E-14	6.63E-15	9.91E-16	5.29E-16
0.00	1	Instantaneous Air Concentration	Ca	ug/m^3	4.45E+02	2.77E+01	1.02E+04	7.45E+03	2.10E+05	7.28E+04	9.18E-03	2.12E-01	1.22E-01	1.82E-02	9.72E-03
0.13	480				2.03E+01	1.27E+00	6.35E+03	3.40E+02	9.58E+03	3.32E+03	4.19E-04	9.69E-03	5.56E-03	8.31E-04	4.44E-04
0.27	960				1.44E+01	8.95E-01	4.49E+03	2.41E+02	6.77E+03	2.35E+03	2.96E-04	6.85E-03	3.93E-03	5.87E-04	3.14E-04
0.40	1440				1.17E+01	7.30E-01	3.67E+03	1.96E+02	5.53E+03	1.92E+03	2.42E-04	5.59E-03	3.21E-03	4.80E-04	2.56E-04
7.60	27360				2.69E+00	1.68E-01	8.41E+02	4.51E+01	1.27E+03	4.40E+02	5.55E-05	1.28E-03	7.36E-04	1.10E-04	5.88E-05
7.73	27840				2.66E+00	1.66E-01	8.34E+02	4.47E+01	1.26E+03	4.37E+02	5.50E-05	1.27E-03	7.30E-04	1.09E-04	5.83E-05
7.87	28320				2.64E+00	1.65E-01	8.27E+02	4.43E+01	1.25E+03	4.33E+02	5.45E-05	1.26E-03	7.24E-04	1.08E-04	5.78E-05
8.00	28800				2.62E+00	1.63E-01	8.20E+02	4.39E+01	1.24E+03	4.29E+02	5.41E-05	1.25E-03	7.18E-04	1.07E-04	5.73E-05
		15 Minute average air concentration	Ca	ug/m^3	160	30	21083	8033	2.26E+05	7.85E+04	9.89E-03	2.29E-01	1.31E-01	1.96E-02	1.05E-02
		Day 1: Average 8-hour air concentration	Ca	ug/m^3	5	0	1492	80	2.25E+03	7.81E+02	9.84E-05	2.28E-03	1.31E-03	1.95E-04	1.04E-04
8.13	29280				2.60E+00	1.62E-01	8.13E+02	4.36E+01	1.23E+03	4.26E+02	5.36E-05	1.24E-03	7.12E-04	1.06E-04	5.68E-05
8.27	29760				2.58E+00	1.61E-01	8.06E+02	4.32E+01	1.22E+03	4.22E+02	5.32E-05	1.23E-03	7.06E-04	1.06E-04	5.64E-05
8.40	30240				2.56E+00	1.59E-01	8.00E+02	4.29E+01	1.21E+03	4.19E+02	5.28E-05	1.22E-03	7.01E-04	1.05E-04	5.59E-05
8.53	30720				2.54E+00	1.58E-01	7.94E+02	4.25E+01	1.20E+03	4.16E+02	5.24E-05	1.21E-03	6.95E-04	1.04E-04	5.55E-05
31.60	113760				1.32E+00	8.22E-02	4.12E+02	2.21E+01	6.22E+02	2.16E+02	2.72E-05	6.29E-04	3.61E-04	5.40E-05	2.88E-05
31.73	114240				1.32E+00	8.20E-02	4.12E+02	2.20E+01	6.21E+02	2.16E+02	2.71E-05	6.28E-04	3.60E-04	5.38E-05	2.88E-05
31.87	114720				1.31E+00	8.18E-02	4.11E+02	2.20E+01	6.20E+02	2.15E+02	2.71E-05	6.27E-04	3.60E-04	5.37E-05	2.87E-05
32.00	115200				1.31E+00	8.17E-02	4.10E+02	2.20E+01	6.18E+02	2.15E+02	2.70E-05	6.25E-04	3.59E-04	5.36E-05	2.86E-05
		Day 2: Average 8-hour air concentration	Ca	ug/m^3	1.40E+00	8.75E-02	4.39E+02	2.35E+01	6.63E+02	2.30E+02	2.90E-05	6.70E-04	3.85E-04	5.75E-05	3.07E-05
32.13	115680				1.31E+00	8.15E-02	4.09E+02	2.19E+01	6.17E+02	2.14E+02	2.70E-05	6.24E-04	3.58E-04	5.35E-05	2.86E-05
32.27	116160				1.30E+00	8.13E-02	4.08E+02	2.19E+01	6.16E+02	2.14E+02	2.69E-05	6.23E-04	3.57E-04	5.34E-05	2.85E-05
32.40	116640				1.30E+00	8.12E-02	4.07E+02	2.18E+01	6.15E+02	2.13E+02	2.69E-05	6.21E-04	3.57E-04	5.33E-05	2.85E-05
32.53	117120				1.30E+00	8.10E-02	4.07E+02	2.18E+01	6.13E+02	2.13E+02	2.68E-05	6.20E-04	3.56E-04	5.32E-05	2.84E-05
