3.0   EXCAVATION AND REMOVAL

3.1   Process Description

Excavation and removal of soils contaminated with fuels is a common practice. If removal is the selected remedy, the excavated soil typically is transported off site for subsequent disposal in a landfill. Excavation activities also are typically part of on-site treatment processes such as incineration, thermal desorption, *ex-situ* biotreatment, and certain chemical and physical treatment methods. The soil is excavated and transported to the process unit, treated, and the treated soil may be used as fill at the site. The information presented in this section for excavation and removal is generally applicable to other soils handling operations such as dumping, grading, short-term storage, and sizing and feeding soil into treatment processes.

The magnitude of volatile organic compound (VOC) emissions depends on a number of factors, including the type of compounds present in the waste, the concentration and distribution of the compounds, and the porosity and moisture content of the soil. The key operational parameters are the duration and vigorousness of the handling, and the size of equipment used. The longer or more energetic the moving and handling, the greater likelihood that organic compounds will be volatilized. The larger the volumes of material being handled per unit operation, the lower the percentage of VOCs that are stripped from the soil, because the surface area to volume ratio is minimized.

The success of excavation and removal for a given application depends on numerous factors with the three key criteria being: 1) the nature of the contamination;

2) the operating practices followed; and 3) the proximity of sensitive receptors. Each of these criteria is described below.

As previously discussed, spills or leaks of fuels typically involve liquids containing dozens of different constituents. Excavation and removal is generally a viable option, except for those cases where air emissions potentially pose an unacceptable risk. For example, soil containing percent levels of benzene or other volatile carcinogens would likely pose a large risk to on-site workers and the surrounding populace if it were to be excavated. In-situ remediation methods, such as soil vapor extraction, would be preferable for such a site, either in lieu of excavation or prior to excavation to reduce the emissions potential.

The magnitude of emissions from soils handling operations will vary with the operating conditions. The rate of excavation and dumping, the drop height, the amount of exposed surface area, the length of time that the soil is exposed, the shape of the storage piles, and the dryness of the surface soil layers will all influence the levels of VOC emissions. Add-on control technologies are available for minimizing emissions, but they are relatively ineffective and costly to implement compared with controls for point sources. VOC emission control also can be achieved by controlling the operating conditions within preset parameters. Large reductions in emissions can be achieved by identifying and operating within acceptable ranges of conditions.

Some release of volatile contaminants is inevitable during excavation and removal unless unusual measures are taken (e.g., enclose the remediation within a dome), so the proximity of downwind receptors (i.e., people) will influence

whether or not excavation is an acceptable option. Excavation of contaminated areas that abut residential areas, schoolyards, etc. may require more extensive controls, relocation of the affected population, or remediation only during certain periods (e.g., summertime for school sites).

The relative advantages of excavation and removal over other remediation approaches are that:

• Earth-moving equipment and trained operators are widely available;

• Large volumes of soil can be quickly moved in a cost-effective manner; and

• Residual contamination remaining at the site is minimal.

The major disadvantages of excavation and removal versus other remediation approaches are that:

• The magnitude of air emissions may be high;

• Air emissions from excavation are difficult to control; and

• The contaminants are only removed, they are not destroyed.

3.2   Identification of Air Emission Points

VOC emissions from handling operations result from the exchange of contaminant-laden soil-pore gas with the atmosphere when soil is disturbed and from diffusion of contaminants through the soil. There are several potential emission points involved in excavation as shown in Figure

3-1; all are considered to be fugitive area sources. For excavation, the main emission points of concern are emissions from:

• exposed waste in the excavation pit;

• material as it is dumped from the excavation bucket; and

• waste/soil in short-term storage piles.

In addition, the earth-moving equipment will be additional sources of emissions of VOC, particulate matter, nitrogen oxides, etc.

3.3   Typical Air Emission Species of Concern

The emissions of concern from soils handling operations such as excavation can be any contaminant that is present in the soil. Relatively large amounts of VOCs may be released from soil during handling, so VOCs are typically the emissions of most concern. Emissions of particulate matter and associated metals and semi-volatile compounds may be of concern at some sites.

