APPENDIX C

Fugitive Dust Model

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APPENDIX C – Fugitive Dust Model

1.1 INTRODUCTION

A box dispersion model (US EPA 1991, Cowherd 1985) was used to estimate fugitive dust emissions due to wind erosion at the project site located in Washington, DC. Dust generated from vehicle traffic on site was not calculated since vehicle traffic is assumed to only occur on the paved or graveled portion of the site. The model estimated the inhalable fraction of dust (particles less than 10 μm in diameter, PM_{10}) within the breathing zone of workers and recreational users of the site. The concentrations of the chemicals of potential concern (i.e., arsenic, iron, and lead) associated with the PM_{10} were then used in exposure equations to determine the dose received by a receptor present on site. Details regarding the model used to estimate fugitive dust emissions from wind are presented below, along with pertinent input parameters for each model.

Sample calculations used in these models for estimation of particulate emission factors are also provided for clarity. Finally, concentrations of fugitive dust from erosion were used to estimate potential exposure of on-site receptors to contaminants of potential concern in fugitive dust.

1.2 BOX DISPERSION MODEL FOR WIND/SOIL FUGITIVE DUST

The fugitive dust model used in this study to estimate wind generated emissions uses principles described by Cowherd *et al.* (1985; for US EPA), which have been adopted by US EPA (1991), for a rapid assessment procedure applicable to a contaminated site where the surface contamination provides a relatively continuous and constant potential for emission over a period of years. For this risk assessment, emissions were evaluated for the entire site, which is approximately 201,200 m^2.

The particulate emission factor (PEF) relates the contaminant concentration in soil with the concentration of respirable particles in the air due to wind-driven fugitive dust emissions from surface contamination. Dust generated from open sources is termed “fugitive” because it is not discharged to the atmosphere in a confined flow stream but rather as uncontrolled dispersion. The modeling assumes that the entire area under consideration is contaminated with a uniform contaminant concentration. Cowherd’s emission assessment methodology addresses only respirable particulate matter, defined as particles equal to or smaller than 10 μm aerodynamic diameter (denoted as PM_{10}). PM_{10} particulate matter is most relevant for human exposure assessment because particles (and adsorbed contaminants) larger than 10 μm generally do not deposit in the lungs due to the natural filtering abilities of the human respiratory system. The concentration of contaminant in the respirable particulate emissions is assumed to be the same as that measured in surface soils.

The emission rate of particulate matter with an aerodynamic diameter less than 10 µm (E_{10}) is a function of the erodibility of the surface material. The model employed is representative of a surface with "unlimited erosion potential", which is characterized by bare surfaces of finely divided material with an unlimited reservoir of erodible particles. In general, these surfaces erode at low wind speeds, and particulate emission rates are relatively time-independent at a given wind speed. The Cowherd model was selected because it provides conservative estimates for the emission rates of respirable particulates (US EPA, 1991).

Other assumptions used in this model are listed below:

- Fugitive dust emissions generated from wind erosion are "continuous and steady";
- Surface contamination provides a relatively continuous and constant potential for emission over a period of years;
- Meteorology is the same at the source and the receptor;
- Concentrations of particulates in the breathing zone (*i.e.*, ground level concentrations) are conservative because deposition of particulates are not considered;
- Only respirable-size particles (< 10 µm) are considered (*i.e.*, PM_{10}); and,
- Emissions are uniform over the source area.

1.2.1 Input Parameters for Wind Erosion Fugitive Dust Model

The box model requires a number of site-specific or regional input parameters in order to determine the local exposures to contaminated dust. These parameters are set out in Table C-1 and are described in more detail in the remainder of the section.

Table C-1: Input parameters for the dust dispersion model.

