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ESTIMATED WORKER EXPOSURE TO 2378 TCDD AND 2378 TCDF FROM PROCESSING AND COMMERCIAL USE OF PULP AND PAPER MILL SLUDGE

by

Radha Krishnan, Chris Meyer, Bob Goodman,
Mary Beth Foerst

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OFFICE OF TOXIC SUBSTANCES
401 M STREET, S.W.
WASHINGTON, D.C. 20460

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SECTION 1

INTRODUCTION

Various isomers of polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) have been found to be formed during bleaching of wood pulp with chlorine or chlorine-based bleaching chemicals. Quantitative studies conducted by the U.S. Environmental Protection Agency (EPA) and the paper industry have shown that PCDDs and PCDFs may be retained in low levels in bleached pulp, crude paper products (e.g., unconverted paper, paperboard, fibers), and finished commercial and consumer grade pulp-/paper-based products. Furthermore, PCDDs and PCDFs may also be retained in wastewater and sludge generated during the manufacture of these products and possibly be released to ambient air.

On July 27, 1988, the EPA entered into a Consent Agreement with the Environmental Defense Fund and National Wildlife Federation regarding a schedule for review of PCDDs and PCDFs from pulp and paper mills. In response to the Consent Decree, EPA is preparing risk assessments for PCDDs and PCDFs from pulp and paper mill products and wastes in order to determine what, if any, control actions are necessary.

The purpose of this report is to aid OTS in its assessment of worker exposure to PCDDs and PCDFs during the processing and commercial use of sludge generated from wastewater treatment operations in pulp and paper mills.

This report is organized into four sections. This section (Section 1) provides the background and purpose of the study. Section 2 provides a profile of industrial processes and operations that may result in exposure to PCDDs and PCDFs during the processing and commercial use of pulp and paper mill sludges. It summarizes the results of the 5-Mill and 104-Mill studies (which are discussed in detail in Sections 2.2.1 and 2.2.2) and includes a workforce characterization for different operations involving the processing and commercial use of pulp and paper mill sludge. Section 3 discusses the potential for dermal and inhalation exposure to specific PCDDs and PCDFs for the processes/operations discussed in Section 2. It includes engineering estimates of the levels of inhalation and dermal exposure for workers involved in different operations. Section 4 presents the conclusions and recommendations of this study, including a summary of 2,3,7,8-tetrachlorodibenzo-p-dioxin (2378 TCDD) and 2,3,7,8-tetrachlorodibenzofuran (2378 TCDF) daily exposure, toxicity equivalent (TEQ) daily exposures and lifetime average daily exposures, and average and population risks for workers involved in the processing and commercial use of pulp and paper mill sludge. Appendix A presents 2378 TCDD and 2378 TCDF concentrations for sludge on a dry basis as reported in the 104-Mill Study. Appendices B through E present the methodologies for estimating the exposed population and particulate matter emission rates for sludge handling/ processing operations, landfilling operations, land application operations, and composting operations, respectively. Appendix F presents the methodology employed in this report to calculate average and population risks.

SECTION 2

INDUSTRY PROFILE

This section discusses wastewater sludge formation, processing, and disposal operations in pulp and paper mills that may result in worker exposure to PCDDs and PCDFs. Quantitative analyses of the sludge are presented for 2,3,7,8-tetrachlorodibenzo-p-dioxin (2378 TCDD) and 2,3,7,8-tetrachlorodibenzofuran (2378 TCDF) from the 5-Mill and the 104-Mill studies which are described later in this section. In addition, a workforce characterization is presented for sludge formation, processing, and disposal operations.

2.1 SLUDGE FORMATION, PROCESSING, AND DISPOSAL OPERATIONS

There are limited data available in the literature to characterize typical sludge formation, processing, and disposal operations at pulp and paper mills. For the most part, pulp and paper mills process and dispose of their sludge much in the same manner as municipal wastewater treatment facilities, using dewatering to reduce sludge volume followed by disposal via landfilling, land application, or composting. Consequently, parallels were drawn between municipal wastewater sludge treatment and disposal operations and those of pulp and paper mills. This section describes sludge formation, processing, and disposal operations which may be employed at pulp and paper mills.

2.1.1 Sludge Formation and Processing

Two kinds of sludge are generated by wastewater treatment at pulp and paper mills: primary and secondary sludge. Typical wastewater treatment operations at pulp and paper mills include primary clarification, aerobic suspended-growth treatment processes, and secondary clarification. Primary clarification results in the formation of primary sludge by gravity settling of heavy suspended solids. Aerobic suspended-growth treatment processes include activated sludge processes, aeration basins, aerated lagoons, and aerobic stabilization ponds in which nonsettleable colloidal solids are coagulated and organic matter is stabilized by biological treatment. Secondary clarification results in the formation of secondary sludge by gravity settling of biological solids.

Primary sludges consist of solids which are lost from the pulp and paper manufacturing process and are subsequently removed by primary clarification (Ledbetter 1976). These solids are composed of fibers, clay filler materials, coating clays, and other chemical additives (Kirk-Othmer 1981). In addition to fibers, other organic components such as wood dust, fiber debris, ray cells, starches, dextrine, resins, and protein may be present. Solids losses in primary sludges from most categories of paper manufacture represent 2 to 4 percent of production. Typical water contents of non-dewatered primary sludges from pulp and paper manufacturing operations may range from 90 to 98 percent (Ledbetter 1976).

Secondary sludges are largely biological in nature and are harder to handle and dewater (Kirk-Othmer 1981). Secondary sludge water contents may range from 98 to 99.5 percent (Hammer 1975).

The primary and secondary sludges must be processed for volume reduction prior to disposal. Processing techniques which involve sludge volume reduction include thickening, conditioning, and dewatering (Kirk-Othmer 1981).

Thickening is primarily accomplished using either gravity settling, which is applied to mixtures of primary and secondary sludges, or dissolved air flotation which is usually applied to secondary sludges only. Thickening will increase solids content on an average to 5 percent (Hammer 1975). Conditioning is performed to improve the sludge dewatering characteristics. Chemicals such as ferric chloride, lime, alum, and organic polymers are added prior to dewatering to coagulate solids, resulting in release of absorbed water. Dewatering is accomplished using centrifugation, vacuum filtration, or pressure filtration. Solids content may be increased to 20 to 45 percent by centrifugation, vacuum filtration and pressure filtration (Metcalf & Eddy 1979). Dewatering may be performed on the primary and secondary sludges individually or on a mixture of both. The dewatered sludge cake is discharged on to a conveyor belt and proceeds to disposal operations (Hawks 1989).

No data are available in the literature to characterize the typical unit operations at the wastewater treatment facilities of pulp and paper mills. The vast majority employ primary treatment and some form of secondary treatment along with dewatering of sludges from these operations.

The mechanism by which contamination from PCDDs and PCDFs occurs in pulp and paper mill sludges is currently being investigated by the industry. PCDDs and PCDFs are known to be formed during chlorine or chlorine derivative bleaching operations employed in pulp mills, and may be present in bleach plant and paper machine wastewater. The PCDDs and PCDFs have a strong affinity for organic matter, and binding with organic matter in primary and secondary sludge may occur (Olson 1988).

2.1.2 Sludge Disposal Operations

Sludge from pulp and paper mills is disposed in a manner similar to that used for municipal sewage sludge. Figure 2-1 presents a schematic of various pulp and paper mill sludge processing and disposal techniques. Disposal methods include landfilling, incineration, surface impoundments, land application, and distribution as a salable product (e.g., fertilizers, soil conditioners). Some of the disposal techniques (e.g., incineration, landfilling) may be conducted on-site or off-site. Table 2-1 presents the disposal operations used at mills involved in the 104-Mill Study (described later in Section 2.2.2), as well as total and average sludge production by disposal operation. Table 2-1 shows that landfilling is the predominant disposal operation of choice currently in industry, although a number of mills are also using incineration and surface impoundments. Sixteen of the 104 mills employed more than one type of sludge disposal operation. For the purpose of determining sludge production values by disposal operation, the amount of sludge production at each of these 16 facilities was not disaggregated, but rather was assigned to each disposal operation employed.

2.1.2.1 Landfilling--

Landfilling involves the disposal of sludge in company-owned, publicly-owned, or privately-owned landfills. In this disposal operation, sludge is almost universally dewatered to a solids content of 20 to 25 percent to reduce its volume and lower transportation costs (EPA 1979). Typically the dewatered sludge is transferred from the dewatering operations to storage or directly to heavy duty dump trucks. If storage operations are used, the dewatered sludge will be loaded into dump trucks by a front-end loader (Ledbetter 1976). The dewatered sludge is hauled to the landfill where the basic operations involve spreading, compacting, and covering the sludge with excavated soil daily (Hammer 1975).

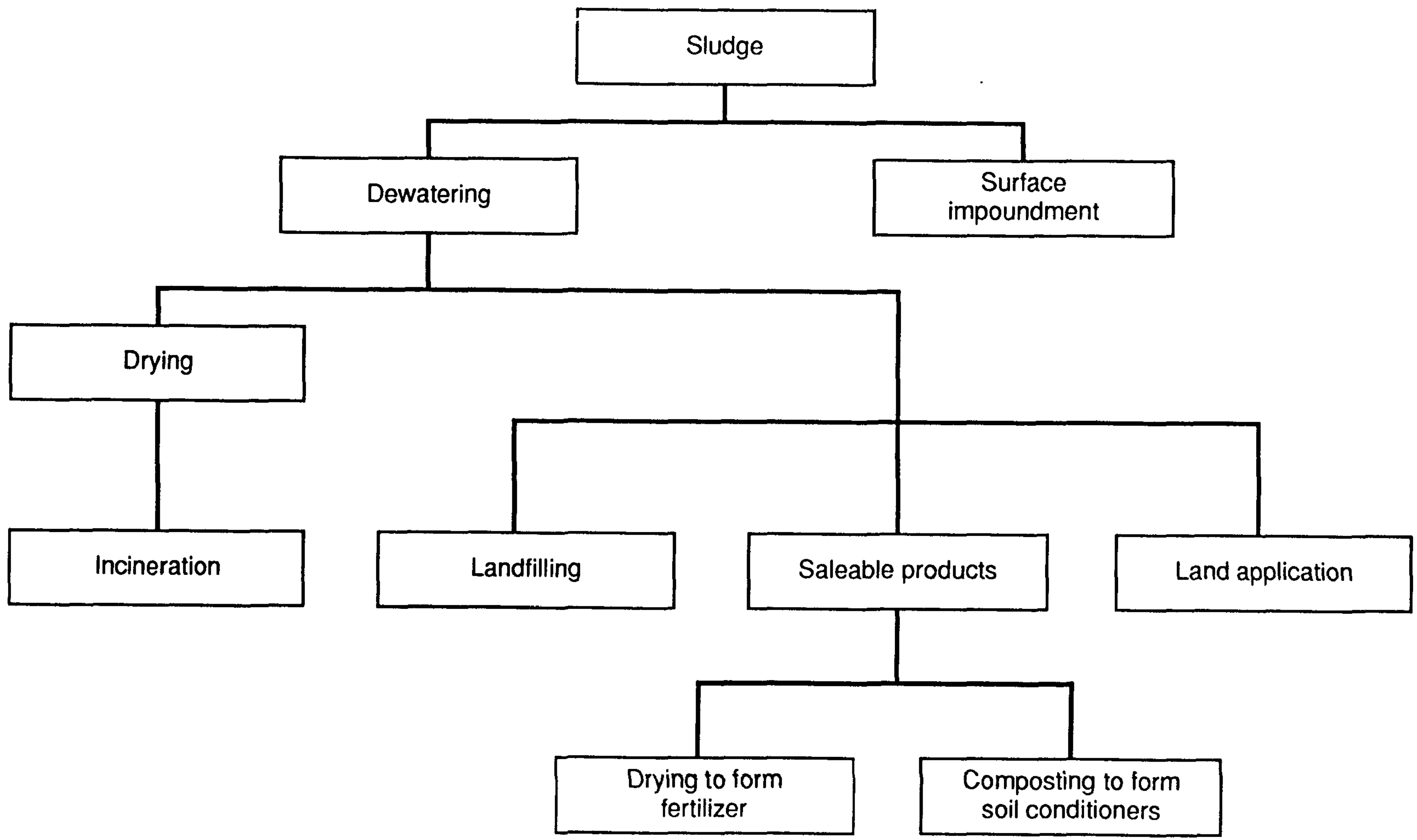

Figure 2-1. Schematic of Pulp and Paper Mill Sludge Processing and Disposal Techniques

TABLE 2-1. SLUDGE DISPOSAL OPERATIONS REPORTED IN THE 104-MILL STUDY[a]

Sludge Disposal Operation	Number of facilities employing particular operation[b]	Total sludge production (dry tons/yr)	Sludge contribution of average mill (dry ton/day)[c]	Sludge contribution of average mill (wet ton/day)[d]
Landfilling	60	1,641,416.8	75.0	250.0
Incineration	22	401,408.8	50.0	166.7
Surface impoundment	20	547,430.8	75.0	250.0
Land application	7	160,582.5	62.8	209.5
Distribution as salable product	7	205,636.0	80.5	268.3
Others	6	NA[e]	NA[e]	NA[e]

[a] Information furnished by U.S. Environmental Protection Agency, Washington, D.C., based on 104-Mill survey; updated results provided in computer diskette form.

[b] Total exceeds 104 because 16 mills employ more than one type of disposal operation.

[c] Calculated by assuming 365 days per year operation. This was verified by review of daily sludge production listed in footnotes associated with sludge disposal techniques.

[d] Calculated by assuming solids content of dewatered sludge of 30 percent.

[e] NA - Not available.