55.60	200160				9.94E-01	6.20E-02	3.11E+02	1.67E+01	4.69E+02	1.63E+02	2.05E-05	4.74E-04	2.72E-04	4.07E-05	2.17E-05
55.73	200640				9.93E-01	6.19E-02	3.11E+02	1.66E+01	4.69E+02	1.63E+02	2.05E-05	4.74E-04	2.72E-04	4.06E-05	2.17E-05
55.87	201120				9.91E-01	6.18E-02	3.10E+02	1.66E+01	4.68E+02	1.62E+02	2.05E-05	4.73E-04	2.72E-04	4.06E-05	2.17E-05
56.00	201600				9.90E-01	6.17E-02	3.10E+02	1.66E+01	4.67E+02	1.62E+02	2.04E-05	4.73E-04	2.71E-04	4.05E-05	2.17E-05
		Day 3:Average 8-hour air concentration	Ca	ug/m^3	1.03E+00	6.41E-02	3.22E+02	1.72E+01	4.86E+02	1.68E+02	2.12E-05	4.91E-04	2.82E-04	4.21E-05	2.25E-05
56.13	202080				9.89E-01	6.17E-02	3.09E+02	1.66E+01	4.67E+02	1.62E+02	2.04E-05	4.72E-04	2.71E-04	4.05E-05	2.16E-05
56.27	202560				9.88E-01	6.16E-02	3.09E+02	1.66E+01	4.66E+02	1.62E+02	2.04E-05	4.72E-04	2.71E-04	4.04E-05	2.16E-05
56.40	203040				9.87E-01	6.15E-02	3.09E+02	1.65E+01	4.66E+02	1.62E+02	2.04E-05	4.71E-04	2.70E-04	4.04E-05	2.16E-05
56.53	203520				9.86E-01	6.14E-02	3.08E+02	1.65E+01	4.65E+02	1.61E+02	2.03E-05	4.70E-04	2.70E-04	4.03E-05	2.15E-05
79.60	286560				8.31E-01	5.18E-02	2.60E+02	1.39E+01	3.92E+02	1.36E+02	1.71E-05	3.96E-04	2.28E-04	3.40E-05	1.82E-05
79.73	287040				8.30E-01	5.17E-02	2.60E+02	1.39E+01	3.91E+02	1.36E+02	1.71E-05	3.96E-04	2.27E-04	3.40E-05	1.81E-05
79.87	287520				8.29E-01	5.17E-02	2.59E+02	1.39E+01	3.91E+02	1.36E+02	1.71E-05	3.96E-04	2.27E-04	3.39E-05	1.81E-05
80.00	288000				8.29E-01	5.17E-02	2.59E+02	1.39E+01	3.91E+02	1.36E+02	1.71E-05	3.95E-04	2.27E-04	3.39E-05	1.81E-05
		Day 4: Average 8-hour concentration	Ca	ug/m^3	8.50E-01	5.30E-02	2.66E+02	1.43E+01	4.01E+02	1.39E+02	1.75E-05	4.06E-04	2.33E-04	3.48E-05	1.86E-05
80.13	288480				8.28E-01	5.16E-02	2.59E+02	1.39E+01	3.91E+02	1.36E+02	1.71E-05	3.95E-04	2.27E-04	3.39E-05	1.81E-05
80.27	288960				8.27E-01	5.16E-02	2.59E+02	1.39E+01	3.90E+02	1.36E+02	1.71E-05	3.95E-04	2.27E-04	3.39E-05	1.81E-05
80.40	289440				8.26E-01	5.15E-02	2.59E+02	1.39E+01	3.90E+02	1.35E+02	1.71E-05	3.94E-04	2.26E-04	3.38E-05	1.81E-05
80.53	289920				8.26E-01	5.15E-02	2.58E+02	1.38E+01	3.90E+02	1.35E+02	1.70E-05	3.94E-04	2.26E-04	3.38E-05	1.81E-05
103.60	372960				7.28E-01	4.54E-02	2.28E+02	1.22E+01	3.42E+02	1.19E+02	1.50E-05	3.47E-04	1.99E-04	2.98E-05	1.59E-05
103.73	373440				7.28E-01	4.54E-02	2.28E+02	1.22E+01	3.42E+02	1.19E+02	1.50E-05	3.47E-04	1.99E-04	2.98E-05	1.59E-05
103.87	373920				7.27E-01	4.53E-02	2.28E+02	1.22E+01	3.42E+02	1.19E+02	1.50E-05	3.47E-04	1.99E-04	2.98E-05	1.59E-05
104.00	374400				7.27E-01	4.53E-02	2.27E+02	1.22E+01	3.42E+02	1.19E+02	1.50E-05	3.47E-04	1.99E-04	2.97E-05	1.59E-05
		Day 5: Average 8-hour air concentration	Ca	ug/m^3	7.41E-01	4.62E-02	2.32E+02	1.24E+01	3.49E+02	1.21E+02	1.53E-05	3.54E-04	2.03E-04	3.03E-05	1.62E-05