PARAMETER		
Weather Data	U_{Air}	Annual average wind speed [m/s] from the nearest reference weather station (usually a nearby airport)
	Z_{met}	Measurement height at source of the weather data [m]
	Z_{0Air}	Surface roughness length [m] at the source of weather data
Site Data	Z_0	Local surface roughness [m]
	V_f	Fraction of the site covered by vegetation (often assumed to be 0%)
	d_m	The mode (most prevalent) particle diameter of the surface material [μm]
	L_s	The cross-wind dimension of the site [m] (the user should select the lesser of the length or width of the site)
	A	The exposed area of the site [m^2]
	D_h	The diffusion [m], or the height through which the emissions are to be mixed (this is typically set to 2 m)

Mean Annual Wind Speed (U_{Air})

Mean annual wind speeds (U_{air}) at the Ronald Reagan National Airport (DCA) reference station were used to represent the wind speed. Based on wind data supplied by the National Climatic Data Center (2002), the mean annual wind speed at DCA was 4.25 m/s.

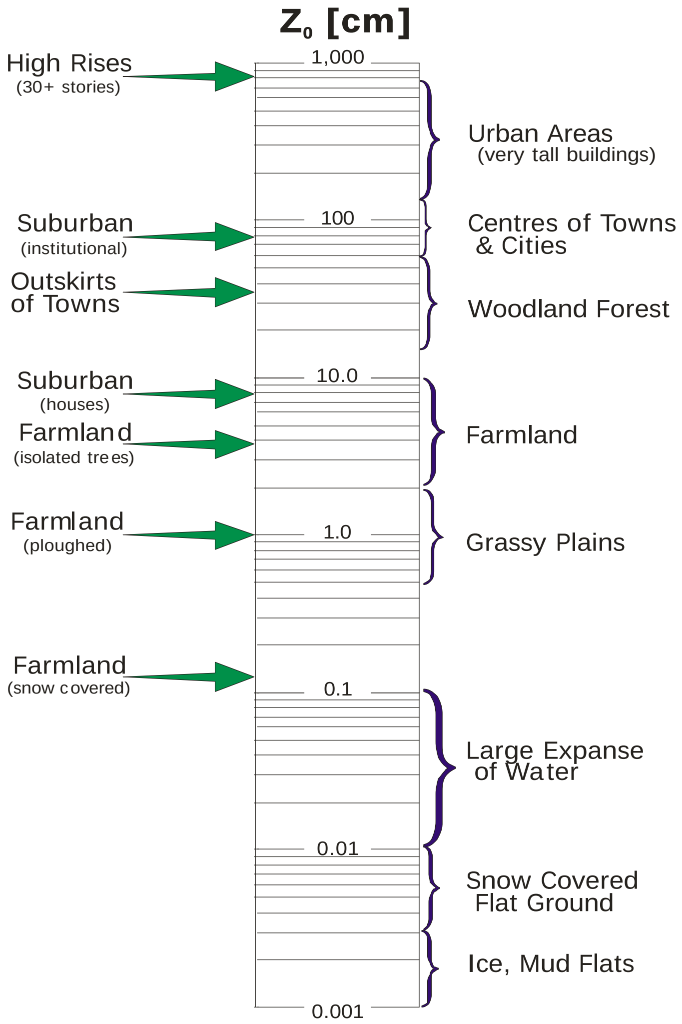
Measurement Height at the Reference Station (Z_{met})

At DCA, wind speeds were collected at 10 ft (3.05 m).

Surface Roughness Height at the Reference Station (Z_{0Air})

The surface roughness at the reference location (Z_{0Air}) is a function of the local land use and the presence of obstruction. The surface roughness has been described as the height where the wind speed becomes zero (Stull 1988). This parameter is important for describing the local wind profiles (i.e., how the wind speeds vary with height). A simple graph of typical roughness lengths is provided in Figure C-1 (reproduced from Cowherd et al 1985, Stull 1988). From this figure, a suitable roughness length for the land use in the immediate area of the reference weather station can be selected. The reference weather station is located at the airport station and as such, the area immediately surrounding it is flat and open for miles. Based on the above description and Figure C-1, the surface roughness height was estimated to be 0.01 m.