The type and number of equipment used in landfilling operations depend on the landfill design methods and dimensions as well as sludge quantity. Landfill design methods include the trench and area fill methods, and (in the case of disposal in a publicly or privately-owned landfill) the codisposal method. The trench method will involve the use of trenching machines, backhoes with a loader, track dozers, and excavators. Two or more trench machines will be used to landfill sludge quantities in excess of 500 wet tons per day (as compared to one or none for smaller operations); a track loader, track dozer, backhoe with a loader, and excavator may or may not be used. The area fill method will involve the use of backhoes with a loader, track loaders, wheel loaders, track dozers, scrapers, and draglines. Two or more track dozers will be used to landfill sludge quantities in excess of 500 wet tons per day (as compared to one or none for smaller operations); a scraper, track loader, wheel loader, and backhoe with a loader may or may not be used. The codisposal method will involve the use of track loaders, track dozers, tractors with discs, and graders. Two or more track loaders and tractors with discs will be used to landfill sludge quantities in excess of 500 wet tons per day (as compared to one or none for smaller operations); a track dozer and grader may or may not be used. The total pieces of equipment used will range between 1 and 5 and may even be greater in the case of large quantities of sludge (EPA 1979).

The majority of landfilling operations occur on land owned by the pulp and paper mills. According to the 104-Mill Study data, 22 mills use on-site landfilling for disposal of sludges, 32 mills use off-site landfills of which 20 are owned by the mill, and the location of landfills for 6 mills was not reported. The landfills may also receive bottom and fly ash from sludge incineration, that may be contaminated with PCDDs and PCDFs.

2.1.2.2 Incineration--

Incineration is a two-step oxidation process involving drying of the sludge followed by combustion. This process may occur in separate pieces of equipment or successively in a single unit (EPA 1979). Prior to incineration, the sludge is dewatered in a centrifuge, vacuum filter, or pressure filter to a solids content of at least 30 percent. The dewatered sludge proceeds directly to incineration by means of conveyors. Incineration converts the sludge into an inert ash which is handled in wet or dry form (Hanmer 1975). In wet form, the ash is slurried with scrubber water and is pumped to an ash lagoon. In dry form, the ash is conveyed mechanically by a bucket elevator to a storage hopper for discharge into a dump truck for eventual disposal in a landfill (Metcalf & Eddy 1979).

According to the 104-Mill Study data, all mills that practice sludge incineration burn the sludge in waste fuel- or combination-power boilers. In the case of waste fuel-power boilers, sludge is mixed with wood waste, which may consist of bark, knots, and/or sawdust, and is burned to produce steam. In combination-power boilers, the sludge or a mixture of sludge and wood waste may be mixed with coal, oil, or natural gas and burned to produce steam.

A current study by the National Council of the Paper Industry for Air and Stream Improvement, Inc. (NCASI) has found measurable PCDD and PCDF concentrations in bottom ash and fly ash from incineration of sludge in power boilers. Even though detectable PCDD and PCDF concentrations were found in the residual ash, a substantial reduction of the PCDDs and PCDFs in the sludge was attained in the incineration process (Fisher 1989). The quantity of ash produced is also much smaller compared to the sludge. Exposure to PCDDs and PCDFs associated with incineration is not addressed in this report. These exposures are the topic of a report being developed by EPA's Office of Air Quality and Planning Standards (OAQPS).

2.1.2.3 Surface Impoundments--

Surface impoundments or "sludge ponds" are excavations or areas enclosed by dikes for the purpose of retaining sludge. According to the 104-Mill Study data, nondewatered sludge is pumped directly from clarifiers to on-site sludge ponds, and primary sludge (versus secondary sludge) is chiefly disposed in the sludge ponds. One facility dewaters its sludge and then transfers its sludge to an off-site surface pond by barge.

2.1.2.4 Land Application--

Land application involves disposal of sludge by surface spreading or subsurface injection, usually on agricultural lands. Dewatered sludge is usually applied to land by a conventional fertilizer or manure spreader. Liquid sludges are surface spread by tank truck or injected below the surface (Metcalf & Eddy 1979). Surface spreading may require movement and burying of the sludge below the soil by plows, graders, or bulldozers (EPA 1979).

According to the 104-Mill Study data, only one of the seven facilities utilizes on-site disposal of sludge by land application. Two facilities landspread the sludge as fertilizer on company-owned pine tree plantations. One company disposes its sludge in abandoned coal mine reclamation projects where the sludge is either deep-filled into the coal mines or used as surface topdressing. The other three facilities utilize off-site disposal of sludge by land application.

2.1.2.5 Distribution of Sludge as a Salable Product--

Sludge is processed for distribution as a salable product by heat-drying or composting techniques. The sludge is usually dewatered prior to processing to reduce the water content (EPA 1979).

Heat-drying is employed to remove moisture from sludge so that it can be efficiently processed into fertilizer. Heat-drying is also employed prior to incineration to ensure proper combustion of the sludge. The drying of the sludge is necessary in fertilizer manufacturing to permit grinding of the dried sludge. Drying is accomplished by flash spray, rotary, or multiple hearth dryers which will reduce the moisture content of the sludge to less than 10 percent (Metcalf & Eddy 1979).

Composting is undertaken to biologically degrade the sludge into a stable end product which is used as a soil conditioner. The composting process involves three steps: 1) preparation of the wastes to be composted, 2) decomposition of the prepared wastes, and 3) preparation and marketing of the product. The preparation step may include addition of wood chips or bark as bulking agents for moisture and porosity control and addition of organic nutrients such as sawdust. The decomposition step is accomplished using windrow or aerated pile techniques. In windrow composting, prepared sludge is placed in windrows in open fields and is frequently mixed and turned by mobile equipment to maintain aerobic conditions (Metcalf & Eddy 1979). The windrow is turned two or three times daily for the first five days and then turned daily for thirty days (EPA 1979). The composted material is then cured for an additional two to four weeks (Metcalf & Eddy 1979). If bulking agents are used, the cured compost is screened and the bulking agents recycled. In aerated pile composting, aeration is induced by forced air circulation (EPA 1979). Composted material is removed, screened, and finally cured for an additional period of three to four weeks. Final product preparation of compost from the windrow or aerated pile techniques may involve fine grinding, blending with various additives, granulating, bagging, storing, and shipping (Metcalf & Eddy 1979).

The type and number of pieces of equipment used in these operations depends on the composting technique employed and the size and location of the operations. Front-end loaders are used to load dewatered sludge into dump trucks and for initial preparation and placement of the sludge. Mixing machines are used to turn windrows to ensure aeration. Rotary or vibrating screens are used to remove bulking agents, namely wood chips, for reuse (EPA 1979). Additional equipment may be required if the compost is ground, blended, or further processed in some manner prior to distribution.

According to the 104-Mill Study data, only one of the seven facilities which distribute sludge as a salable product practices flash drying of sludge for use as a fertilizer ingredient. One facility sells the sludge to an outside contractor who converts it into insulation or hydromulch. Three facilities send their sludge off-site for composting. One facility composts the sludge with paunch manure from an adjacent meat processing plant and, after composting is complete, disposes the sludge in an on-site landfill. The site of composting operations at one facility could not be determined.

2.2 DIOXINS IN PULP AND PAPER MILL SLUDGES

Sampling of sludge from pulp and paper mills that produce and/or process bleached pulp and bleached pulp-based products has shown that two PCDD and PCDF isomers, 2378 TCDD and 2378 TCDF, are predominantly present in primary and secondary sludges formed during wastewater treatment operations.

In an attempt to quantify concentrations of 2378 TCDD and 2378 TCDF produced during pulp and paper manufacturing operations, several recent studies have been undertaken by the U.S. EPA and the paper industry. These studies include the Cooperative Dioxin Screening Study (or 5-Mill Study), the 104-Mill Study, and the 25 Bleach Line Study. Results have been published for the 5-Mill Study and 104-Mill Study; however, the results of the 25 Bleach Line Study, which is sponsored by the paper industry, will not be available until the end of 1989 (Bond 1989). All of these studies involve the measurement of 2378 TCDD and 2378 TCDF dioxin concentrations in sludge on a dry basis as well as in pulp and wastewater effluent.

2.2.1 The 5-Mill Study

The 5-Mill Study was conducted from June 1986 to January 1987 at five bleached Kraft pulp and paper mills. These mills were identified in the study as Mills A, B, C, D, and E. Mill A has a wastewater treatment system consisting of primary clarification, an activated sludge process, and secondary clarification. Primary and secondary sludges are combined and dewatered by pressure filtration prior to landfill disposal. The wastewater treatment system of Mill B consists of primary clarification, a holding pond, an aeration pond, and secondary clarification in two tanks. Primary and secondary sludges are dewatered separately and secondary sludge undergoes conditioning prior to dewatering. Primary sludges are landfilled on-site, whereas secondary sludges are landfilled off-site. The wastewater treatment system of Mill C consists of primary clarification, an aerated stabilization basin, an activated sludge process, and secondary clarification in two tanks. Secondary sludge is thickened and combined with primary sludge prior to dewatering. The dewatered sludge is either processed for commercial use or is landfilled. The wastewater treatment system of Mill D consists of primary clarification in two tanks, an activated sludge process, dissolved air flotation for secondary sludge thickening, and secondary clarification in two tanks. The primary and secondary sludges are combined, dewatered, and sent to a landfill for disposal. The wastewater treatment system of Mill E consists of primary clarification, an aeration lagoon, and secondary clarification. Secondary sludge is gravity thickened prior to dewatering with the primary sludge on sludge presses (EPA 1988a). Table 2-2 summarizes the wastewater treatment operations at the five mills. Table 2-3 presents operational and sludge characteristics for the pulp and paper mills in the 5-Mill Study.

TABLE 2-2. SUMMARY OF WASTEWATER TREATMENT OPERATIONS AT THE PULP AND PAPER MILLS INVOLVED IN THE 5-MILL STUDY

	Mill				
Process operation	A	B	C	D	E
Primary clarification	x	x	x	x	x
Holding pond/aerated stabilization basin		x	x		
Aeration pond/lagoon		x			x
Activated sludge	x		x	x	
Secondary clarification	x	x	x	x	x
Conditioning/thickening		x	x	x	
Dewatering	x	x	x	x	x
Landfilling of sludge	x	x	x	x	x
Commercial use of sludge			x		

TABLE 2-3. OPERATIONAL AND SLUDGE CHARACTERISTICS FOR THE PULP AND PAPER MILLS INVOLVED IN THE 5-MILL STUDY[a]

		Primary Sludge		Secondary Sludge		Combined Dewatered Sludge	
Mill	Bleached Kraft pulp capacity (tons/day)	Average production (tons/day)	Average solids content[b] (%)	Average production (tons/day)	Average solids content[b] (%)	Average production (dry tons/day)	Average solids content (%)
A	365	55	NA[c]	7.2	1.6	62	38
B	775	40	17	9	13	N/A[d]	N/A[d]
C	1000	2500	8	5800	0.6	800[e]	27
D	460	2550[f]	2.2	1700[g]	0.5	75	16.5
E	1200	NA[c]	NA[b]	35[h]	NA[c]	200	NA[c]

[a] EPA 1988a.

[b] Average solids content prior to dewatering.

[c] NA - Not available.

[d] N/A - Not applicable.

[e] Average daily production in wet tons/day.

[f] Average production reported as 600,000 gal/day and converted using specific gravity of primary sludge of 1.02 (Reference 4).

[g] Average production reported as 400,000 gal/day and converted using specific gravity of waste activated sludge of 1.005 (Reference 4).

[h] Average daily production in dry tons/day.

Table 2-4 presents individual concentrations of 2378 TCDD and 2378 TCDF, in various sludges from the five mills. The table shows that 2378 TCDD and 2378 TCDF concentrations are much higher in secondary sludges as compared to primary and combined dewatered sludges. Combined dewatered sludges, which are a mixture of secondary and primary sludge, have higher 2378 TCDD and 2378 TCDF concentrations than primary sludges. Concentrations of 2378 TCDD and 2378 TCDF may be higher in secondary sludges as compared to primary sludges because secondary solids are comprised of organic biological solids for which PCDDs and PCDFs have an affinity.

Table 2-5 presents a summary of the range of concentrations for toxicity equivalents (TEQ) and the corresponding range of 2378 TCDD and 2378 TCDF concentrations in various sludges from the five mills. The TEQ values reflect the relative toxicity of 2378 TCDF with respect to 2378 TCDD. Equation 1 is used to calculate TEQ while Equation 2 is used for calculating percent contribution due to TCDD.

$$TEQ = C_{TCDD} + (0.1)\, C_{TCDF} \qquad \text{Equation 1}$$

$$\%TCDD = \frac{C_{TCDD}}{C_{TCDD} + C_{TCDF}} \times 100 \qquad \text{Equation 2}$$

Where:

TEQ = toxicity equivalent, ppt
C_{TCDD} = concentration of 2378 TCDD in sludge, ppt
C_{TCDF} = concentration of 2378 TCDF in sludge, ppt
%TCDD = percent contribution due to 2378 TCDD, percent

The low and high plant TEQs provide the data points for the lower and upper range of 2378 TCDD and 2378 TCDF concentrations used for exposure and risk assessment estimates in this report. It must be noted, however, that the range of concentrations presented in Table 2-5 may not necessarily be representative of all pulp and paper mills.