3.4   Summary Of Air Emissions Data

Given the frequency with which excavation of contaminated soils is employed, surprisingly little air emissions or emission rate data for excavation has been published. The measurement of emission rates from dynamic processes, such as excavation, is difficult and relatively expensive, and so has rarely been attempted.

Volume III of the Series of Air-Superfund Guidance Manuals (Eklund, et

Figure 3-1. Summary of Air Emission Points For Excavation and Removal.

Source: Saunders, 1990.

al., 1989) for estimating clean-up emissions indicates that soils handling operations such as excavation increase VOC emission rates from contaminated soil over baseline rates. The increase in emissions is typically a factor of ten or more, and the increased emission rate decays exponentially back to near the baseline rate over short time periods (e.g., 4 days). A database of baseline emission rate measurement data (Eklund, et al., 1991) is available.

Emission rate measurements were made at two sites for EPA's Superfund program (Eklund, 1990). Measured emission rates from combined excavation and dumping operations were as high as 4 g/min for specific compounds. Most of the mass of VOCs present in the soil was stripped from the soil during excavation, based on a comparison of measured total emissions versus the mass of these same contaminants in the soil (calculated from soil concentration data). This was true for both sites, despite differences in soil concentrations and soil type. Excavation was found to decrease the soil moisture content by 35% to 56% and tended to somewhat decrease (e.g., -13%) the dry bulk density of the soil.

A few additional studies have been performed using open path monitoring with a Fourier-Transform Infrared (FTIR) instrument to measure ambient concentrations downwind of excavation activities. Under certain meteorological conditions, these measurements can be used to calculate emission rates.

FTIR measurements were performed at the Gulf Coast Vacuum Superfund site during pilot-scale excavation activities (Scotto, et al., 1992). Results were obtained for total C8+ branched-chain and for C8+

straight-chained hydrocarbons, as shown in Table 3-1. No individual VOCs were identified [the detection limit for benzene, toluene, ethylbenzene, and xylenes (BTEX) was about 10 g/sec]. Emission rate measurements were made every one to two minutes over a 30-minute period when excavation was underway. The emission rates were found to vary by about a factor of two over both the full 30-minute period and from one minute to the next (Kagann, et al., 1993).

FTIR measurements also were performed during the excavation of trenches at the Westminster Superfund site (Kagann, et al., 1993). The site contained acidic sludges. Data were reported only for sulfur dioxide; these results are given in Table 3-2.

Theoretical models for estimating emissions (Eklund, et al., 1992a) indicate that about 70% of the mass of a volatile compound such as xylene is emitted during excavation of soil with a starting contaminant concentration of 1 ppm under the assumed typical conditions. Another theoretical study (Saunders, 1990) of soils handling emissions estimated that relative to excavation, other soils handling operations would have the following emissions: 1) Truck Filling - 0.58; 2) Transport - 5.23; and 3) Exposed soil - 1.47 (emissions/excavation emissions).

Field experience indicates that actual emissions may be substantially lower than the stripping percentages discussed above. For dry, porous soils containing low ppb levels of contaminants it can be assumed that most or all of the more volatile VOCs will be lost to the atmosphere during soils handling. For sites with moist soils

Table 3-1
Results of Emission Measurements at Gulf Coast Vacuum Site

Activity	Sludge Volume in m^3 (yd^3)	Exposed Surface Area in m^2 (yd^2)	C8+ Hydrocarbon Emission Rate in g/sec
Sludge Disturbance	25 - 27 (33 - 35)	45 - 125 (54 - 150)	1.33
Sludge Excavation	26 - 48 (34 - 63)	125 - 261 (150 - 312)	7.76
Sludge Dewatering	1.7 (2.2)	3.3 (4.0)	1.24
Post- Disturbance	26 (34)	91 (109)	1.11

Source: Scotto, et al., 1992.