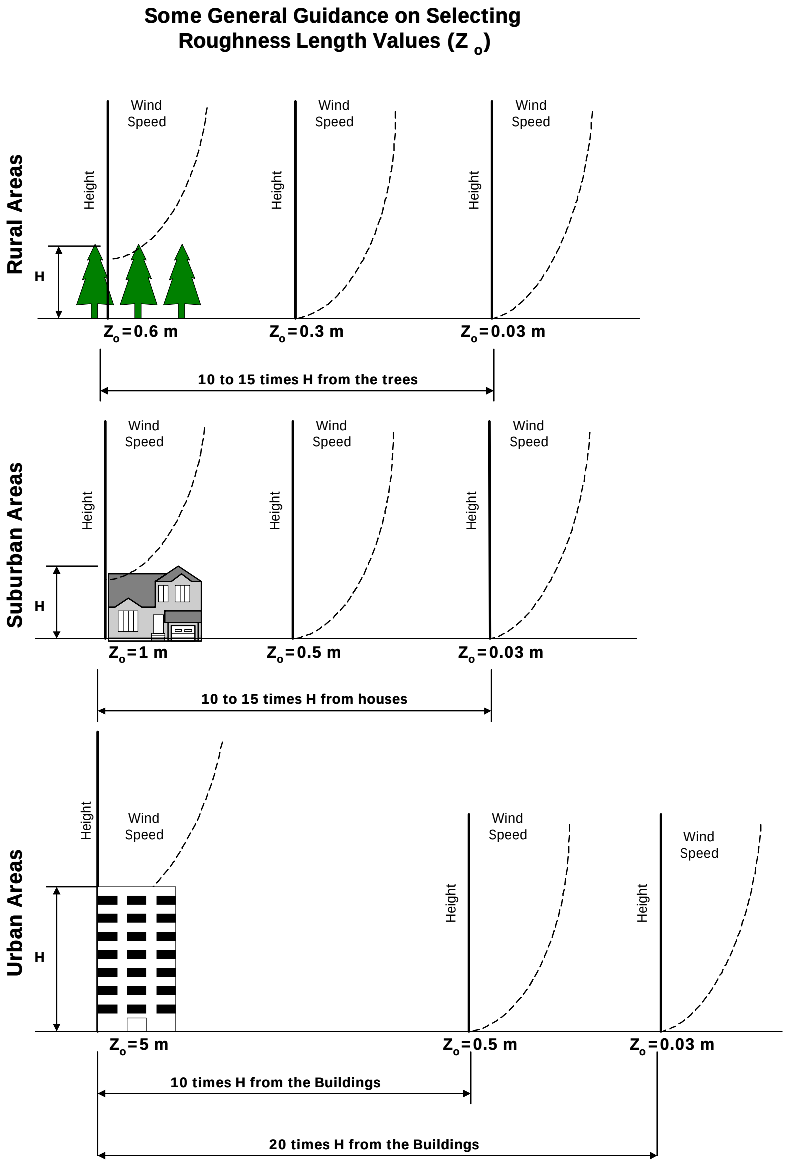
Figure C-1: Typical surface roughness values.



Local Surface Roughness Height (Z_0)

The local surface roughness (Z_0) is a function of the local land use and the presence of obstruction. This parameter is important for describing the local wind profiles (how the wind speeds vary with height) and therefore, Z_0 for the site was selected very carefully. Typical roughness lengths have been provided in Figure C-1 (after Cowherd et al 1985 and Stull 1988). Figure C-2 provides further guidance for selecting Z_0. The roughness length diminishes by distance from an obstruction (such as a building; Figure C-2). Based on the site characteristics, a roughness of 0.2 m was selected.

Figure C-2: Surface roughness with distance.



Vegetation Cover on the Site (V_f)

The fraction of the contaminated site that is covered with vegetation has a direct effect on the amount of particulate matter that will be emitted. As most of the site is vegetated, and only a portion of the site may be exposed by demolition and construction activities, this parameter was conservatively set to 33 %.