2.2.2 The 104-Mill Study

The 104-Mill Study was conducted from April 1988 to August 1989 at 104

TABLE 2-4. CONCENTRATIONS OF 2378 TCDD AND 2378 TCDF IN VARIOUS SLUDGES (5-MILL STUDY)[a]
(ppt)

	2378 TCDD	2378 TCDF
Mill A		
Primary sludge	24	380
Secondary sludge	710	10,900
Combined dewatered sludge	37	680
Mill B		
Primary sludge	19	100
Secondary sludge[b]	89	810
Mill C		
Secondary sludge	11	75
Combined dewatered sludge	3.3	39
Mill D		
Primary sludge	17	32
Secondary sludge	36	78
Combined dewatered sludge	18	34
Mill E		
Secondary sludge	500	2100
Combined dewatered sludge	180	760

[a] EPA 1988a. Concentrations reported on a dry basis.

[b] Secondary sludge sampled before conditioning.

TABLE 2-5. SUMMARY OF TEQ AND CORRESPONDING 2378 TCDD and 2378 TCDF CONCENTRATIONS IN VARIOUS SLUDGES (5-MILL STUDY)[a], ppt

	TEQ		2378 TCDD	2378 TCDF
Sludge type	No. of Samples	Range[b]	Range	Range
Primary	3	20.2(35)-62(6)	17-24	32-380
Secondary	5	18.5(13)-1800(6)	11-710	75-10,900
Combined dewatered	4	7.2(8)-256(19)	3.3-180	39-760

[a] EPA 1988a. Concentrations reported on a dry basis. Mean and median concentrations may not necessarily be representative of all pulp and paper mills.

[b] Values in parentheses are percent contribution due to 2378 TCDD.

domestic pulp and paper mills using chlorine-based bleaching processes (chlorine, chlorine dioxide, or hypochlorite) in the manufacture of bleached chemical pulp. Eighty-seven of the 104 mills used the Kraft (sulfate) process while the remaining 17 used the sulfite process (EPA 1989a). In this study, concentrations of 2378 TCDD and 2378 TCDF were measured in combined dewatered wastewater sludge and non-dewatered wastewater sludge (as well as bleached pulp following the final stage of bleaching and treated wastewater effluent prior to dilution with cooling water) (UPIU 1989). Appendix A of this report presents individual 2378 TCDD and 2378 TCDF concentrations on a dry basis in sludge samples for the 104 mills.

PEI evaluated the reported concentrations of 2378 TCDD and 2378 TCDF in combined dewatered and non-dewatered sludges. For the purpose of calculating TEQ, PEI assumed the concentrations of samples in which 2378 TCDD and 2378 TCDF were not detected to be half of the detection level, and samples which were not quantified were rejected. A value of the detection limit was not used in the calculations for quantifying nondetected concentrations since by definition such concentrations are below the detection limit; a value lower than the sampling limit of detection is therefore appropriate for quantifying the nondetected measurements. As described by Hornung and Reed (Hornung 1987), there are two methods for calculating this value: nondetected values may be replaced by one-half the limit of detection for highly-skewed data, or the limit of detection divided by the square root of two for clustered data. Since the 2378 TCDD and 2378 TCDF concentration data are highly skewed, nondetected concentrations were calculated as the limit of detection divided by 2.

The TEQ and corresponding lower and upper range concentrations of 2378 TCDD and 2378 TCDF in combined dewatered sludges and non-dewatered sludges are presented in Tables 2-6 and 2-7, respectively. Tables 2-6 and 2-7 show that the concentrations of 2378 TCDF are greater than those of 2378 TCDD. These results concur with those of the 5-Mill Study. Comparison of sludge analyses between the two studies is limited only to combined dewatered sludge because information on the type of non-dewatered sludge (primary or secondary) sampled in the 104-Mill Study was not available. Median TEQ in combined dewatered sludges were 63.2 and 56.5 ppt for the 5-Mill Study and the 104-Mill Study, respectively, whereas the corresponding mean TEQ were 97.4 and 167.2 ppt, respectively.

It must be noted that concentrations of 2378 TCDD and 2378 TCDF measured in the various sludges do not necessarily represent worker exposure to these compounds during sludge handling, processing, and disposal operations. Worker exposure depends on a variety of conditions (e.g., engineering controls, personal protective equipment, work practices) which are addressed in Section 3.

2.3 SLUDGE HANDLING/DISPOSAL WORKFORCE CHARACTERIZATION

No previous studies have been conducted specifically on workforce characterization in sludge handling and disposal operations at pulp and paper mills (Fisher 1989). No data were available in the literature regarding job categories and activities for workers involved in the formation, processing, or disposal of pulp and paper mill sludge. PEI hence characterized the workforce for these operations based on parallels with municipal sewage sludge handling and disposal operations. The levels of exposure associated with various worker activities are estimated in Section 3.

TABLE 2-6. SUMMARY OF TEQ AND CORRESPONDING 2378 TCDD AND 2378 TCDF CONCENTRATIONS MEASURED IN COMBINED DEWATERED SLUDGE (104-MILL STUDY)[a] (ppt)

	TEQ			2378 TCDD	2378 TCDF
No. of samples	Range[b]	Mean	Median	Range	Range
104[c]	1.0(19)-3100(8)	167.2	56.5	0.7-1390	3.0-17,100

[a] Information furnished by U.S. Environmental Protection Agency, Washington, D.C., based on 104-Mill survey; updated results provided in computer diskette form. Concentrations reported on a dry basis.

[b] Values in parenthesis are percent contribution due to 2378 TCDD.

[c] 2378 TCDD was not detected in 3 samples at detection levels ranging from 1.4 to 3.0 ppt.

TABLE 2-7. SUMMARY OF TEQ AND CORRESPONDING 2378 TCDD AND 2378 TCDF CONCENTRATIONS MEASURED IN NON-DEWATERED SLUDGE (104-MILL STUDY)[a] (ppq)

	TEQ			2378 TCDD	2378 TCDF
No. of samples	Range[b]	Mean	Median	Range	Range
15	6.6(50)-5900(24)	1002.9	281.0	6-4500	6-14,000

[a] Information furnished by U.S. Environmental Protection Agency, Washington, D.C., based on 104-Mill survey; updated results provided in computer diskette form. Concentrations reported on a dry basis.

[b] Values in parentheses are percent contribution due to 2378 TCDD.

PEI utilized many sources for information on the number of workers exposed during the handling of pulp and paper mill sludge. These sources included EPA literature, NIOSH databases, industry data, and discussions with NCASI and the United Paperworkers International Union (UPIU). Information pertaining to the range in the number of workers per facility in various job categories was obtained from EPA literature and discussions with NCASI and UPIU. In the absence of data, PEI made assumptions such as the number of workers per facility would be equivalent to the number of pieces of equipment used during landfilling and land application operations. Assumptions that were used to estimate the exposed population in specific job categories are detailed in Appendices B through E.

2.3.1 Sludge Formation and Processing Operations

Three job categories of workers are postulated for the sludge formation and processing operations: waste treatment plant operators, sludge haulers, and front-end loader operators.

The wastewater treatment plants at pulp and paper mills operate 24 hours a day with 3 shifts on-duty and one off-duty, similar to the mill operation (Sullivan 1989). Waste treatment operations involving the formation of sludge and sludge processing techniques such as thickening, conditioning, and dewatering may require as many as five operators per shift to as few as one or two per shift (Fisher 1989). Sludge processing techniques generally do not have workers dedicated exclusively to them but rather are handled by waste treatment plant operators or maintenance staff. These personnel are dedicated to waste treatment operations. A large staff is generally not required because the waste treatment plant and sludge processing operations are fully automated (Hawks 1989).

Typical waste treatment operator activities will include sludge sampling, maintenance, and cleanup. Samples of dewatered sludge are usually taken once per shift to determine if the dewatering equipment is operating properly. Samples of sludge prior to dewatering may also be taken to determine if the primary and secondary treatment operations are achieving their designed functions (Fisher 1989). Operators may take readings from gauges or various pieces of equipment. The waste treatment operator may perform repairs on dewatering equipment, pumps, conveyors, and other miscellaneous equipment. The operator is responsible for cleanup of the waste treatment facility including cleanup of wet sludge or dewatered sludge which has fallen off conveyors, or cleanup of equipment prior to maintenance.

The waste treatment operator population potentially exposed to PCDDs and PCDFs is estimated to be approximately 1300 workers. This estimate is based on the assumption that there are an average of three operators on each of the four shifts within the 104 mills. The use of four shifts to estimate worker population represents worst case conditions; however, four shifts are typically used in the operation of the wastewater treatment plants.

Sludge processing operations will involve preparation of the waste sludge for disposal. In most cases, the sludge is loaded into dump trucks by conveyors or a front-end loader and is hauled away for disposal. The number of employees per shift required for truck loading operations could be as few as one per shift (sludge hauler) in the case of sludge directly conveyed to the dump truck, or two per shift (sludge hauler and front-end loader operator) in the case of sludge conveyed on to a pile. The number of shifts for the sludge haulers and front-end loader operators is generally two, as this is the number of shifts used in landfilling operations.

Typical activities of sludge haulers and front-end loader operators will center around their respective equipment. Front-end loader operators will operate, maintain, and clean their equipment, if necessary. The front-end loader operator drives the front-end loader and transfers sludge from storage piles into dump trucks. The sludge hauler drives the dump truck and may maintain and clean it if necessary. The sludge hauler will transport the sludge to the disposal site.

The sludge hauler and front-end loader operator population exposed to PCDDs and PCDFs is estimated to be approximately 400 workers. This estimate is based on the assumption that there is one hauler and one front-end loader operator per shift on two shifts within the 104 mills. The use of both a sludge hauler and front-end loader operator to determine work force population represents worst-case conditions. Some plants may only employ a sludge hauler; however, the extent of this occurrence in the industry is unknown. Two shifts were assumed because disposal operations are generally not conducted during the night, and landfill operations are conducted on two shifts.

2.3.2 Sludge Disposal Operations

The number of workers involved with sludge disposal operations depends on the specific disposal technique applied by the facility, the quantity of sludge disposed and the location of final disposal.

2.3.2.1 Landfilling Operations--

Landfilling operations may involve pulp and paper mill employees if sludge is landfilled on company-owned land, or employees of waste disposal firms if the sludge is landfilled at a site not affiliated with the pulp and paper mill. These employees are dedicated to sludge disposal operations only. Landfilling operations are usually done in two shifts (Sullivan 1989). Only one job category of workers is postulated for landfilling operations: equipment operators.

At the landfill site, the number of equipment operators depends on the landfill technique selection and quantity of sludge to be disposed. The total pieces of equipment may range between one and five and may even be greater in the case of large quantities of sludge (EPA 1979). Thus, the number of equipment operators per shift may range from one to five, depending on whether one operator is exclusively dedicated to one piece of equipment.

Typical activities of landfill equipment operators will center around their equipment. The landfill equipment operators will drive the equipment which is used to spread, compact, and bury the sludge. These activities may include maintenance and cleanup of the equipment as well.

The landfill equipment operator population exposed to PCDDs and PCDFs is estimated to be approximately 400 workers. This estimate is based on the assumption that there are three equipment operators on each of the two shifts within the 60 mills which dispose of sludge by landfilling. The number of equipment operators, derived from the EPA 1979 study, showed that a landfill operation disposing of 250 wet tons of sludge (which is exactly the average sludge production for landfilling operations in the 104-Mill Study as shown in Table 2-1) uses an average of three pieces of equipment. PEI assumed that each piece of equipment had a dedicated operator. This assumption represents worst-case conditions as the equipment may not have its own dedicated operator; however, typically each piece of equipment will have a dedicated operator.

2.3.2.2 Incineration--

All of the mills involved in the 104-Mill Study which incinerate sludge do so on-site, and thus sludge incineration operations will involve only pulp and paper mill employees. Disposal of residual bottom ash and fly ash, however, will also involve landfilling personnel as previously described. Sludge is typically burned with wood waste and fuel in power boilers for energy recovery. Thus, incineration of sludge and subsequent disposal of bottom ash and fly ash will involve power plant operators and maintenance staff. The number of workers will depend on the size of the mill and the number of boilers operated. Exposure levels to PCDDs and PCDFs associated with this disposal technique, however, are not addressed in this report, but rather are the subject of a report being developed by OAQPS.

2.3.2.3 Surface Impoundment--

Most of the pulp and paper mills that use surface impoundments pump non-dewatered sludge or slurried bottom ash and fly ash directly to on-site surface impoundments. There is no data available in the literature regarding municipal or pulp and paper mill surface impoundment worker activities or job categories. The only data available is from the 104-Mill Study, which stated that the sludge is pumped to surface impoundments. Given this description, it was assumed that there would probably be no workers dedicated only to a pumping operation but rather these operations would be handled by the waste treatment operators. Thus, the workers involved in surface impoundment operations have already been counted in the waste treatment operator category previously described.

2.3.2.4 Land Application--

One job category of workers is postulated for land application operations: equipment operators who are dedicated to land application operations only. Sludge application will involve equipment operators to operate fertilizer spreaders, tank trucks, plows, bulldozers, or other equipment depending on the type of sludge application. The number of equipment operators will depend on the quantity of sludge to be disposed, the sludge application techniques, and whether one operator is exclusively dedicated to one piece of equipment.

Typical activities of land application equipment operators will center around their equipment. The land application equipment operator will drive the equipment which spreads and plows the sludge into the ground. These activities may include maintenance and cleanup of the equipment as well.

The land application equipment operator population exposed to PCDDs and PCDFs is estimated to be approximately 20 workers. This estimate is based on the assumption that there are 2 equipment operators on one shift within the 7 mills which dispose of sludge by land application. It was assumed that a dedicated operator was necessary for spreading and plowing equipment, respectively. This assumption represents worst-case conditions as the spreading and plowing equipment may not each have a dedicated operator. Typically, however, spreading and plowing equipment will have dedicated operators. Also, it is assumed that the equipment operators are dedicated to land application operations. Given that land application can be seasonal, the latter assumption also represents worst-case conditions on exposed population estimates.