c - Assuming emitted mass is bound in a box volume, bound by125 m in height x area of contamination ($400m^2$)

TABLE E.6
EX SITU EXPOSURE DURING ALLU SOIL TREATMENT

Parameter	Symbol	Units	SM Bucket	M Bucket	LG Bucket	References / Notes
Bucket volume	-	m^3	1	2	4	US EPA, 1993
Soil processing rate	AR	m^3/hr	50	150	240	US EPA, 1993
Allu processing rate	Q	m^3/hr	37.5	112.5	180	25% slower processing than excavation, assumed
Excavation hours	-	hr	16	5.33	3.33	800 m^3
Allu aeration hours	tr	hr	21.3	8.0	4.4	2 passes through allu
Total soil mass		kg	1120000			Function of bulk density
Wind Speed	U	m/s	4			Environment Canada, 2008
Total soil volume	Vsoil	m^3	800			Assumed
Source length	L	m	20			Assumed
Source area	SA	m^2	400			Assumed
Height of Allu bucket	$Allu_h$	m	2			Assumed

Calculated Parameter	Symbol	Unit	Benzene	Toluene	Ethyl-benzene	Xylenes	F1	F2
AENV Tier 1 FG Commerical Soil Guideline	SQG	mg/kg	0.046	0.52	0.11	15	320	260
Average concentration of contaminant in soil	Cs	mg/kg	0.49	0.036	16.7	15.9	277	1272.0
Maximum Concentration of contaminant in soil	Cs	mg/kg	3.22	0.09	227	246	3340	47200
Short term emission rate to AENV Soil Guideline	ER	g/s	1.23E-01	BG	8.82E+00	8.98E+00	1.17E+02	1.83E+03
Cs)	ER	g/s	1.91E-02	1.40E-03	6.50E-01	6.18E-01	1.08E+01	4.95E+01
Short-term Ex Situ Air Concentration	$C_{air\_ex\text{-}situ}$	mg/m^3	7.71E-01	BG	5.51E+01	5.61E+01	7.34E+02	1.14E+04
Long-term Ex Situ Air Concentration	$C_{air\_ex\text{-}situ}$	mg/m^3	1.19E-01	8.72E-03	4.06E+00	3.86E+00	6.73E+01	3.09E+02
Long-term Ex Situ Air Concentration (with biofilter)	C_{air_BF}	mg/m^3	4.78E-02	3.49E-03	1.62E+00	1.55E+00	2.69E+01	1.24E+02
8-hour Occupational Exposure Limit		mg/m^3	1.60	188	434	434	-	-
15 Minute Short-term Exposure Limit		mg/m^3	7.99	-	543	651	-	-