Mode of the Particle Size Distribution (d_m)

There are no site-specific data on grain size distribution. The mode of the particle size distribution (d_m) for surface soil was set to 250 µm, which was used in the model to determine the threshold wind velocities required to erode the soil.

Exposed Site Area (A) and Cross-Wind Site Dimension (L_s)

The area and the cross-wind length of the site were obtained from site diagrams. The approximate area of the contaminated site is used to calculate the total emissions and the exact shape of the area is not relevant at the screening level assessment stage. The area of the site is approximately 201,200 m^2. Assuming that the shape of the impacted portion of the site is rectangular, the length of the longest side (418 m) was used to represent the cross-wind length.

Diffusion Height or Box Model Mixing Height (D_h)

The diffusion height used in the box model is the height over which the airborne particles are mixed. The US EPA (1991) suggests a conservative diffusion height of 2 m be assumed. This height corresponds well with the breathing zone of human receptors. The box model mixing height is independent of receptor height and is considered conservative for both child and adult receptors.

Calculation of Local Wind Speed

The box model spreadsheet calculates the local wind speeds at two separate heights:

- The local wind speed (U_{local}) is calculated at a 7 m reference height, and is used to estimate emissions at the site; and
- The wind speed in the breathing zone (V) is calculated at the diffusion height (D_h = 2 m). This wind speed is used to calculate the on-site exposures.

Local Wind Speed (U_{local})

The meteorological parameter that is the most influential to the emission of dust is the wind speed. Since local wind speed at the site was unavailable, local wind speed at 7 meters was estimated using:

- Data from the closest meteorological station (U_{Air});
- The surface roughness from the closest meteorological station (Z_{0Air});
- The site surface roughness height (Z_0);
- The height of the meteorological tower at the closest station (Z_{met}); and,
- The depth of the well-mixed boundary layer (δ).

The local wind speed at 7 m was estimated using a power law expression for the variation of wind speed with height. This relationship assumes the wind velocities at the top of the atmospheric boundary layer are the same at both locations. The relationship is given in the following equation:

$$U_{local} = U_{air}\left(\frac{d}{z_{met}}\right)^{P_{air}} \times \left(\frac{z_{local}}{d}\right)^{P_{local}}$$

The exponents P_{air} and P_{local} depend on roughness lengths at the closest meteorological station and the contaminated site, respectively, as well as the atmospheric stability class. The values derived by Irwin (1979) were used in the model and have been reproduced in Table C-2. For simplicity, the model uses a constant surface boundary layer thickness of δ equal to 500 m, and assumes that P_{air} is in a terrain roughness of z_O=0.01 m and P_{local} is in a terrain roughness of 0.2 m. The stability class used for this assessment is the average of Classes "C", "D" and "E". This is not a worst-case scenario and is meant to approximate the average stability. Based on the information provided above, the local wind speed (U_{local}) was estimated to be 2.1 m/s.

Table C-2: Wind speed power law exponents for varying atmospheric stability class and roughness lengths.

WIND SPEED EXPONENTS (P_{AIR} AND P_{LOCAL})			
PASQUILL-GIFFORD STABILITY CLASS	ROUGHNESS LENGTH		
	z_O=0.01M	z_O=0.1M	z_O=1.0M
A – Very unstable	0.05	0.08	0.17
B – Unstable	0.06	0.09	0.17
C – Slightly unstable	0.06	0.11	0.20
D – Neutral	0.12	0.16	0.27
E – Stable	0.34	0.32	0.38
F – Very stable	0.53	0.54	0.61

Note: from Irwin (1979)

Wind Speed in the Breathing Zone (V)

The wind speed in the breathing zone (V) was calculated in the same manner as the local wind speed. Data from the closest meteorological station were converted to local speeds at the diffusion height (D_h) using a power law expression. This relationship assumes:

- The wind velocities at the top of the atmospheric boundary layer are the same at both locations;
- A constant boundary layer thickness (δ) is equal to 500 m;
- The exponents P_{air} and P_{local} depend on roughness lengths and stability class; and,
- The P value is equal to the average of P values provided by Irwin (1979) for stability classes "C", "D" and "E" were used in the model.