2.3.2.5 Distribution of Sludge as a Salable Product--

Sludge is converted into a salable product by heat-drying or composting. Heat-drying will require skilled operators for the dryers (EPA 1979). Other employees may be used to aid in conveying and bagging of the dried sludge prior to shipment to fertilizer manufacturers. The fertilizer manufacturing operations will employ various personnel in the processing of the dried sludge.

Composting operations may involve personnel not affiliated with the pulp and paper mill when composting is done off-site, as is generally the case. These operations are usually conducted only during the daylight shift. There may be three job categories of workers in composting operations: equipment operators, screen operators, and compost haulers. Equipment operators perform unloading and placement of the sludge into windrows or aerated piles. In windrow composting, equipment operators operate turning machines which mix the composting sludge. Equipment operators remove the compost from the windrows and piles and load it into screens. They also load the finished compost into dump trucks for distribution. A municipal sewage sludge composting operation that uses windrow composting techniques to process 400 to 600 wet tons of sludge daily employs 20 operators and mechanics per shift (excluding sludge haulers). Another municipal sewage sludge composting operation that uses aerated pile composting techniques to process 60 to 120 wet tons of sludge daily employs 6 people per shift (excluding sludge haulers). If the compost is screened, an equipment operator and screen operator are necessary (EPA 1979). Other personnel may be required if the compost is ground, blended or further processed in some manner prior to distribution. The screen operator is responsible for proper maintenance and operation of the screen, e.g., unplugging the screen if the compost is too wet. The compost hauler transports the finished product to farms or other facilities which may further process the compost.

The equipment operator population exposed to PCDDs and PCDFs is estimated to be approximately 150 workers, based on the assumption that there are 20 operators on one shift within the 7 mills that dispose of sludge through composting. The number of equipment operators was derived from the EPA 1979 study which showed that a composting operation handling 80 to 120 dry tons of sludge/day (the average sludge production for mills which practice distribution of sludge as a salable product was 80.5 dry tons/day as shown in Table 2-1) used 20 equipment operators.

The screen operator population exposed to PCDDs and PCDFs is estimated to be approximately 20 workers, based on the assumption that there are 2 screen operators on one shift within the 7 mills that dispose of sludge through composting. This assumption represents worst-case conditions, as only one screen operator may be employed; however, the extent of this occurrence in the industry is unknown. The compost hauler population exposed to PCDDs and PCDFs is estimated to be approximately 50 workers, based on the assumption that there are 7 haulers on one shift within the 7 mills that dispose of sludge through composting. The number of haulers was derived based on average compost production and the assumption that 6 cubic yard dump trucks were used and that each round trip took one hour. This assumptions represents worst-case conditions as less haulers or larger dump trucks may be employed; however, the extent of these occurrences in the industry is unknown. Appendix E shows the calculations used to determine the number of sludge haulers.

The number of exposed workers in each job category for the various sludge disposal operations are presented in the summary tables in Sections 3 and 5.

SECTION 3

WORKER EXPOSURE

Although considerable data have been collected on concentrations of 2378 TCDD and 2378 TCDF for pulp, sludge, and wastewaters in the pulp and paper industry, no inhalation or dermal exposure data for 2378 TCDD and 2378 TCDF are currently available. This is in part because of the lack of a validated sampling and analytical method for measuring worker exposure to these chemicals. Furthermore, little information is available on the effectiveness of engineering controls or the use of personal protective equipment in this industry. PEI hence had to resort to exposure modeling techniques based on numerous assumptions in order to estimate worker exposure to 2378 TCDD and 2378 TCDF.

Workers processing and commercially using pulp and paper sludge may be exposed to 2378 TCDD and 2378 TCDF either through dermal contact with the sludge or through inhalation exposure of either volatilized 2378 TCDD/2378 TCDF or particulates containing these chemicals. The potential for volatilization exposure should be minimal because these chemicals have a low vapor pressure and have a tendency to bind with organic matter rather than volatilize freely. The inhalation exposure levels computed in this report provide an estimate of the quantities of 2378 TCDD and 2378 TCDF that would freely volatilize; the values hence represent worst-case estimates since the effects on volatilization of 2378 TCDD and 2378 TCDF due to binding with organic matter and from interferences due to other chemicals present in the sludge are not considered. There is some potential for inhalation exposure from particulates during sludge handling operations such as loading/unloading spreading, compacting, plowing into soil, and composting. There is some potential for dermal exposure to 2378 TCDD and 2378 TCDF through handling of contaminated sludge, although this would be minimal because most operations are highly automated with generally little contact between the sludge and employees except in cases of emergency maintenance and cleanup.

3.1 POTENTIAL FOR WORKER EXPOSURE

The potential for dermal and inhalation exposure from sludge processing, disposal, and commercial use will vary in the industry depending on the job description of the worker, extent of automation, and equipment layout.

3.1.1 Sludge Formation and Processing

In sludge formation and processing, the potential for PCDD and PCDF exposure for waste treatment plant operators exists through dermal contact with wet sludge when taking samples and when performing maintenance. Dermal contact is otherwise limited by the high degree of automation of sludge processing operations. Samples of dewatered sludge are usually taken once per shift to determine if the dewatering equipment is operating properly. Samples of non-dewatered sludge may also be taken (Fisher 1989). Contact with sludge can occur through cleanup of spills of non-dewatered sludge or dewatered sludge that has fallen off the conveyors. Cleanup is usually done with shovels, minimizing dermal contact (Hawks 1989). Repair of dewatering equipment, pumps, and conveyors may also result in dermal contact. There were no available data on the duration of dermal exposure to the waste treatment plant operators. Since the process is highly automated and cleanup is usually done with a shovel, dermal exposure should be minimal. Therefore, as a worst case, PEI estimates that typical maintenance and cleaning activities may result in 2 hours of dermal contact with the wet sludge during a shift.

The potential for inhalation exposure to waste treatment operators exists through volatilization of 2378 TCDD and 2378 TCDF in the wet sludge and inhalation of particulate matter generated during sludge handling operations. Waste treatment plant operators may be exposed to 2389 TCDD and 2378 TCDF through volatilization when inspecting and/or repairing equipment, taking samples, and cleanup of spilled sludge. There were no data available on the duration of inhalation exposure to the waste treatment plant operators from volatilization. The waste treatment plant operators are located near the wastewater equipment for sampling, cleanup, and maintenance. These activities were assumed to involve approximately half of the waste treatment plant operator's 8-hour shift. Therefore, PEI estimated that the duration of inhalation exposure via volatilization for a typical waste treatment plant operator to be 4 hours per shift. Waste treatment plant operators may also be exposed to 2378 TCDD and 2378 TCDF through the generation of particulate matter during sludge handling operations. The quantity of particulate matter generated is estimated to be minimal because of the high moisture content of the sludge (approximately 70 percent). There were no available data on the duration of inhalation exposure to the waste treatment plant operators from particulate matter generated during sludge handling operations. Particulate matter is generated during loading and unloading from the sludge storage pile; these activities will typically be handled by haulers and front-end loader operators. Since the waste treatment plant operator would only be in the area during sampling and cleanup, the duration of inhalation exposure to particulate matter should be minimal for the waste treatment plant operator. Therefore, PEI estimated that the typical waste treatment plant operator would be exposed to 2378 TCDD and 2378 TCDF through inhalation of particulate matter generated during sludge handling for approximately 1 hour per shift.

Sludge haulers and front-end loader operators may be exposed to PCDDs and PCDFs through handling and loading of the sludge. Front-end loader operators remove the sludge from a pile and load it into the dump truck. The sludge haulers then transport the sludge to its final disposal site. Exposure to 2378 TCDD and 2378 TCDF may occur through inhalation of particulate matter generated during sludge handling and loading, volatilization of 2378 TCDD and 2378 TCDF from the wet sludge, and dermal contact during maintenance activities. It is estimated that these workers may be exposed to 2378 TCDD and 2378 TCDF through volatilization and inhalation of particulate matter for 4 hours per shift, assuming loading activities represent half of the work done during an 8-hour shift. The hauler spends the other half of his shift transporting the sludge to its disposal site. The time of dermal exposure for these workers is estimated to be 1 hour per shift because the equipment operators will generally not be in contact with the wet sludge unless maintenance is required.

The following is an estimation of both inhalation and dermal exposures for waste treatment operators, sludge haulers, and front-end loader operators. The concentrations of 2378 TCDD and 2378 TCDF in the sludge used for the worker exposure calculations in sludge handling/processing operations are the low and high concentrations for 2378 TCDD and 2378 TCDF reported for the combined dewatered sludge from the 104-Mill Study corresponding to the calculated low and high TEQ. These values were previously shown in Table

2-5. Particulate matter emissions from sludge handling operations were calculated using AP-42 emission factors and are documented in Appendix B; exposed population calculations are also presented in Appendix B. Particulate matter emissions from sludge loading and unloading into dump trucks were calculated using an emission factor for unloading and loading of various materials presented in Section 11.2.3 of AP-42 (EPA 1988d). This approach was taken after review of a EPA study (EPA 1988b), which presented a methodology to calculate PCDD and PCDF releases using emission factors presented in AP-42 (EPA 1988d).

3.1.1.1 Level of Inhalation Exposure--

In sludge handling/processing operations, there are three job categories of workers (waste treatment plant operators, sludge haulers and front-end loader operators) who are potentially exposed to 2378 TCDD and 2378 TCDF through inhalation of vapors and particulate matter containing dioxin and dibenzofuran. The inhalation exposure levels for sludge haulers and front-end loader operators were treated the same because both are involved to a similar degree in sludge-loading operations.

Volatilization--There are no existing data available to determine inhalation exposure from volatilization of 2378 TCDD/2378 TCDF during sludge handling/processing. In the absence of exposure monitoring data, PEI estimated worker exposure to 2378 TCDD/2378 TCDF using a mass balance model.

There are many mass balance models available for estimating worker exposure. Table 3-1 presents some of the mass balance models (equations and solutions) which can be used to estimate concentrations of a chemical in an enclosed space. Most of these models, however, are based on estimating concentrations from point sources. During sludge handling/processing operations, volatilization occurs from an area source that is not in an enclosed

TABLE 3-1. MASS BALANCE MODELS
(Clement 1981)

Mass balance equation	Solution	Equation
$V \frac{dC}{dt} = - CQ$	$C = C_o e^{-(Q/V)t}$	(1)
$V \frac{dC}{dt} = - kCQ$	$C = C_o e^{-k(Q/V)t}$	(2)
$V \frac{dC}{dt} = G - CQ$	$C = G/Q + (C_o - G/Q)e^{-(Q/V)t}$	(3)
$V \frac{dC}{dt} = G - kCQ$	$C = G/Q + (C_o - G/Q)e^{-k(Q/V)t}$	(4)
$V \frac{dC}{dt} = G + C_iQ - CQ$	$C = C_o e^{-(Q/V)t} + (C_i + G/Q)\ (1 - e^{-(Q/V)t})$	(5)
$V \frac{dC}{dt} = G + kC_iQ - kCQ$	$C = C_o e^{-k(Q/V)t} + (C_i + G/Q)\ (1 - e^{-k(Q/V)t})$	(6)
$V \frac{dC}{dt} = G + C_iQ_i - CQ_i - CEQ_r$	$C = C_o\ e^{-((Q_i + EQ_r)/V)t} + \frac{C_iQ_i + G}{Q_i + EQ_r}\ (1 - e^{-((Q_i + E_r)/V)\ t}$	(7)
$V \frac{dC}{dt} = G(t) + kC_iQ_i - kCQ_i - KCEQ_r$	Variable--depends on the function G(t)	(8)

area. At present, there are no widely accepted models for estimating on-site concentrations from an area source. However, on-site 2378 TCDD/2378 TCDF concentrations in air were estimated based on a "box model" approach, which was used to simulate the dilution impacts of the wind in an out door setting, by using Equation 3.

$$Cm = \frac{G}{(L)\ (MH)\ (V)} \times 1000 \qquad \text{Equation 3}$$

where:

- Cm = 2378 TCDD/2378 TCDF vapor concentration in air, mg/m^3
- G = generation rate of 2378 TCDD/2378 TCDF, g/sec
- L = equivalent side length of the area source perpendicular to the direction of the winds, m
- MH = mixing height of vapors before inhalation by an individual, m
- V = average wind speed at the inhalation height, m/sec

The average wind speed chosen was 2.2 m/s and the mixing height chosen was 1.5 m (EPA 1988b). The length of the area-source in the direction of the wind is calculated in Appendix B through E. The "box model" approach used assumes that 2378 TCDD/2378 TCDF present at the site travels only a short distance before it is inhaled by the worker.