Table 3-2
Emission Rates Measured at the Westminster Superfund Site

Activity in Trenches	Measurement Time		Sulfur Dioxide (SO_2) Emission Rate (g/sec)
	Start	End	
Excavate First Trench, Apply Foam	13:30	13:35	0.55
Apply Foam	13:45	13:50	0.92
Foam in Place	14:05 14:20 14:25	14:10 14:25 14:30	0.45 0.73 0.54
Refill Trench	14:30	14:35	1.1
Remove Topsoil from 2nd Trench	16:05	16:10	0.07
Encounter Waste Material	16:20	16:25	1.0
Apply Foam	16:35	16:40	0.42
Remove 60 Buckets of Material	16:50	16:55	0.41

Source: Kagann, et al., 1993.

and ppm levels of contaminants, however, a reasonable assumption may be that only 5 to 10% of the VOCs are emitted to the atmosphere during each handling step. More measurement data are needed to support these assumptions.

No valid emission factors were found. A theoretical study of the emissions from the clean-up of leaking underground storage tank sites (U.S. EPA-OUST, 1989) estimated that emissions from storage piles of contaminated soil with a surface area of 186 m^2 ($2,000 \text{ ft}^2$) were:

Average Benzene Emission Rate = 1 lb/hr
Total Benzene Emissions = 336 lb
Average VOC Emission Rate = 50 lb/hr
Total VOC Emissions = 16,800 lb

The total emissions are based on a two-week time period. Emissions from the actual excavation process, as opposed to soils storage, were not estimated.

3.5   Identification of Applicable Control Technologies

A number of methods are available for controlling VOC and particulate matter emissions from soils. In general, any method designed primarily for particulate control will also reduce VOC emissions and vice versa. Compared to point source controls, VOC emission controls for excavation and other area sources are difficult to implement and only moderately effective. The choice of controls also can effect treatment and disposal options. For example, controls such as water sprays or foams will alter the percent moisture, bulk density, and average heating value of the soil and may in some cases make thermal treatment infeasible.

VOC emission controls for soil area sources are described below including:

- Covers and physical barriers;
- Temporary and long-term foams;
- Water sprays;
- Operational controls;
- Complete enclosures; and
- Wind Barriers.

Additional information is given in Eklund, et al., 1992b.

3.5.1   Covers and Physical Barriers

The most commonly used VOC control approach for area sources is the use of covers to provide a physical barrier to vapor transport. The simplest barrier is the use of relatively clean soil as a cover for contaminated soil. The soil layer increases the necessary transport distance for vapor diffusion and thus greatly reduces, at least temporarily, the emission rate. Soil covers are widely used at sanitary landfills to control the emissions of odorous compounds and to control wind-borne pollution. The effectiveness of soil covers will depend on the depth of the cover and the percent of contaminated soil that can be covered. Measured emission rates may be substantially reduced (e.g., >95%) by the addition of compacted soil (Suder and Schmidt, 1992); however, lateral migration of VOCs may still occur. Soil covers will be less effective over long time periods and their use will tend to increase the total volume and mass of material that must be treated.

Synthetic covers are typically used to control VOC emissions from excavated soil in short-term storage piles. Synthetic covers are also widely used to control VOC emissions during transport by rail or truck.

The cover may be thin (4-6 mil) plastic sheeting or relatively thick (30-40 mil) plastic sheeting or geotextile material. The resistance of various polymers to chemicals, weather, gas permeability, and tears is documented (Landeeth, et al., 1983). The barrier material is available in large rolls and can be quickly applied to even large soil piles. The synthetic cover must be secured against wind.

The barrier can be left in place indefinitely, though physical and photodegradation of the polymer will tend to limit the effective lifetime of thin barriers to a few weeks. The effectiveness of the cover will depend on its permeability to the vapors that are present and the percentage of the soil pile that is adequately covered. Laboratory measurements of a 20 mil PVC membrane showed relatively poor performance for limiting vapor diffusion (Springer, et al., 1986). The PVC membrane proved to be only as effective as a covering of a few inches of porous soil.

Numerous mulch materials, such as sawdust, wood chips, straw, and wood fibers can also be used as a cover for soil undergoing long-term storage (U.S. EPA, 1991). The mulch acts primarily to control diffusion by insulating the soil surface and thereby lowering the soil temperature. The mulch material also limits diffusion somewhat if it is used as a cover, but if mixed in with the contaminated soil the mulch will generally increase the porosity of the soil and thereby increase the emission rate. The mulch also increases the volume and mass of contaminated material to be treated or disposed.