BG - below guideline

TABLE E.7
CONTAMINANT SOURCE EMISSIONS OF GREENHOUSE GASES

	Units	Benzene ($C_6H_{6)}$	Toluene ($C_7H_{8)}$	Ethyl-benzene ($C_8H_{10)}$	Xylenes	Aliphatic F1 (C6-C8)	Aliphatic F1 (C8-C10)	Aromatic F1 (C8-C10)	Aliphatic F2 (C10 - C12)	Aliphatic F2 (C12 - C16)	Aromatic F2 (C10 - C12)	Aromatic F2 (C12 - C16)	VOC
Fraction of Petroleum Hydrocarbon Subfraction in Soil	unitless	-	-	-	-	0.55	0.36	0.09	0.36	0.44	0.09	0.11	-
Average measured soil concentration at an example site prior to remedial activities	mg/kg	0.4913077	0.035875	16.71264286	15.894706	152	100	25	458	560	114	140	
Calculation of Greenhouse Gase Emissions from Ex Situ													
Contaminant emission mass (kg)[a] assuming no transformation	kg	5.50E+02	4.02E+01	1.87E+04	1.78E+04	1.71E+05	1.12E+05	2.79E+04	5.13E+05	6.27E+05	1.28E+05	1.57E+05	1.77E+06
Molar mass of carbon in compound	g/mol	72.0642	84.0749	96.0856	96.0856	108.0963	108.0963	108.0963	132.1177	168.1498	120.107	144.1284	-
Molecular mass of contaminant	g/mol	7.81E+01	9.21E+01	1.06E+02	1.06E+02	1.00E+02	1.30E+02	1.20E+02	1.60E+02	2.00E+02	1.30E+02	1.50E+02	-
Relative mass portion of carbon	fraction	0.92	0.91	0.91	0.91	1.08	0.83	0.90	0.83	0.84	0.92	0.96	
Mass of carbon emitted	Tonnes	0.51	0.037	17	16	184	93	25	423	527	118	151	1556
Mass of carbon dioxide emitted[b]	Tonnes	1.9	0.13	62	59	676	341	92	1553	1933	434	552	5705
Calculation of Greenhouse Gas Emissions From Landfill Disposal													
Total Mass of Carbon from Contaminants	Tonnes	1556											
Predicted Landfill Methane Emission	Tonnes	455											
Predicted Landfill Carbon Dioxide Emissions	Tonnes	1284											

a - Assuming a uniform soil contaminant concentration and a soil volume of 800 m^3, an area of 400m^2 with a contaminant depth of 2 m

b - Assuming aerobic transformation of contaminants solely over the lifecycle of the emitted compound

* Concentrations adjusted for the fraction of petroleum hydrocarbon subfraction in soil.
Concentrations of F3 and F4 were not considered

TABLE E.8
REMEDIAL RELATED PARTICULATE EMISSIONS

Calculation	Symbol	Units	Value	Assumptions
Particle Emission Due to Soil Handling				
Emissions from all transfer operations, FG PM2.5	$E_{Transfer1}$	g	13748.9	
Emissions from all transfer operations, FG PM10	$E_{Transfer2}$	g	43746.5	
Emissions from soil spreading (i.e. bulldozer, tractor blade), FG	$E_{Spreading1}$	g/sec	0.19	
Particulate emissions From Vehicular Traffic				
Emissions from unpaved industrial surfaces (PM2.5)	$EF_{Unpaved1}$	g/VKT	64.5	
Emissions from unpaved industrial surfaces (PM10)	$EF_{Unpaved2}$	g/VKT	649.9	
Emissions from unpaved industrial surfaces (TPM)	$EF_{Unpaved3}$	g/VKT	2387.6	
Ex Situ Remedial Activities				
Emissions from all transfer operations, FG PM2.5		g	54995.6	Soil volume moved 4x (excavation, allu x2, soil replacement)
Emissions from all transfer operations, FG PM10		g	174986.1	Soil volume moved 4x (excavation, allu x2, soil replacement)
Total Emissions from soil spreading and levelling		g	2702	4 hours of levelling and spreading
Emissions from unpaved industrial surfaces (PM2.5)		g	1613.20	25 km travelled onsite, all equipment
Emissions from unpaved industrial surfaces (PM10)		g	16247.19	25 km travelled onsite, all equipment
Emissions from unpaved industrial surfaces (TPM)		g	59690.26	25 km travelled onsite, all equipment
Excavator engine emissions during excavation and allu		g	655.66	12 hr excavating, and 12 hr of alluing
Front-end loader engine emissions during levelling		g	106.47	6 hr of active levelling and compacting
Generator engine emissions		g	340.926	24 hr of generator power output
TOTAL PM2.5 from transfer operations and unpaved site traffic		**Kg**	**56.609**	
TOTAL PM10 from tranfer operations and unpaved site traffic		**Kg**	**191.2**	
TOTAL PARTICULATE EMISSIONS FROM ALL ON-SITE EX-SITU REMEDIAL ACTIVITIES		**Kg**	**238.5**	
Landfill Disposal				
Emissions from all transfer operations into and out of haul truck, FG PM2.5		g	27497.8	Soil volume moved 2x, into and out of haul truck only
Emissions from all transfer operations into and out of haul truck, FG PM10		g	87493.0	Soil volume moved 2x, into and out of haul truck only
Emissions from spreading and levelling into landfill cell		g	1351.2	2 hr to incorporate into landfill cell
Emission from unpaved industrial surfaces (PM2.5)		g	8066.0	25 km onsite equipment travel and 100 km to landfill
Emissions from unpaved industrial surfaces (PM10)		g	81235.9	25 km onsite equipment travel and 100 km to landfill
Emissions from unpaved industrial surfaces (TPM)		g	298451.3	25 km onsite equipment travel and 100 km to landfill
Excavator engine emissions during excavation		g	327.83	12 hr of active excavation
Front-end loader emission during levelling		g	212.93	12 hr of levelling and compacting into landfill cell
Generator engine emissions		g	340.926	24 hr of generator power output
TOTAL PM2.5 from transfer operations and unpaved onsite and offsite traffic		**Kg**	**35.56**	
TOTAL PM10 from tranfer operations and unpaved onsite and offsite traffic		**Kg**	**168.7**	
TOTAL PARTICULATE EMISSIONS FROM ALL LANDFILL DISPOSAL ACTIVITIES		**Kg**	**388.2**	