The generation rate used in Equation 3 is calculated from Equation 4. For Equation 4, there are many models which can be used to estimate an emission rate per unit area. Abt Associates explored two models for estimating the emission rate per unit area from a landfill, herein referred to as the "EPA Model" and the "SESOIL Model" (Abt 1989). The first model is based on an emission rate per unit area from a set of Equations presented in EPA (1986), and Hwang and Falco (1986) as described in EPA (1988b). The SESOIL model uses Farmer's Equations to estimate the movement of volatilized contaminants between layers of the soil column, and estimates releases of the contaminant from the topmost layer to the ambient air. The EPA model was selected by PEI to estimate emission rates in this report since the EPA model is more conservative. Equations 5 through 7 present the equations for the EPA model for calculating the emission rate per unit area.

$$G = Na \times A \qquad \text{Equation 4}$$

where:

$$N_a = \frac{2 \times D_i \times E^{4/3} \times K_{as} \times C_{so}}{(PI \times ALPHA \times T]^{1/2}} \qquad \text{Equation 5}$$

and

$$ALPHA = \frac{D_i \times E^{4/3}}{E + RHO_s \times (1 - E)/K_{as}} \qquad \text{Equation 6}$$

$$K_{as} = 41\ H_c/K_d \qquad \text{Equation 7}$$

Where:

G = generation rate in g/sec

Na = rate of emissions from the soil surface, g/cm^2-s

A = surface area where emissions occur, m^2

D_i = the molecular diffusivity of contaminant vapor in air, cm^2/s

E = effective porosity of soil, unitless

K_{as} = the air/soil partition coefficient, mg/cm^3 in air per mg/g in soil

C_{so} = the initial 2378 TCDD/2378 TCDF concentration in the soil, g/g

PI = mathematical constant, unitless (3.14159)

ALPHA = intermediate variable used to calculate rate of emissions from the soil surface, cm^2/s

T = duration of exposure, s

RHO_s = true density of soil, g/cm^3

H_c = Henry's law constant, atm-m^3/mole

K_d = the soil/water partition coefficient, $\frac{mg}{g}$ in soil per $\frac{mg}{cm_3}$ in water

The conversion factor of 41 in Equation 7 (based on the ideal gas law) is needed to convert H_c/K_d in the specified units to the units for K_{as}. The daily inhalation exposure from volatilization (in mg/day)is then calculated using Equation 8. It should be noted that the calculated inhalation exposure levels from volatilization are biased high because no percent reductions are incorporated in the calculations for 2378 TCDD/2378 TCDF binding with organic matter and the presence of other chemicals in the matrices that could interfere with the volatilization of the 2378 TCDD/2378 TCDF. No estimates could be found in the literature or provided by knowledgeable contacts in the field regarding the quantitative reductions in volatilization from such interferences.

$$Iv = Cm \times 1.25\ m^3/h \times ED \qquad \text{Equation 8}$$

where:

- Cm = concentration of 2378 TCDD/2378 TCDF in the vapor, mg/m^3
- Iv = daily inhalation exposure from volatilization, mg/day
- ED = exposure duration, h/day

Table 3-2 summarizes the variables and results using Equations 3 through 8. It presents estimated daily inhalation exposure to 2378 TCDD and 2378 TCDF for waste treatment plant operators and haulers/front-end loader operators via volatilization from wet sludge.

The relative toxicity of 2378 TCDF with respect to 2378 TCDD can be determined by calculating toxicity equivalents (TEQ). In addition, the percent exposure due to 2378 TCDD can also be calculated. Equation 9 presents the equation for calculating TEQ while Equation 10 is used for calculating the percent of the exposure due to 2378 TCDD. These equations are found in EPA 1989b. Table 3-3 presents the daily and lifetime average daily TEQ and percent exposure due to 2378 TCDD from volatilization for workers handling/ processing wet sludge.

$$DTEQv = Iv_{TCDD} + 0.1\ Iv_{TCDF} \qquad \text{Equation 9}$$

$$\%TCDDv = \frac{Iv_{TCDD}}{Iv_{TCDD} + Iv_{TCDF}} \times 100 \qquad \text{Equation 10}$$

where:

- DTEQv = daily toxicity equivalents from volatilization of 2378 TCDD and 2378 TCDF
- Iv_{TCDD} = daily inhalation exposure to 2378 TCDD from volatilization, mg/day
- Iv_{TCDF} = daily inhalation exposure to 2378 TCDF from volatilization, mg/day
- %TCDDv = percent of the exposure from volatilization due to 2378 TCDD, %

TABLE 3-2. ESTIMATED INHALATION EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR WASTE TREATMENT PLANT OPERATORS AND HAULERS/FRONT-END LOADER OPERATORS FROM VOLATILIZATION

	2378 TCDD		2378 TCDF		
Variable	Low	High	Low	High	Reference
Henry's Law Constant, atm-m³/mole (Hc)	1.6×10^{-5}	1.6×10^{-5}	8.6×10^{-5}	8.6×10^{-5}	Abt 1989
Soil/water partition coefficient, mg/g in soil per mg/cm³ in water (Kd)	1.4×10^{6}	1.4×10^{6}	4900	4900	Abt 1989
Air/soil partition coefficient, mg/cm³ in air per mg/g in soil (K_{as})	4.7×10^{-10}	4.7×10^{-10}	7.2×10^{-7}	7.2×10^{-7}	Calculated
Molecular diffusivity of 2378 TCDD/2378 TCDF in air, cm²/s (Di)	0.047	0.047	0.048	0.048	Abt 1989
Effective porosity of soil, unitless (E)	0.25	0.25	0.25	0.25	Abt 1989
True density of soil, g/cm³ (RHO_s)	2.65	2.65	2.65	2.65	Abt 1989
Intermediate variable to calculate rate of emission from the soil surface, cm²/s (ALPHA)	1.8×10^{-12}	1.8×10^{-12}	2.7×10^{-9}	2.7×10^{-9}	Calculated
Initial 2378 TCDD/2378 TCDF concentration in the soil on a dry basis, g/g (C_{so})	0.7×10^{-12}	1.39×10^{-9}	3.0×10^{-12}	1.71×10^{-8}	104-Mill study data
Duration of exposure, s (T)	2.21×10^{9}	2.21×10^{9}	2.21×10^{9}	2.21×10^{9}	Abt 1989
Emission rate of 2378 TCDD/2378 TCDF from the soil surface, g/cm²-s	4.4×10^{-23}	8.8×10^{-20}	7.5×10^{-21}	4.3×10^{-17}	Calculated

(continued)

TABLE 3-2 (continued)

Variable	2378 TCDD Low	2378 TCDD High	2378 TCDF Low	2378 TCDF High	Reference
Surface area, cm^2 (A)					
-haulers/front-end loading operators	29,729	29,729	29,729	29,729	See Table 3-5
-waste treatment plant operators	92,903	92,903	92,903	92,903	See Table 3-5
Generation rate, g/s (G)					
-haulers/front-end loading operators	$1.3x10^{-18}$	$2.6x10^{-15}$	$2.2x10^{-16}$	$1.3x10^{-12}$	Calculated
-waste treatment plant operators	$4.1x10^{-18}$	$8.1x10^{-15}$	$7.0x10^{-16}$	$4.0x10^{-12}$	Calculated
Molecular weight, g/g-mole (M)	322	322	306	306	EPA 1989c
Equivalent side length of area source perpendicular to the direction of the wind, m(L)					
-haulers/front-end loading operators	2.44	2.44	2.44	2.44	Appendix B
-waste treatment plant operators	3.00	3.00	3.00	3.00	Appendix B
Mixing height of the vapors before inhalation by an individual, m (MH)	1.5	1.5	1.5	1.5	EPA 1988b
Average wind speed of the inhalation height, m/s (V)	2.2	2.2	2.2	2.2	EPA 1988b

(continued)

TABLE 3-2 (continued)

Variable	2378 TCDD Low	2378 TCDD High	2378 TCDF Low	2378 TCDF High	Reference
Concentration of 2378 TCDD/2378 TCDF in the vapor, mg/m^3 (Cm)					
-haulers/front-end loader operators	$1.6x10^{-16}$	$3.2x10^{-13}$	$2.8x10^{-14}$	$1.6x10^{-10}$	Calculated
-waste treatment plant operators	$4.1x10^{-16}$	$8.2x10^{-13}$	$7.0x10^{-14}$	$4.0x10^{-10}$	Calculated
Exposure duration, h/day (ED)					
-haulers/front-end loader operators	4	4	4	4	See Table 3-5
-waste treatment plant operators	4	4	4	4	See Table 3-5
Daily inhalation, mg/day (Iv)					
-haulers/front-end loader operators	$8.1x10^{-16}$	$1.6x10^{-12}$	$1.4x10^{-13}$	$7.9x10^{-10}$	Calculated
-waste treatment plant operators	$2.1x10^{-15}$	$4.1x10^{-12}$	$3.5x10^{-13}$	$2.0x10^{-9}$	Calculated

TABLE 3-3. ESTIMATED TOXICITY EQUIVALENTS AND PERCENT EXPOSURE DUE TO 2378 TCDD FOR WASTE TREATMENT PLANT OPERATORS AND HAULERS/FRONT-END OPERATORS FROM VOLATILIZATION

Job category	Daily TEQ, mg/day (DTEQv)[a]		Lifetime average daily TEQ, mg/day-kg (LTEQv)[a]	
	Low	High	Low	High
Haulers/front-end operators	1.5×10^{-14} (0.6%)	8.0×10^{-11} (0.2%)	8.2×10^{-17} (0.6%)	5.4×10^{-13} (0.2%)
Waste treatment plant operators	3.7×10^{-14} (0.6%)	2.0×10^{-10} (0.2%)	2.1×10^{-16} (0.6%)	1.4×10^{-12} (0.2%)

[a] Values in parentheses are percent exposure due to 2378 TCDD.

In addition to daily TEQ, the lifetime average daily TEQ (LTEQv) for workers was also calculated. This is presented in Equation 10:

LTEQv = DTEQv x DY x LF/(BW x LE) Equation 11

where:

LTEQv = lifetime average daily TEQ from volatilization, mg/day-kg
DTEQv = daily TEQ from volatilization, mg/day
DY = number of days per year exposed, day/year
LF = number of years of exposure per lifetime, years/lifetime
BW = average body weight for a worker, kg
LE = lifetime expectancy, days/lifetime

The number of years of exposure per lifetime (LF) was assumed to be 40 years and the lifetime expectancy (LE) was assumed to be 25,550 days (i.e., 70 years). The average body weight for male workers (BW) is 70 kg and a female worker is 58 kg (NCASI 1988). PEI assumed that the worker would be in the plant for 250 days per year. Table 3-3 presents the lifetime average daily TEQ. Table 3-4 presents the assumptions and uncertainties of those variables used to calculate lifetime average daily TEQ from daily TEQ.

Table 3-5 presents the assumptions and uncertainties in the variables used to calculate inhalation exposure from volatilization from wet sludge as presented in Tables 3-2.

The following is an example of the calculation procedure used for estimating levels of daily inhalation exposure to 2378 TCDD and 2378 TCDF from volatilization from wet sludge:

Lower limit of 2378 TCDD inhalation exposure levels from volatilization for haulers/front-end loader operators

$K_{as} = 41\ H_c/K_d$

$= 41 \times 1.6\text{x}10^{-5}/1.4\text{x}10^{6}$

$= 4.7\text{x}10^{-10}$ mg/cm³ in air per mg/g in soil

TABLE 3-4. ASSUMPTIONS AND UNCERTAINTIES IN VARIABLES FOR CALCULATING LIFETIME AVERAGE DAILY TEQ FROM DAILY TEQ

Uncertainty	Associated assumption	Reasonable possible variance of assumption	Effects on results
Number of days per year workers are exposed.	Workers were assumed to be exposed for 250 days per year. (PEI estimate)	A maximum exposure duration is 365 days.	Maximum of 1.5 times greater exposure.
Number of years of exposure per lifetime	Workers were assumed to be exposed for 40 years. (EPA 1989b)	-	-
Average body weight of a worker	The average body weight of a male worker is 70 kg and a female worker is 58 kg (NCASI 1988).	-	-
The lifetime expectancy of worker	Workers were assumed to live for 70 years (NCASI 1988).	-	-

TABLE 3-5. ASSUMPTIONS AND UNCERTAINTIES IN ESTIMATING INHALATION EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR WASTE TREATMENT PLANT OPERATORS AND HAULERS/FRONT-END LOADER OPERATORS FROM VOLATILIZATION

Uncertainty	Associated assumption	Reasonable possible variance of assumption	Effects on results
The open surface area where the hauler/front end loader operator would be exposed to 2378 TCDD and 2378 TCDF.	The open surface area of a dump truck was assumed to be 4 ft by 8 ft on a 6 yd^3 dump truck.	-	-
The open surface area where the waste treatment plant operator would be exposed to 2378 TCDD and 2378 TCDF.	The open surface area of a conveyor was assumed to be 2.5 ft by 40 ft.	-	-
Inhalation exposure duration for hauler/ front end loader operator.	The duration of the exposure was assumed to be 4 hours since the operator conducts loading operations for 1/2 the shift.	Reasonable range in the duration would be 2 to 8 hours.	Exposure would range from 0.5 to 2 times the exposure level.
Inhalation exposure duration for waste treatment plant operator.	The duration of the exposure was assumed to be 4 hours since the operator is near the equipment for 1/2 the shift.	Reasonable range in the duration would be 2 to 8 hours.	Exposure would range from 0.5 to 2 times the exposure level.

$$ALPHA = \frac{D_i \times E^{4/3}}{E + RHOs \times (1-E)\ K_{as}}$$

$$= \frac{0.047 \times (0.25)^{4/3}}{0.25 + 2.65\ (1-0.25)/4.7x10^{-10}}$$

$$= 1.8 \times 10^{-12}\ cm^2/s$$

$$Na = \frac{2 \times D_i \times E^{4/3} \times K_{as} \times C_{so}}{[PI \times ALPHA \times T]^{1/2}}$$

$$= \frac{2 \times 0.047 \times (0.25)^{4/3} \times 4.7 \times 10^{-10} \times 0.7 \times 10^{-12}}{[3.14159 \times 1.8 \times 10^{-12} \times 2.21 \times 10^{9}]^{1/2}}$$

$$= 4.4 \times 10^{-23}\ g/cm^2\text{-}s$$

$$G = Na \times A$$

$$= 4.4 \times 10^{-23}\ \frac{g}{cm^2\text{-}s} \times 29{,}729\ cm^2$$

$$= 1.3 \times 10^{-18}\ g/s$$

$$Cm = \frac{G}{(L)\ (MH)\ (V)} \times 1000$$

$$= \frac{1.3 \times 10^{-18}\ g/s}{(2.44\ m)\ (1.5\ m)\ (2.2\ m/s)} \times 1000\ \frac{mg}{g}$$

$$= 1.6 \times 10^{-16}\ mg/m^3$$

$$Iv = 1.6 \times 10^{-16}\ mg/m^3 \times 1.25\ m^3/h \times 4\ h/day$$

$$= 8.1 \times 10^{-16}\ mg/day$$

The following is an example of the calculation procedure for estimating TEQ and percent daily exposure due to 2378 TCDD from volatilization from wet sludge.