3.5.2 Temporary and Long-Term Foam Covers

Modified fire-fighting foams are commonly used to control VOC emissions during the remediation of hazardous waste sites containing volatile toxic compounds. At least six types of foam products are available (Evans and Carroll, 1986) from vendors such as Rusmar and 3M. The different foams vary in their compatibility and effectiveness for various classes of contaminants. Specialized equipment is available for applying foams over large areas. The foam is applied to a depth of 6-18 inches and coverage rates of 100 m^2/min are possible. The liquid foam concentrate is applied via an air-aspirating nozzle or chute. The degree of expansion (how many gallons of foam produced from a gallon of liquid concentrate) can be high (250:1), low (20:1), or medium.

Two general types of foams are used: temporary and long-term. The temporary foams provide coverage for up to an hour, at which time 25% or more of the liquid incorporated in the foam will have been released. Long-term foams contain a stabilizing additive to extend the useful life of the foam to days or even weeks. The effectiveness of foams is quite high for the areas that are covered. Short-term emission reductions of 75% to 95% (for total paraffins and total aromatics, respectively) have been measured in the field over 20 minute time periods (Alm, et al., 1987). Emission reductions for total VOCs of 99% to 100% using stabilized foam have been measured in the field over 24-hour time periods (Alm, et al., 1987).

The two primary advantages of foams are that they can be highly effective and they can be applied directly to the backhoe bucket and the exposed contaminated soil. There are several disadvantages of foams to consider. The

thick layers of foam required for emissions control can be applied more effectively to horizontal surfaces than to vertical surfaces such as the sides of the excavation pit. Incomplete coverage of the emitting surfaces will markedly decrease the effectiveness of the controls. The foam concentrates are usually over 90% water and the addition of this water increases the weight of the soil, makes it more difficult to handle, and makes it less amenable to thermal treatment. The foam is difficult to apply on windy days and, under any conditions, frequent application or re-application of the foam may be necessary.

3.5.3   Water Sprays

Water sprays are a commonly used control method for particulate matter (PM) emissions. The addition of dust control chemicals such as polymers or acrylics to the water increases the effectiveness of the spraying. The water added to the soil will decrease the air-filled porosity of the soil and will also tend to cool the surface soil temperature. The reduction in vapor transport will diminish VOC emissions, though the effectiveness of water sprays for VOC control is not documented. Water sprays are certainly much less effective than water-based foams, and they have essentially the same limitations as those listed above for foams.

3.5.4   Operational Controls

Operational controls can be effective in minimizing VOC emissions. These controls may involve controlling the rate of excavation, the amount of contaminated soil area that is exposed, and the duration that soil piles are left uncovered. The timing of excavation can also be important. Scheduling excavation during times of the day or seasons of the year when wind speeds

and temperatures are low can reduce emissions. Stagnant wind conditions, however, may lead to unacceptable ambient air concentrations at the work site. The work can also be scheduled to avoid seasons with dry soil conditions to further minimize emissions.

3.5.5   Complete Enclosures

If warranted, complete enclosure of the excavation-site can be accomplished to minimize VOC emissions. The enclosure acts to collect any emissions, which can then be vented to some type of control device suitable for point sources (see Section 5.5). The enclosure may be either air supported or self supported. Self-supported domes are more practical if trucks or other heavy equipment must regularly enter and leave the structure. If properly designed and operated, the enclosure may reduce VOC emissions to negligible levels.

There are severe limitations that limit the use of complete enclosures to the few sites where other control options are not acceptable. The capital cost of the structure is relatively high. Operating costs also can be very high if large volumes of air must be treated and exhausted to keep the concentrations of contaminants in the atmosphere within the dome at levels that are safe for the workers. Air temperatures within the structure may be high enough to affect worker productivity and safety. The added safety requirements along with the added time needed for getting trucks in and out of the structure likely will extend the time to complete the excavation and thereby increase the cost.

The U.S. EPA conducted a feasibility study of excavation with an enclosure (Dosani and Aul, 1992). Even with a gas

exhaust system in operation, ambient concentrations of sulfur dioxide and other pollutants within the structure made it necessary for workers to wear Level B or Level A personal protective equipment (PPE).