The resulting equation for V is given below:

$$V = U_{air}\left(\frac{d}{z_{met}}\right)^{P_{air}} \times \left(\frac{D_h}{d}\right)^{P_{local}}$$

Based on the above equation and the information provided, the wind speed in the breathing zone (V) was estimated to be 3.47 m/s.

Wind Erosion Emissions

The box model calculates the wind erosion using two site-specific surface erosion parameters:

- Threshold frictional velocity (U_{*t}); and,
- Threshold velocity (U_t)

Threshold Frictional Velocity (U_{*t})

The threshold friction velocity (U_{*t}) was determined as a function of the most prevalent particle diameter, or mode, of the surface material (d_m). This was done by solving the empirical relationship given in Figure 3-4 of Cowherd, (1985). Using the equations below, the threshold frictional velocity (U_{*t}) was estimated to be 0.363 m/s for the site. Figure C-3 reproduces the figure from Cowherd that gives a solution in the form of:

$$U_{*t} = S_a \times (d_m)^{S_b}$$

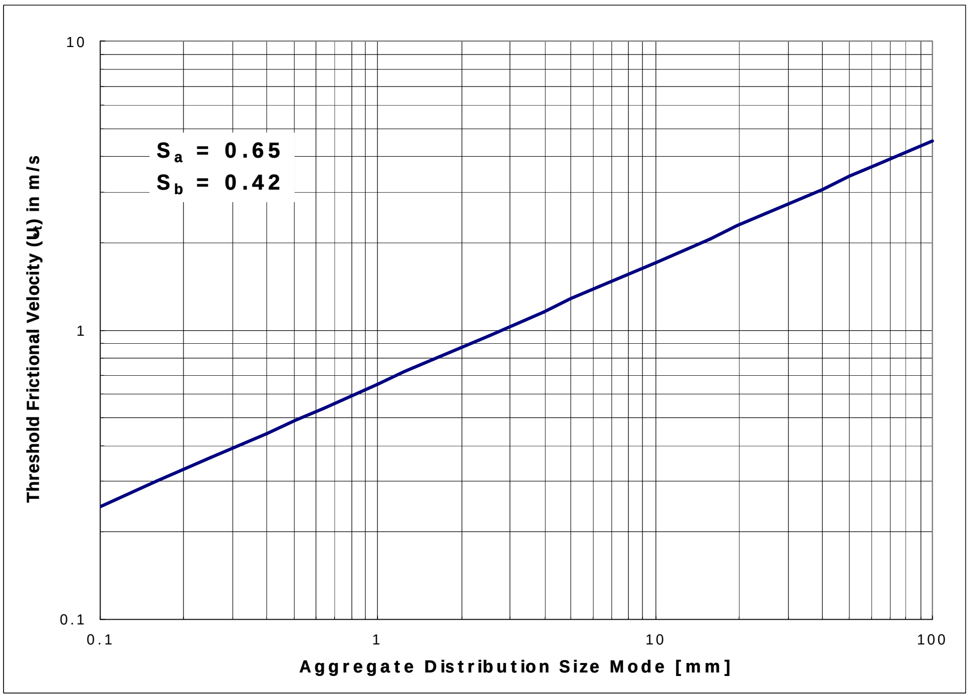
Where:

d_m = mode of aggregate size distribution [mm]

When the parameters from Figure C-3 are substituted into the above equation, the formula to calculate U_{*t} becomes:

$$U_{*t} = 0.65\left(\frac{d_m}{1000\frac{mm}{mm}}\right)^{0.421}$$

Figure C-3: Relationship between the threshold frictional velocity (U_{*t}) and the mode of the particle distribution (d_m).