Lower limit for daily TEQ and percent daily exposure due to 2378 TCDD for haulers/ front-end loader operators from volatilization

$$TEQv = 8.1 \times 10^{-16} + (0.1 \times 1.4 \times 10^{-13})$$

$$= 1.5 \times 10^{-14} \text{ mg/day}$$

$$\%TCDDv = \frac{8.1 \times 10^{-16}}{8.1 \times 10^{-16} + 1.4 \times 10^{-13}} \times 100$$

$$= 0.6\%$$

The following is an example of the calculation procedure for estimating lifetime average daily TEQ.

Lower limit for lifetime average daily TEQ from volatilization

$$LADEv = (1.5 \times 10^{-14} \text{ mg/day} \times 250 \text{ days/yr} \times 40 \text{ years/lifetime})/(70 \text{ kg} \times 25{,}550 \text{ days/lifetime})$$

$$= 8.2 \times 10^{-17} \text{ mg/day-kg}$$

Inhalation exposure from particulate matter--Equation 12 was used to calculate the inhalation exposure from 2378 TCDD and 2378 TCDF contained in particulate matter generated during sludge handling/processing operations. This equation is similar to equation 8 except that Cm in this equation represents the total particulate concentration rather than the 2378 TCDD and 2378 TCDF concentration.

$$Ip = Cm\ (mg/m^3) \times 1.25\ m^3/h \times ED\ (h/day) \times WF \qquad \text{Equation 12}$$

where Ip = daily inhalation from particulate matter, mg/day
Cm = concentration of particulate matter, mg/m^3
WF = weight fraction of 2378 TCDD/2378 TCDF in the dry sludge
ED = exposure duration, h/day

The concentration of 2378 TCDD/2378 TCDF in the particulate matter was assumed to be equal to the concentration of 2378 TCDD/2378 TCDF in the sludge. The dry weight concentration of 2378 TCDD/2378 TCDF, as reported in the 104-Mill Study, was used in the calculations because the particulate matter which is emitted is assumed to be dry.

The concentration of particulate matter was calculated using Equation 13 (EPA 1988b).

$$Cm = \frac{Qp}{(L)(MH)(V)} \qquad \text{Equation 13}$$

where
- Cm = particulate concentration, mg/m^3
- Qp = total particulate matter emission rate, mg/s
- L = equivalent side length of the site perpendicular to the direction of the winds, m
- MH = mixing height of the particulate matter before inhalation by an individual (assumed to be 1.5 m)
- V = average wind speed at the inhalation height (assumed to be 2.2 m/s)

Equation 13 estimates the on-site concentration of particulate matter in ambient air. It assumes that the particulate matter present at the site has traveled only a short distance before it is inhaled by the workers. The equation considers mixing of the particulate matter with winds but ignores dispersion effects. Total particulate emission rates for a given disposal scenario, which in this case is dewatered sludge loading and unloading, are used in the equation. The length of the area from which the particulate matter is being emitted corresponds to the length of an open area of the dump truck, length of daily landfill and land application areas, and length of the area of composting activities. The mixing height corresponds to the height at which the individual would inhale the particulate matter and the wind speed corresponds to the wind speed at the inhalation height.

The assumed values for mixing height and wind speed used in the release calculations from Equation 13 are suggested average default values presented in the EPA 1988b study. Particulate matter emission rate for sludge handling were calculated using AP-42 emission factors and concentration calculations are presented in Appendix B. These AP-42 emission factors are widely used for estimating particulate emission rates for similar applications.

Table 3-6 summarizes the variables used to calculate the exposure to workers from the particulate matter containing PCDDs and PCDFs generated during sludge handling/processing operations. It presents estimated daily inhalation exposure to 2378 TCDD and 2378 TCDF for waste treatment plant operators and haulers/front-end loader operators from particulate matter.

The relative toxicity of 2378 TCDF in respect to 2378 TCDD can be determined by calculating TEQ values. The percent exposure due to 2378 TCDD can also be calculated. Equations 9 and 10 are used to calculate these two variables. In these two equations, the daily inhalation exposure from volatilization (Iv) for 2378 TCDD and 2378 TCDF are replaced with the daily inhalation exposure from particulate matter (Ip) for 2378 TCDD and 2378 TCDF. Table 3-7 presents the daily and lifetime average daily TEQ and percent exposure due to 2378 TCDD from particulate matter for workers handling/ processing sludge.

The following is an example of the calculation procedure used for estimating levels of daily inhalation exposure for haulers/front-end loader operators exposed to 2378 TCDD from particulate matter:

Lower limit for 2378 TCDD inhalation exposure level from particulate matter for haulers/front-end loader operators

$$Ip = 0.017 \text{ mg/m}^3 \times 1.25 \text{ m}^3\text{/h} \times 4 \text{ h/day} \times 0.7 \times 10^{-12}$$
$$= 5.9 \times 10^{-14} \text{ mg/day}$$

The following is an example of the calculation procedure for estimating TEQ and percent daily exposure due to 2378 TCDD from particulate matter.

Lower limit for daily TEQ and percent daily exposure due to 2378 TCDD for haulers/front-end loader operators from particulate matter

$$TEQp = 5.9 \times 10^{-14} + (0.1 \times 2.6 \times 10^{-13})$$
$$= 8.5 \times 10^{-14} \text{ mg/day}$$

TABLE 3-6. ESTIMATED INHALATION EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR WASTE TREATMENT PLANT OPERATORS AND HAULERS/FRONT-END LOADER OPERATORS FROM PARTICULATE MATTER

Variable	2378 TCDD		2378 TCDF		Reference
	Low	High	Low	High	
Concentration of particulate matter, mg/m³ (Cm)[a]					
- haulers/front-end loader operators	0.017	0.017	0.017	0.017	Calculated (see Appendix B)
- waste treatment plant operators	0.0095	0.0095	0.0095	0.0095	Calculated (see Appendix B)
Weight fraction of 2378 TCDD/ 2378 TCDF in the dry sludge, dry basis (WF)	0.7×10^{-12}	1.39×10^{-9}	3.0×10^{-12}	1.71×10^{-8}	(Table 2-5, 104-Mill Study data)
Exposure duration, h/day (ED)					
- haulers/front-end loader operators	4	4	4	4	Engineering judgment[b]
- waste treatment plant operators	1	1	1	1	Engineering judgment[c]
Daily inhalation, mg/day (Ip)					
- haulers/ front-end loader operators	5.9×10^{-14}	1.2×10^{-10}	2.6×10^{-13}	1.5×10^{-9}	Calculated
- waste treatment plant operators	8.3×10^{-15}	1.7×10^{-11}	3.6×10^{-14}	2.0×10^{-10}	Calculated

[a] These concentrations are below the OSHA nuisance dust standard of 15 mg/m³.

[b] The haulers would be exposed to particulate matter during loading and unloading the sludge. Since the haulers spend approximately half the shift loading and unloading sludge, it was estimated the workers would be exposed to particulate matter for 4 hours per day.

[c] The waste treatment plant operator would only be in the area during sampling and cleanup, there would be minimal exposure potential to particulate matter. Therefore, it was estimated the exposure duration would be 1 hr/day.

TABLE 3-7. ESTIMATED TOXICITY EQUIVALENTS AND PERCENT EXPOSURE DUE TO 2378 TCDD FOR WASTE TREATMENT PLANT OPERATORS AND HAULERS/FRONT-END OPERATORS FROM PARTICULATE MATTER

Job category	Daily TEQ, mg/day (DTEQp)[a]		Lifetime average daily TEQ, mg/day-kg (LTEQp)[a]	
	Low	High	Low	High
Haulers/front-end operators	$8.5x10^{-14}$ (19%)	$2.6x10^{-10}$ (8%)	$4.8x10^{-16}$ (19%)	$1.8x10^{-12}$ (8%)
Waste treatment plant operators	$1.2x10^{-14}$ (19%)	$3.7x10^{-11}$ (8%)	$6.6x10^{-17}$ (19%)	$2.5x10^{-13}$ (8%)

[a] Values in parentheses are percent exposure to 2378 TCDD.

$$\%TCDDp = \frac{5.9 \times 10^{-14}}{5.9 \times 10^{-14} + 2.6 \times 10^{-13}} \times 100$$

$$= 19\%$$

3.1.1.2 Level of Dermal Exposure--

Dermal exposure levels to 2378 TCDD and 2378 TCDF were computed based on the assumption that workers do not wear any types of gloves that are effective in limiting exposure to PCDDs and PCDFs. Dermal exposure levels for sludge haulers and front-end loader operators were assumed to be equal because of their similar job functions.

There are a few different approaches available for estimating dermal exposure. The approach selected by PEI was that agreed upon by EPA, Federal Drug Administration, and the Consumer Product Safety Commission (EPA 1989d) for use in this project. This approach considers the partitioning of PCDD/PCDF from the appropriate matrix (e.g., soil, sludges, pulp, paper) to a liquid (i.e., water, skin oils, urine, blood) and percutaneous absorption of PCDDs and PCDFs from the liquid. In this reference, common assumptions for the assessment of dermal exposure are presented. However, in this reference, equations for estimating dermal exposures were not present. CPSC supplied three equations to PEI for estimating dermal exposure (CPSC 1989). These equations are for estimating dermal exposure to pulp, paper, and sludge/soil. The equation for handling wet sludge/soil was selected for the sludge haulers and front-end loader operator handling wet sludge and is presented in Equation 14.

$$DEW = DC\ (ppt) \times \rho\ (mg/cm^3) \times FT\ (cm) \times B \times AD\ (h^{-1}) \times S\ (cm^2) \times ED\ (hr/day) \qquad \text{Equation 14}$$

where:

DEW = dermal exposure from handling wet material, mg/day
DC = adjusted 2378 TCDD/2378 TCDF concentration to account for handling of wet sludge, ppt
ρ = density of the dewatered sludge, mg/cm^3
FT = liquid film thickness, cm
B = bioavailability factor for sludge, unitless
AD = absorption coefficient of TCDD/TCDF through the skin, h^{-1}
S = skin surface area, cm^2
ED = exposure duration, h/day

The 2378 TCDD and 2378 TCDF concentrations for sludge from Table 2-5 are reported on a dry basis. Since the workers are handling wet sludge, this concentration was adjusted to a wet basis by adjusting for the estimated percent solids (30%) in the sludge. This corresponds to reducing the dry 2378 TCDD/2378 TCDF concentrations reported in the 104-Mill Study by a factor of 3.33.

No data were available on duration or extent of dermal exposure. Therefore, dermal exposure duration was based on engineering judgment. It was assumed that only the palms and fingers of both hands of the hauler/front-end loader operator would be in contact with the wet sludge, whereas it was assumed that both hands and forearms of the waste treatment plant operator would be in contact with the wet sludge. The density for dewatered sludge is 1058 mg/cm^3 (EPA 1979) and a liquid film thickness for the wet sludge was estimated to be 0.025 cm. It was estimated that 2378 TCDD was absorbed at an average rate of approximately 0.012 h^{-1} (AD) over the time period from 0.5 to 17 hours (EPA 1989d). For the purposes of risk assessment, it was assumed that 15 percent of the sludge-bound 2378 TCDD is available for absorption

(B) (EPA 1989d). Table 3-8 summarizes the variables and results for dermal exposure of waste treatment plant operators and haulers/front-end loader operators to wet sludge.

The relative toxicity of 2378 TCDF in respect to 2378 TCDD can be determined by calculating TEQ values. The percent exposure due to 2378 TCDD can also be calculated. Equations 9 and 10 are used to calculate these two variables. In these two equations, the daily inhalation exposure from volatilization (Iv) for 2378 TCDD and 2378 TCDF are replaced with the daily dermal exposure (DEW) for 2378 TCDD and 2378 TCDF. Table 3-9 presents the daily and lifetime average daily TEQ and percent exposure due to 2378 TCDD from dermal exposure for workers handling/processing sludge. Table 3-10 presents the assumptions and uncertainties in the variables used to calculate the dermal exposures for workers handling/processing wet sludge in Table 3-8.