3.5.6 Wind Barriers

For small work areas, the use of wind barriers can reduce VOC emissions by lowering the effective wind speed at the soil surface. Commercial, porous wind fence material that is typically used for dust control has been found to be more effective than solid fence material (Springer, et al., 1986). For larger working areas, fencing is less practical.

VOC (and PM) emissions from storage piles can be minimized by controlling the placement and shape of the piles. When feasible, the piles can be placed in areas shielded from the prevailing winds at the site. The amount of surface area can be minimized for the given volume of soil by shaping the pile. The orientation of the pile will affect the wind velocity across the pile with the lowest windspeed occurring when the length of the pile is perpendicular to the prevailing wind direction.

3.6 Costs For Remediation

The total costs for the treatment of contaminated soil by excavation and removal will be the sum of the costs for excavation, transport, and treatment or disposal. The total costs will vary widely and are primarily dependent on the disposal or treatment costs. Total costs per ton may range from $75 to $500 or more, for excavation and off-site disposal. All costs shown below for years prior to 1991 have

been converted to 1991 dollars using a 5% annual escalation factor. The cost per cubic yard will tend to increase for smaller levels of effort such as the cleanup of a typical LUST site.

Standard costs for earth-moving activities are available (Means, 1991). Estimates of excavation costs for petroleum contaminated soils are in the range of $2.50 to $6.00 per ton (Troxler, 1992). The costs of excavation will depend the level of personal protective equipment required by the operator and on-site workers. Costs to excavate soil contaminated with hazardous wastes for different safety levels are (Lippitt, et al., 1986):

Hazard Level	Cost per m^3 (yd^3)
No Hazard	$22 ±19 ($29±25)
Level D	$75 ±56 ($95±73)
Level C	$91 ±84 ($119±110)
Level B	$117 ±86 ($153±113)
Level A	$133 ±96 ($148±126)

Published cost estimates for excavation of soil contaminated with hazardous wastes vary widely. The estimated cost to excavate and load sixteen million cubic yards at the Rocky Mountain Arsenal was only $6/$yd^3$ (U.S. GAO, 1986). The cost to excavate large volumes of soils contaminated with explosives has been estimated to be $11.14/ton, or about $13.92/$yd^3$ (Tennessee Valley Authority, 1990). This cost comprised 79% labor, 7% operating expenses, 10% equipment expense, and 4% for site reclamation. The cost to excavate large volumes of soils at

another DOD site were estimated per cubic yard to be (Cullinane, et al., 1986):

Activity	Cost per m³ (yd³)
Dry excavation	5.36 (7.02)
Wet excavation	10.72 (14.03)
Site grading and revegetation	1.66 (2.17)
Site grading	1.15 (1.51)
Backfilling with clean soil	25.84 (33.82)

If high-levels of volatile pollutants are present in the material to be excavated, it may be necessary to perform the removal within an enclosure. For the McColl site, in Fullerton, CA, the cost for excavation of soils contaminated with hydrocarbons and sulfur dioxide was estimated to be $593/ton of in-place waste (Dosani and Aul, 1992). Cost for post-excavation treatment are not included. The $593/ton cost includes the following components: labor (22%), supplies and consumables (21%), equipment (12%), and utilities (11%).

Cost estimates for transportation of petroleum contaminated soils range from $0.08 to $0.15 per ton per mile (Troxler, 1992). Vendor quotes for off-site transportation of soil contaminated with hazardous wastes typically range from $2.50 to $5/yd³ per mile, though they may be higher under some site-specific conditions. Costs for transporting soil will be lower for on-site work and will be lower for off-site transport if it is not necessary to follow the procedures typically employed for transporting soils contaminated with

hazardous wastes. Published cost estimates for off-site transport include an estimate of about $3.80/yd³ per mile (Cullinane, et al., 1986) and an average from ten sites of $0.25/ton per mile (Yang, et al., 1987). A cubic yard of soil can be assumed to weigh about 2500 pounds.