Threshold Velocity (U_t)

The threshold frictional velocity (U_{*t}) for the surface particles was used to determine the threshold velocity (U_t) required to erode the particles at the site. Solving the empirical relationship given in Figure 4-1 in Cowherd (1985) yields the necessary information to determine U_t. The threshold velocity (U_t) was estimated to be 3.27 m/s for a reasonable estimate for the site. Figure C-4 reproduces the figure from Cowherd and the values for substitution in the following equation.

$$\frac{U_t}{U_{*_t}} = R_a + R_b \times \ln(Z_0)$$

Where:

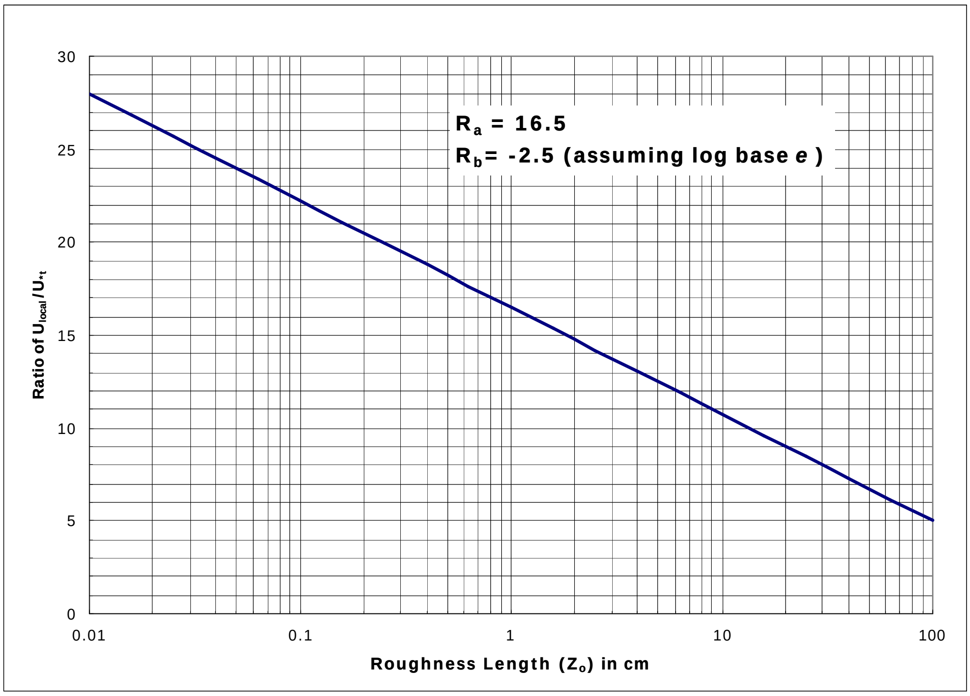
Z_O = surface roughness height [cm]

U_{*_t} = the threshold friction velocity [m/s]

When the parameters from Figure C-4 are substituted into the above equation, the formula to calculate U_t becomes:

$$\frac{U_t}{U_{*_t}} = 16.5 - 2.5 \times \ln(Z_0)$$

Figure C-4: Relationship between roughness length (Z_0) and the ratio of wind speed to frictional velocity (U_{*t}).



Average Emissions of PM_{10} (E_{10})

If it is assumed that the surface of the site has an unlimited erosion potential, then the emissions of inhalable particles, or PM_{10}, can be defined by the following equation from Cowherd (1985):

$$E_{10} = 0.036 \times (1 - V_f) \times \left(\frac{U_{local}}{U_t} \right)^3 \times F(x)$$

Where:

E_{10}	=	PM_{10} emissions [g/m^2-hr]
V_f	=	fraction of soil covered by vegetation [33.3 %]
U_{local}	=	local mean annual wind speed, [= 2.1 m/s,]
U_t	=	threshold velocity [reasonable = 3.27 m/s]
F(X)	=	probability distribution for wind speed [F(x)=1.9]
F(X)	$\Rightarrow$	1.91 as $X \Rightarrow 0$