TABLE E.9
ENGINE COMBUSTION EMISSIONS OF CRITERIA AIR CONTAMINANTS (KG)

Process	L/hr[b]	Operational Hours Ex Situ Scenario	Operational Hours Landfill Disposal Scenario
Material Handling using a front end loader	4.67	6	12
Mass excavation using an excavator	7.19	24	12
Power generation using a generator	4.54	24	24
Contaminated soil transport (hr)	7.57	0.3125	1.5625

Equipment	CH_4	CO	N_20	NO_x (NO_2)	SO_x (SO_2)	CO_2	VOC[c]
Wheeled loader	1.38	138.58	28.60	223.30	6.54	68,158	27.02
Off-road trucks	1.38	79.46	28.60	280.42	6.54	68,253	27.02
Tractor	1.20	194.02	28.60	359.59	6.54	67,849	48.46
Industrial engine	4.15	199.55	28.60	439.41	6.54	67,889	45.74
Ex-Situ							
Equipment	**CH_4**	**CO**	**N_20**	**NO_x (NO_2)**	**SO_x (SO_2)**	**CO_2**	**VOC[c]**
2004 Front-end loader, 6 cylinder, 149 HP	0.002	0.151	0.031	0.244	0.007	74.481	0.030
2002 Generator, 4 cylinder, 108 HP	0.018	0.848	0.122	1.867	0.028	288.489	0.194
2001 Excavator 1, 6 cylinder, 254 HP	0.008	1.306	0.192	2.420	0.044	456.610	0.326
2005 On-highway truck, 6 cylinder, 306 HP	0.000	0.007	0.003	0.026	0.001	6.297	0.002
2005 On-highway truck, 6 cylinder, 306 HP (for biofilter transport)	0.000	0.007	0.003	0.026	0.001	6.297	0.002
Sum	**0.03**	**2.31**	**0.35**	**4.56**	**0.08**	**825.88**	**0.55**
Sum (with biofilter)	**0.03**	**2.32**	**0.35**	**4.58**	**0.08**	**832.17**	**0.56**
Landfill Disposal							
2004 Front-end loader, 6 cylinder, 149 HP	0.003	0.303	0.063	0.488	0.014	148.963	0.059
2002 Generator, 4 cylinder, 108 HP	0.018	0.848	0.122	1.867	0.028	288.489	0.194
2001 Excavator 1, 6 cylinder, 254 HP	0.004	0.653	0.096	1.210	0.022	228.305	0.163
2005 On-highway truck, 6 cylinder, 306 HP	0.001	0.037	0.013	0.129	0.003	31.485	0.012
Sum	**0.03**	**1.84**	**0.29**	**3.69**	**0.07**	**697.24**	**0.43**

a - taken from GHGenius for 2010 western Canada fuel specifications www.ghgenius.ca
b – Frey et al., 2010, rates paired with equipment and activity most applicable.
c – does not consider methane into equipment VOC total

Notes
Emissions applied from off-road trucks were applied to on-highway truck fuel use in lieu of a more appropriate input