Disposal costs are highly dependent on the amount and nature of contamination present in the soil. Vendor quotes for disposal are typically $250 to $350/yd³ of soil. Published estimates (Cullinane, et al., 1986) include costs of $38/yd³ for disposal in a sanitary landfill and $160/yd³ for disposal in a RCRA landfill.

3.7   Costs For Emission Controls

Costs for VOC controls for excavation are not widely available in the literature. Available data are summarized in Table 3-3.

3.8   Equations and Models For Estimating VOC Emissions

The factors that govern excavation emissions are very complex. During excavation, the physical properties of the soil that control the vapor transport rate (e.g. air-filled porosity) are changing with time and the concentration of contaminants may be rapidly decreasing. Predictive equations for estimating VOC emissions from

Table 3-3
Summary of Costs for Emission Controls for Area Sources

Control	Material Cost ($/m^2 except as noted)	Comments
Clay	$4.15	Covers, mat, and membrane
Soil	$1.33	Assume 6" deep; does not include soil transport
Wood chips, plastic net	$0.50	Chip costs vary with site
Synthetic Cover	$4.40	Assume 45 ml thickness
Short-term foam	$0.04	Assume 2.5" thick, $0.7/M^3 foam
Long-term foam	$0.13	Assume 1.5" thick, $3.3/M^3 foam
Wind screen	$40/m	Per linear meter
Water Spray	$0.001 (varies)	Assuming municipal water cost of $1/$1,000 L. Water requires constant re-application. Water truck rental: $500/week.

Additives:
 	
  Surfactant
  Hygro Salt
  Bitu/Adhes.
	
	$0.65
	$2.58
	$0.02
		Costs vary with chemical use

Source: Eklund, et al., 1992b.

excavation have been developed by the U.S. EPA. The predictive equations require assumptions about the size of each scoop of soil, the dimensions of the soil scoops and the excavation pit, and the shape of the soil after it is dumped. Further assumptions are required about the air and soil temperatures and the length of time that dumped soil is exposed before it is covered with more soil or with an emissions barrier.

Since it is rarely feasible or efficient to dig soil and immediately transfer the soil directly to transport vehicles or treatment systems, any estimation procedure must account for each event in which the soil is handled. In most cases, soil will be excavated and placed into a temporary holding area and then handled one to two more times on-site. Elevated levels of VOC emissions are possible each time the soil is handled. When estimating emissions from sequential soil handling steps, it is important to adjust the starting concentrations for each step to account for contaminants emitted during prior steps.

The equations used are shown below. The average emission rate (g/sec) from excavation is equal to the sum of emission rates from the soil pore space and from diffusion:

The total mass of contaminants in a given volume of soil, or for an entire site, can be estimated as follows:

$$M = S_v \, C \, \beta \, 1.0 \qquad \text{(Eq. 3-1)}$$

where:

$M =$ total mass of contaminants in soil (g);

$S_v =$ total volume of contaminated material (m^3);

$C =$ concentration of species i in bulk soil ($\mu g/g$);

$\beta =$ bulk density of soil (g/cm^3); and

$1.0 =$ constant ($g/10^6 \, \mu g/g * 10^6 cm^3/m^3$).

A simple check of the potential total emissions from remediation of a given volume of soil, or for the entire site, can be made by dividing the total mass of contaminants by the projected duration of activity:

$$ER = M / t_{sv} \qquad \text{(Eq. 3-2)}$$

where:

$ER =$ emission rate of species i (g/sec); and

$t_{sv} =$ time to excavate a given volume of soil (sec).

For the remediation of an entire site, t_{sv} is the duration of remediation (sec). The emission rate from equation 3-2 is the theoretical maximum value for the average long-term emission rate for the remediation activities assuming all contamination is transferred to the atmosphere. As a sanity check, it should be demonstrated that any short-term emission rate estimates do not predict a greater mass of contamination being emitted over some time period than the total mass of contamination present in the soil.