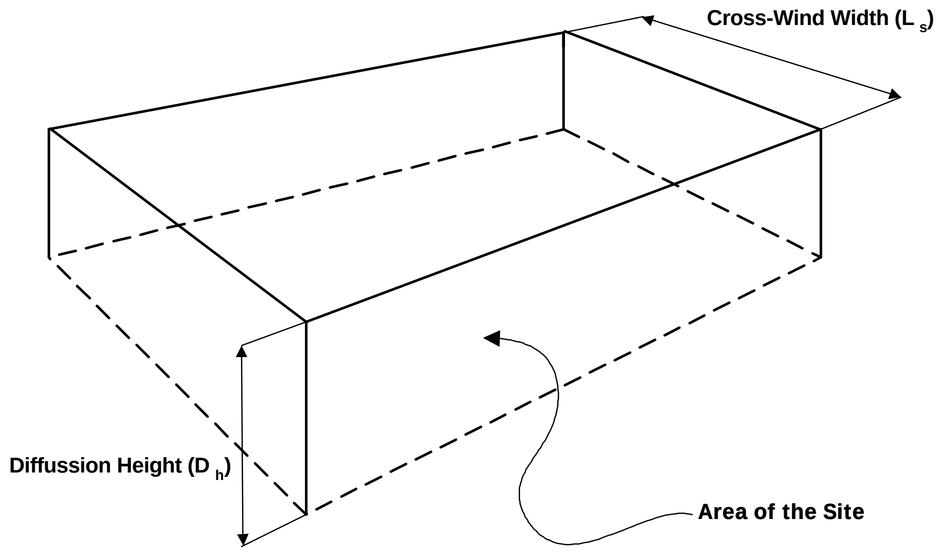
A reasonable estimate of the E_{10} emission rate was calculated to be 1.41 X 10^{-2} g/m^2-hr for the site.

Calculating the Particulate Emission Factor (PEF)

The Particulate Emission Factor (PEF) used in exposure modeling for dust inhalation is based on the simple assumption that the particles released from the site will be evenly mixed into a box with dimensions of (Figure C-5):

- A height equal to the diffusion height (D_h);
- A width equal to the cross-wind dimension (L_s); and
- A length equal to the wind speed in the breathing zone (V).

Figure C-5: US EPA Box Model.



The formula to calculate the PEF is given below:

$$PEF = \frac{\frac{L_s \times V \times D_h}{A} \; x \; 3600 \; \frac{sec}{hr} \times 1000 \frac{g}{kg}}{E_{10}}$$

Where:

PEF	=	particulate emission factor [m^3/kg]
L_s	=	cross-wind dimension of the site [418 m]
V	=	wind speed in the breathing zone [3.47 m/sec]
A	=	the area of the entire contaminated site [201,200 m^2]
E_{10}	=	the PM_{10} emission factor [1.41 x 10^{-2} g/m^2/]

A reasonable estimate of the PEF was calculated to be 3.67 x 10^6 m^3/kg for the site.

Table C-3: Input parameters for Fugitive Dust Model wind erosion

INPUT PARAMETER	VALUE
Area of Concern	
Length of side of contaminated area (L_s)	418 m
Area of contamination (*A*)	201,200 m^2
Vegetated area (V_f)	33.3%
Meteorological Parameters	
Local wind speed (U_{local})	2.21 m/s
Mean annual wind speed at reference (U_{air})	4.17 m/s
Threshold wind speed at 10 m (U_t)	3.27 m/s
Threshold friction factor (u_{*t})	0.363 m/s
Wind speed in mixing zone (*V*)	3.47 m/sec
Height of meteorological tower (z_{met})	3.05 m
Height at site (z_{local})	7 m
Box model mixing height (*DH*)	2 m
Mode of particle size (d_m)	0.250 mm
Local surface roughness (z_o)	0.2 m
Surface roughness at reference (z_{oair})	0.01 m
Wind speed exponent at reference (P_{air})	0.173
Wind speed exponent at site (P_{local})	0.197
Constant surface boundary layer thickness (*d*)	500 m

2. REFERENCES

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