The following is an example of the calculation procedures used for estimating levels of daily dermal exposure for haulers/front-end loader operators potentially exposed to 2378 TCDD and 2378 TCDF during the handling of wet sludge:

<u>Lower limit for 2378 TCDD dermal exposure level for haulers/front-end loader operators</u>

$$DEW = 0.21 \times 10^{-12} \frac{g}{g} \times 1058 \text{ mg/cm}^3 \times 0.025 \text{ cm} \times 0.15 \times 0.012 \text{ h}^{-1} \times 250 \text{ cm}^2 \times 1 \text{ hr/day}$$

$$= 2.5 \times 10^{-12} \text{ mg/day}$$

TABLE 3-8. ESTIMATED DERMAL EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR WASTE TREATMENT PLANT OPERATORS AND HAULERS/FRONT-END LOADER OPERATORS

	2378 TCDD		2378 TCDF		
Variable	Low	High	Low	High	Reference
2378 TCDD/2378 TCDF concentration, of wet sludge, wet basis ppt (DC)	0.21	417	0.90	5,135	See Table 3-10
Density of the sludge, mg/cm^3 (ρ)	1058	1058	1058	1058	EPA 1979
Liquid film thickness of the sludge, cm (FT)	0.025	0.025	0.025	0.025	See Table 3-10
Bioavailability factor for sludge, unitless (B)	0.15	0.15	0.15	0.15	EPA 1989d
Absorption coefficient of TCDD/TCDF through the skin, h^{-1} (AD)	0.012	0.012	0.012	0.012	EPA 1989d
Skin surface area, cm^2 (S)					
- haulers/front-end loader operators	250	300	250	300	See Table 3-10
- waste treatment plant operators	2600	2600	2600	2600	See Table 3-10
Exposure duration, h/day (ED)					
- haulers/front-end loader operators	1	1	1	1	See Table 3-10
- waste treatment plant opertors	2	2	2	2	See Table 3-10

(continued)

TABLE 3-8 (continued)

Variable	2378 TCDD Low	2378 TCDD High	2378 TCDF Low	2378 TCDF High	Reference
Dermal exposure, mg/day (DEW)					
- haulers/ front-end loader operators	2.5×10^{-12}	6.0×10^{-9}	1.1×10^{-11}	7.3×10^{-8}	Calculated
- waste treatment plant operators	5.2×10^{-11}	1.0×10^{-7}	2.2×10^{-10}	1.3×10^{-6}	Calculated

TABLE 3-9. ESTIMATED TOXICITY EQUIVALENTS AND PERCENT EXPOSURE DUE TO 2378 TCDD FOR WASTE TREATMENT PLANT OPERATORS AND HAULERS/FRONT-END OPERATORS FROM DERMAL EXPOSURE

Job category	Daily TEQ, mg/day (DTEQd)[a]		Lifetime average daily TEQ, mg/day-kg (LTEQd)[a]	
	Low	High	Low	High
Haulers/front-end operators	3.6×10^{-12} (19%)	1.3×10^{-8} (8%)	2.0×10^{-14} (19%)	9.0×10^{-11} (8%)
Waste treatment plant operators	7.4×10^{-11} (19%)	2.3×10^{-7} (8%)	4.2×10^{-13} (19%)	1.6×10^{-9} (8%)

[a] Values in parentheses are percent exposure due to 2378 TCDD.

TABLE 3-10. ASSUMPTIONS AND UNCERTAINTIES IN ESTIMATING DERMAL EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR WASTE TREATMENT PLANT OPERATORS AND HAULERS/FRONT-END LOADER OPERATORS

Uncertainty	Associated assumption	Reasonable possible variance of assumption	Effects on results
The 2378 TCDD/2378 TCDF concentration	The 2378 TCDD/2378 TCDF concentrations for sludge from Table 2-5 are reported on a dry basis. However, workers are handling wet sludge. This concentration was adjusted by the percent solids in the sludge. This corresponds to reducing the 2378 TCDD/2378 TCDF concentration by a factor of 3.33.	-	-
Liquid film thickness of the wet sludge on the skin.	The film thickness was assumed to be 0.25 mm.	Film thickness for liquids have ranged from 0.01 mm to 0.25 mm (Wong 1983 and Versar 1984).	Exposure would range from 0.4 to 1.0 times the exposure level.
The skin surface area where the hauler/front end loader operator would be exposed to 2378 TCDD and 2378 TCDF.	The exposed skin surface area was estimated by PEI to be 100 percent of palm and finger surfaces of both hands. The high and low represent the difference between the surface area of a men's and women's hands. The exposed skin surface is 250 cm^2 for females and 300 cm^2 for males (NCASI 1988).	The exposed skin surface area could potentially include exposure to both hands (front and back) and exposure to the forearms. Therefore, skin surface area would increase to 2,600 cm^2 (Popendorf 1982).	Exposure would range from 10 to 10.4 times greater exposure.

(continued)

TABLE 3-10 (continued)

Uncertainty	Associated assumption	Reasonable possible variance of assumption	Effects on results
The skin surface area where the waste treatment plant operator would be exposed to 2378 TCDD and 2378 TCDF.	The exposed skin surface surface area was estimated by PEI to be both hands (front and back) and exposure to the forearms. Therefore, the skin surface area would be 2,600 cm^2 (Popendorf 1982).	-	-
Dermal exposure duration for hauler/front end loader operator.	The duration of the exposure was assumed by PEI to be 2 hours since the process is highly automated and cleanup is usually done with a shovel.	Reasonable range in the duration would be 1 to 4 hours.	Exposure would range between 0.5 to 2 times the exposure level.
Dermal exposure duration for waste treatment plant operator.	The duration of the exposure was assumed to be 1 hour since the operator will not be in contact with wet sludge unless maintenance is required.	Reasonable range in the duration would be 0.5 to to 2 hours.	Exposure would range between 0.5 to 2 times the exposure level.

3.1.2 Sludge Disposal Operations

The route and amount of exposure to 2378 TCDD and 2378 TCDF in sludge disposal operations will depend on the specific sludge disposal technique, the amount of sludge disposed, and the degree of processing of the sludge. In addition, atmospheric events such as wind and rain will affect the degree of exposure in sludge disposal operations conducted outdoors.

3.1.2.1 Landfilling Operations--

Inhalation is the primary route of exposure to 2378 TCDD and 2378 TCDF in landfilling operations. During unloading, spreading, compacting, and burying of the sludge with various pieces of equipment, particulate matter is generated which may be inhaled by the equipment operators. In addition, 2378 TCDD and 2378 TCDF may volatilize from the wet sludge and be inhaled. It is estimated that the equipment operators may be exposed to 2378 TCDD and 2378 TCDF by inhalation throughout their 8-hour shift because their only job function is to operate equipment which is constantly in contact with the sludge, and operations are conducted in open areas.

Dermal exposure to the wet sludge is minimal. It is estimated that the time of dermal exposure for the equipment operators is 1 hour per shift because they are generally not in contact with the wet sludge unless maintenance of the equipment is required.

The following is an estimation of both dermal and inhalation exposures for equipment operators at landfilling operations. The concentrations of 2378 TCDD and 2378 TCDF in sludge used in the exposure calculations for landfill equipment operators are the low and high concentrations in sludges which are landfilled as reported in the 104-Mill Study data corresponding to the calculated low and high TEQ. The mills which practice landfill disposal of sludge were identified in the 104-Mill Study data provided by EPA. Particulate matter emissions from landfilling sludge were calculated using AP-42 emission factors and are documented in Appendix C; exposed population calculations are also presented in Appendix C.

Particulate matter emissions from unloading, spreading, and composting the sludge during landfilling operations were calculated using emission factors from AP-42 (EPA 1985 and EPA 1988d). The emission factors for unloading various materials is presented in Section 11.2.3 of AP-42 (EPA 1988d). The emission factor for agricultural tilling, presented in Section 11.2.2 of AP-42 (EPA 1985), was used to estimate emissions from composting and spreading. The agricultural tilling emission factor was used to estimate particulate emissions from spreading because this was the suggested emission factor in a EPA study (EPA 1988b). All of these emission factors were used because the methodology to calculate PCDD/PCDF releases from particulate matter presented in EPA 1988b uses particulate matter emission factors taken from AP-42 (EPA 1985 and EPA 1988d).

Level of inhalation exposure--In landfilling operations one job category of workers (i.e., equipment operators) is potentially exposed to 2378 TCDD and 2378 TCDF through inhalation of vapors and particulate matter containing dioxin and dibenzofuran. All equipment operators were assumed to be exposed for the entire 8 hours of their shift, since their only job function is to operate equipment which has continual contact with the sludge.

The same calculation procedures previously employed to estimate inhalation exposure to 2378 TCDD and 2378 TCDF by volatilization (using Equations 3 through 8) and particulate matter generation (using Equation 12) for waste treatment plant operators and sludge haulers/front-end loader operators were used to estimate inhalation exposures for landfill equipment operators. Appendix C presents the calculations of particulate emission rates (based on AP-42 emission factors), equivalent length of the area source, and concentrations used in the particulate exposure estimations. Table 3-11 summarizes the variables used to calculate inhalation exposure levels for the landfill equipment operators from volatilization from wet sludge and presents subsequent exposure estimates.

The relative toxicity of 2378 TCDF in respect to 2378 TCDD can be determined by calculating TEQ values. In addition, the percent exposure due to 2378 TCDD can also be calculated. Using equations 9 and 10, these two variables are calculated. Table 3-12 presents the daily and lifetime average daily TEQ and percent exposure due to 2378 TCDD from volatilization from wet sludge for landfill equipment operators. Table 3-13 presents the assumptions and uncertainties in the variables used to calculate the daily exposure for the landfill equipment operators from volatilization.

Table 3-14 summarizes the variables for inhalation of particulate matter generated from sludge unloading, spreading, compacting, and covering operations at landfills. It presents estimated daily inhalation exposure to 2378 TCDD and 2378 TCDF to landfill equipment operators from particulate matter.

The relative toxicity of 2378 TCDF in respect to 2378 TCDD can be determined by calculating TEQ values. The percent exposure due to 2378 TCDD can also be calculated. Equations 9 and 10 are used to calculate these two variables. In these two equations, the daily inhalation exposure from volatilization (Iv) for 2378 TCDD and 2378 TCDF are replaced with the daily exposure from particulate matter (Ip) for 2378 TCDD and 2378 TCDF. Table 3-15 presents the daily and lifetime average daily TEQ and percent exposure due to 2378 TCDD from particulate matter for landfill equipment operators.

TABLE 3-11. ESTIMATED INHALATION EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR LANDFILL EQUIPMENT OPERATORS FROM VOLATILIZATION

Variable	2378 TCDD Low	2378 TCDD High	2378 TCDF Low	2378 TCDF High	Reference
Henry's Law Constant, atm-m³/mole (Hc)	$1.6x10^{-5}$	$1.6x10^{-5}$	$8.6x10^{-5}$	$8.6x10^{-5}$	Abt 1989
Soil/water partition coefficient, mg/g in soil per mg/cm³ in water (Kd)	$1.4x10^{6}$	$1.4x10^{6}$	4900	4900	Abt 1989
Air/soil partition coefficient, mg/cm³ in air per mg/g in soil (K_{as})	$4.7x10^{-10}$	$4.7x10^{-10}$	$7.2x10^{-7}$	$7.2x10^{-7}$	Calculated
Molecular diffusivity of 2378 TCDD/2378 TCDF in air, cm²/s (Di)	0.047	0.047	0.048	0.048	Abt 1989
Effective porosity of soil, unitless (E)	0.25	0.25	0.25	0.25	Abt 1989
True density of soil, g/cm³ (RHO_s)	2.65	2.65	2.65	2.65	Abt 1989
Intermediate variable to calculate rate of emission from the soil surface, cm²/s (ALPHA)	$1.8x10^{-12}$	$1.8x10^{-12}$	$2.7x10^{-9}$	$2.7x10^{-9}$	Calculated
Initial 2378 TCDD/2378 TCDF concentration in the soil on a dry basis, g/g (C_{so})	$0.7x10^{-12}$	$7.1x10^{-10}$	$3.0x10^{-12}$	$1.09x10^{-8}$	104-Mill study data
Duration of exposure, s (T)	$2.21x10^{9}$	$2.21x10^{9}$	$2.21x10^{9}$	$2.21x10^{9}$	Abt 1989
Emission rate of 2378 TCDD/2378 TCDF from the soil surface, g/cm²-s	$4.4x10^{-23}$	$4.5x10^{-20}$	$7.5x10^{-21}$	$2.7x10^{-17}$	Calculated

(continued)

TABLE 3-11 (continued)

Variable	2378 TCDD Low	2378 TCDD High	2378 TCDF Low	2378 TCDF High	Reference
Surface area, cm^2 (A)	$2.0x10^6$	$2.0x10^6$	$2.0x10^6$	$2.0x10^6$	See Table 3-13
Generation rate, g/s(G)	$8.8x10^{-17}$	$9.0x10^{-14}$	$1.5x10^{-14}$	$5.4x10^{-11}$	Calculated
Molecular weight, g/g-mole (M)	322	322	306	306	EPA 1989c
Mixing factor,	0.5	0.5	0.5	0.5	See Table 3-5
Equivalent side length of the area source perpendicular to the direction of the wind, m (L)	14.2	14.2	14.2	14.2	Appendix C
Mixing height of the vapors before inhalation by an individual, m (MH)	1.5	1.5	1.5	1.5	EPA 1988b
Average windspeed at the inhalation height, m (V)	2.2	2.2	2.2	2.2	EPA 1988b
Concentration of 2378 TCDD/2378 TCDF in the vapor, mg/m^3 (Cm)	$1.9x10^{-15}$	$1.9x10^{-12}$	$3.2x10^{-13}$	$1.2x10^{-9}$	Calculated
Exposure duration, h/day (ED)	8	8	8	8	See Table 3-13
Daily inhalation mg/day (Iv)	$1.9x10^{-14}$	$1.9x10^{-11}$	$3.2x10^{-12}$	$1.2x10^{-8}$	Calculated

TABLE 3-12. ESTIMATED TOXICITY EQUIVALENTS AND PERCENT EXPOSURE DUE TO 2378 TCDD FOR LANDFILL EQUIPMENT OPERATORS FROM VOLATILIZATION

Daily TEQ, mg/day (DTEQv)[a]		Lifetime average daily TEQ, mg/day-kg (LTEQv)[a]	
Low	High	Low	High
3.4×10^{-13} (0.6%)	1.2×10^{-9} (0.2%)	1.9×10^{-15} (0.6%)	8.0×10^{-12} (0.2%)

[a] Values in parentheses are percent exposure due to 2378 TCDD.