A model to estimate the short-term emission rate from the excavation of soil has been developed by the U.S. EPA (Eklund, et al., 1992a). The model is presented below; example calculations are given in Appendix C to this report. The derivation of the

excavation model is given in Appendix D. Tabulated physical property data is given in Eklund and Albert, 1993.

$$ER = ER_{PS} + ER_{DIFF}$$

(Eq. 3-3)

$$ER_{PS} = \frac{P\ M_w\ 10^6\ E_a\ Q\ ExC}{R\ T}$$

(Eq. 3-4)

$$ER_{DIFF} = \frac{(C_s)(10{,}000)(A)}{\left(\dfrac{E_a}{K_{eq}\ k_g}\right) + \left(\dfrac{\pi t}{D_e\ K_{eq}}\right)^{\frac{1}{2}}}$$

(Eq. 3-5)

All variables are defined in Table 3-4. Also shown in Table 3-4 are the units of each variable and a typical default value to use if valid field data are not available. Soil concentration data typically are available as $\mu g/g$ (ppm). This type of value can be multiplied by the bulk density of the soil (g/cm^3) and by a conversion factor of 10^{-6} $(g/\mu g)$ to yield units of g/cm^3:

$$C_s = (C)(\beta)(10^{-6})$$ 　　　(Eq. 3-6)

Equation 3-4 is based on the assumption that the soil pore gas is saturated with the compound of interest. If this is not the case, then Equation 3-4 may over predict the emission rate. The output from Equation 3-4 should be multiplied by the duration of excavation (i.e., $ER_{PS} * t_{SV}$) and the result compared to the total mass of contaminants present in the soil calculated from Equation 3-1 or the following (depending on what units of concentration data are available):

$$M = C \ast S_V \ast \frac{10^6\ cm^3}{m^3}$$

(Eq. 3-7)

If $ER_{PS} * t_{SV} > 0.33M$, Equation 3-4 is giving a value that is far too conservative (i.e., is biased high). In such cases, ER_{PS} should be calculated using the following equation instead of Equation 3-4:

$$ER_{PS} = M \ast \frac{0.33}{t_{sv}}$$

(Eq. 3-8)

3.9　Case Study

No suitable case study exists for excavation. Studies that have valid data for emissions, control efficiencies, and costs are referenced above in the applicable subsections.

3.10　References

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Table 3-4
Input Variables for Emission Equations

Variable	Definition	Units	Default Value
A	Emitting surface area	m^2	290
β	Bulk density	g/cm^3	1.5
C	Concentration of species I in bulk soil	$\mu g/g$	--
C_s	Mass loading in bulk soil	g/cm^3	1.35×10^{-4}
C_v	Concentration in soil gas	$\mu g/m^3$	--
D_e	Effective diffusivity in air	cm^2/sec	0.0269
E_a	Air-filled porosity	Dimensionless	0.44
ER	Total emission rate	g/sec	--
ER_{PS}	Emission rate due to soil pore space gas	g/sec	--
ER_{DIFF}	Emission rate due to diffusion	g/sec	--
ExC	Soil-gas to atmosphere exchange constant	Dimensionless	0.33
K_{eq}	Equilibrium coefficient	Dimensionless	0.613
M_W	Molecular weight	g/g-mol	100
M	Total mass of contaminant	g	--
P	Vapor pressure	mm Hg	35
π	Pi	Dimensionless	3.14
Q	Excavation rate	m^3/sec	0.042
R	Gas constant	mm Hg-cm^3/g-mol°K	62361
S_V	Volume of soil moved	m^3	150
T	Temperature	Degrees Kelvin	298
t	Time to achieve best curve fit (use default value)	sec	60
t_{sv}	Time to excavate a given volume of soil	sec	72 (per m^3)
10,000	Conversion factor	cm^2/m^2	--
10^6	Conversion factor	cm^3/m^3	--

Table 3-4
(Continued)

Variable	Definition	Units	Default Value
	Other Variables Required to Calculate Certain Variables Listed Above		
k_g	Gas-phase mass transfer coefficient	cm/sec	0.15
ρ	Particle density	g/cm^3	2.65
D_a	Diffusivity in air	cm^2/sec	0.1
U	Wind speed	m/sec	2
μ_a	Viscosity of air	g/cm-sec	1.81 x 10^{-4}
ρ_a	Density of air	g/cm^3	0.0012
d_e	Diameter of emitting area	m	24

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