TABLE 3-13. ASSUMPTIONS AND UNCERTAINTIES IN ESTIMATING INHALATION EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR LANDFILL EQUIPMENT OPERATORS FROM VOLATILIZATION

Uncertainty	Associated assumption	Reasonable possible variance of assumption	Effects on results
The open surface area of an open landfill where the workers would be exposed to 2378 TCDD and 2378 TCDF	The daily application surface area was based on applying 250 tons/day (104 Mill Study), specific gravity of 1.06 (Hammer 1975) and a rate of 5,700 yd^3/acre (EPA 1979). See Appendix C for calculations.	Reasonable range for the sludge application rates is 500 ft^3/acre to 15,000 ft^3/acre. This corresponds to 1.8×10^5 cm^2 and 5.3×10^6 cm^2, respectively.	Exposure would range from 0.09 to 2.6 times greater exposure.
Inhalation exposure duration for landfill equipment operators.	The duration of the exposure was assumed to be 8 hours since this would be the worst case exposure duration.	-	-

TABLE 3-14. ESTIMATED INHALATION EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR LANDFILL EQUIPMENT OPERATORS FROM PARTICULATE MATTER

Variable	2378 TCDD		2378 TCDF		Reference
	Low	High	Low	High	
Concentration of particulate matter, mg/m^3 (Cm)[a]	0.62	0.62	0.62	0.62	Calculated (see Appendix C)
Weight fraction of 2378 TCDD/2378 TCDF in the dry sludge, dry basis (WF)	$0.7x10^{-12}$	$7.1x10^{-10}$	$3.0x10^{-12}$	$1.09x10^{-8}$	104-Mill Study data
Exposure duration, h/day (ED)	8	8	8	8	Engineering judgment[a]
Daily inhalation, mg/day (Ip)	$4.3x10^{-12}$	$4.4x10^{-9}$	$1.9x10^{-11}$	$6.8x10^{-8}$	Calculated

[a] These concentrations are below the OSHA nuisance dust standard of 15 mg/m^3.

[b] The exposure duration was assumed to be 8 hours since this would be the worst-case exposure duration.

TABLE 3-15. ESTIMATED TOXICITY EQUIVALENTS AND PERCENT EXPOSURE DUE TO 2378 TCDD FOR LANDFILL EQUIPMENT OPERATORS FROM PARTICULATE MATTER

Daily TEQ, mg/day (DTEQp)[a]		Lifetime average daily TEQ, mg/day-kg (LTEQp)[a]	
Low	High	Low	High
$6.2x10^{-12}$ (19%)	$1.1x10^{-8}$ (6%)	$3.5x10^{-14}$ (19%)	$7.5x10^{-11}$ (6%)

[a] Values in parentheses are percent exposure due to 2378 TCDD.

Level of dermal exposure--Dermal exposure levels were based on the assumption that the equipment operators do not wear any types of gloves that are effective in limiting exposure to PCDDs and PCDFs. The same calculation procedure as that used to estimate dermal exposure for waste treatment plant operators and haulers/front-end loader operators was used to estimate dermal exposure levels for the landfill equipment operator.

The 2378 TCDD and 2378 TCDF concentrations for sludge from Table 2-5 are reported on a dry basis. Since the workers are handling wet sludge, this concentration was adjusted to a wet basis by adjusting for the estimated percent solids (30%) in the sludge. This corresponds to reducing the 2378 TCDD/2378 TCDF concentrations by a factor of 3.33.

In the absence of data on the extent and duration of dermal exposure, dermal exposure duration was based on engineering judgment. It was assumed that only the palms and fingers of both hands of the landfill equipment operator would come in contact with the wet sludge. The density for dewatered sludge is 1058.8 mg/cm^3 and a liquid film thickness for the wet sludge was estimated to be 0.25 mm. Table 3-16 summarizes the variables and results for dermal exposure for landfill equipment operators.

The relative toxicity of 2378 TCDF in respect to 2378 TCDD can be determined by calculating TEQ values. The percent exposure due to 2378 TCDD can also be calculated. Equations 9 and 10 are used to calculate these two variables. In these two equations, the daily inhalation exposure from volatilization (Iv) for 2378 TCDD and 2378 TCDF are replaced with the daily dermal exposure (DEW) for 2378 TCDD and 2378 TCDF. Table 3-17 presents the daily and lifetime average daily TEQ and percent exposure due to 2378 TCDD from dermal exposure for landfill equipment operators. Table 3-18 presents

TABLE 3-16. ESTIMATED DERMAL EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR LANDFILL EQUIPMENT OPERATORS

Variable	2378 TCDD		2378 TCDF		Reference
	Low	High	Low	High	
2378 TCDD/2378 TCDF concentration of wet sludge, wet basis, ppt (DC)	0.21	213	0.90	3273	See Table 3-18
Density of the sludge, mg/cm³ (ρ)	1058	1058	1058	1058	EPA 1979
Liquid film thickness of the sludge, cm (FT)	0.025	0.025	0.025	0.025	See Table 3-10
Bioavailability factor for sludge, unitless (B)	0.15	0.15	0.15	0.15	EPA 1989d
Absorption coefficient of TCDD/TCDF through the skin, h^{-1} (AD)	0.012	0.012	0.012	0.012	EPA 1989d
Skin surface area, cm² (S)	250	300	250	300	See Table 3-18
Exposure duration, h/day (ED)	1	1	1	1	See Table 3-18
Dermal exposure, mg/day (DEW)	$2.5x10^{-12}$	$3.1x10^{-9}$	$1.1x10^{-11}$	$4.7x10^{-8}$	Calculated

TABLE 3-17. ESTIMATED TOXICITY EQUIVALENTS AND PERCENT EXPOSURE DUE TO 2378 TCDD FOR LANDFILL EQUIPMENT OPERATORS FROM DERMAL EXPOSURE

Daily TEQ, mg/day (DTEQd)[a]		Lifetime average daily TEQ, mg/day-kg (LTEQd)[a]	
Low	High	Low	High
3.6×10^{-12} (19%)	7.7×10^{-9} (6%)	2.0×10^{-14} (19%)	5.2×10^{-11} (6%)

[a] Values in parentheses are percent exposure due to 2378 TCDD.

TABLE 3-18. ASSUMPTIONS AND UNCERTAINTIES IN ESTIMATING DERMAL EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR LANDFILL EQUIPMENT OPERATORS

Uncertainty	Associated assumption	Reasonable possible variance of assumption	Effects on results
The 2378 TCDD/2378 TCDF concentration	The TCDD/TCDF concentrations for sludge from Table 2-5 are reported on a dry basis. However, workers are handling wet sludge. This concentration was adjusted by the percent solids in the sludge. This corresponds to reducing the TCDD/TCDF concentration by a factor of 3.33.	-	-
The skin surface area where the landfill equipment operators would be exposed to 2378 TCDD and 2378 TCDF.	The exposed skin surface area was estimated by PEI to be 100 percent of palm and finger surfaces of both hands. The high and low represent the difference between the surface area of men's and women's hands. The exposed skin surface area is 250 cm^2 for females and 300 cm^2 for males (NCASI 1988).	The exposed skin surface area could potentially include exposure to both hands (front and back) and exposure to the forearms. Therefore, the skin surface area would increase to 2,600 cm^2 (Popendorf 1982).	Exposure would range from 10 to 10.4 times greater exposure.
Dermal exposure duration for landfill equipment operators.	The duration of the exposure was assumed to be 1 hour since the operator will not be in contact with wet sludge unless maintenance is required.	Reasonable range in the duration would be 0.5 to 2 hours.	Exposure would range from 0.5 to 2 times greater exposure.

the assumptions and uncertainties in the variables used to calculate the dermal exposures for landfill equipment operators in Table 3-16.

3.1.2.2 Land Application--

Exposure to 2378 TCDD and 2378 TCDF through land application is very similar to that of landfilling operations. Inhalation is the primary route of exposure to 2378 TCDD and 2378 TCDF in land application operations. Particulate matter generated during unloading, spreading, and plowing operations may be inhaled by the equipment operators. In addition, 2378 TCDD and 2378 TCDF may volatilize from the wet sludge and consequently be inhaled. It is estimated that the equipment operators may be exposed via inhalation throughout their entire 8-hour shift because their only job function is to operate equipment which has continuous contact with the sludge, and operations are performed in open areas.

It is assumed that land application operations are conducted throughout the year. Operations could be seasonal, but in as much as some facilities apply their sludge to pine tree plantations, PEI assumed, for worst-case conditions, that land application operations are performed daily.

Dermal exposure to the wet sludge is minimal. It is estimated that the time of dermal exposure for the equipment operators is only 1 hour per shift because they are generally not in contact with the wet sludge unless maintenance of the equipment is required.

The following is an estimation of both inhalation and dermal exposure for equipment operators at land application operations. The concentrations of 2378 TCDD and 2378 TCDF in sludge used for the exposure calculations for land application equipment operators are the low and high concentrations reported for the sludges disposed by land application as reported in the 104-Mill Study data corresponding to the calculated low and high TEQ. The mills which practice disposal of sludge by land application were identified in the 104-Mill Study data provided by EPA. Particulate matter emissions from land application of sludge were calculated using AP-42 emission factor and are documented in Appendix D; exposed population calculations are also presented in Appendix D.

Particulate matter emissions from unloading, spreading, and plowing the sludge during land application operations were calculated using emission factors from AP-42 (EPA 1985 and EPA 1988d). The emission factor for unloading various materials is presented in Section 11.2.3 of AP-42 (EPA 1988d). The emission factor for agricultural tilling, presented in Section 11.2.2 of AP-42 (EPA 1985), was used to estimate emissions from compacting and spreading. The agricultural tilling emission factor was used to estimate particulate emissions from spreading because this was the suggested emission factor in EPA 1988b. All of these emission factors were used because the methodology to calculate PCDD/PCDF releases from particulate matter presented in the EPA 1988b study uses particulate matter emission factors taken from AP-42 (EPA 1985 and EPA 1988d).

Level of inhalation exposure--In land application operations, there is one job category of workers (i.e., equipment operators) potentially exposed to PCDDs and PCDFs through inhalation of vapors and particulate matter containing dioxin and dibenzofuran. All equipment operators were assumed to be exposed for the entire 8 hours of their shift since their only job function is to operate equipment which has continual contact with the sludge, and operations are performed in open areas.

The same calculation procedures previously employed to estimate inhalation exposure via volatilization (Equations 3 through 8) and particulate matter generation (Equation 12) for waste treatment plant operators and sludge haulers/front-end loader operators were used to estimate inhalation exposures for land application equipment operators. Appendix D presents the calculation of particulate emission rates (based on AP-42 emission factors), equivalent length of the area source, and particle concentrations used in the exposure estimations. Table 3-19 summarizes the variables used to calculate inhalation exposure levels for the land application equipment operators from volatilization of 2378 TCDD and 2378 TCDF from the wet sludge and presents subsequent exposure estimates.

The relative toxicity of 2378 TCDF in respect to 2378 TCDD can be determined by calculating TEQ values. In addition, the percent exposure due to 2378 TCDD can also be calculated. Using equations 9 and 10, these two variables are calculated. Table 3-20 presents the daily and lifetime average daily TEQ and percent exposure due to 2378 TCDD from volatilization from wet sludge for land application equipment operators. Table 3-21 presents the assumptions and uncertainties in the variables used to calculate the daily exposure for the land application operators from volatilization in Table 3-19.

Table 3-22 summarizes the variables for inhalation of particulate matter generated from sludge unloading, spreading, and plowing operations at land application sites. It presents estimated daily inhalation exposure to 2378 TCDD and 2378 TCDF for land application operators from particulate matter.

The relative toxicity of 2378 TCDF in respect to 2378 TCDD can be determined by calculating TEQ values. The percent exposure due to 2378 TCDD can also be calculated. Equations 9 and 10 are used to calculate these two variables. In these two equations, the daily inhalation exposure from volatilization (Iv) for 2378 TCDD and 2378 TCDF is replaced with the daily exposure from particulate matter (Ip) for 2378 TCDD and 2378 TCDF. Table 3-23 presents the daily and lifetime average daily TEQ and percent exposure due to 2378 TCDD from particulate matter for land application equipment operators.

<u>Level of dermal exposure</u> - Dermal exposure levels to 2378 TCDD and 2378 TCDF were based on the assumption that the equipment operators do not wear

TABLE 3-19. ESTIMATED INHALATION EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR LAND APPLICATION EQUIPMENT OPERATORS FROM VOLATILIZATION

	2378 TCDD		2378 TCDF		
Variable	Low	High	Low	High	Reference
Henry's Law Constant, atm-m^3/mole (Hc)	$1.6x10^{-5}$	$1.6x10^{-5}$	$8.6x10^{-5}$	$8.6x10^{-5}$	Abt 1989
Soil/water partition coefficient, mg/g in soil per mg/cm^3 in water (Kd)	$1.4x10^{6}$	$1.4x10^{6}$	4900	4900	Abt 1989
Air/soil partition coefficient, mg/cm^3 in air per mg/g in soil (K_{as})	$4.7x10^{-10}$	$4.7x10^{-10}$	$7.2x10^{-7}$	$7.2x10^{-7}$	Calculated
Molecular diffusivity of 2378 TCDD/2378 TCDF in air, cm^2/s (Di)	0.047	0.047	0.048	0.048	Abt 1989
Effective porosity of soil, unitless (E)	0.25	0.25	0.25	0.25	Abt 1989
True density of soil g/cm^3 (RHO_s)	2.65	2.65	2.65	2.65	Abt 1989
Intermediate variable to calculate rate of emission from the soil surface, cm^2/s (ALPHA)	$1.8x10^{-12}$	$1.8x10^{-12}$	$2.7x10^{-9}$	$2.7x10^{-9}$	Calculated
Initial 2378 TCDD/ 2378 TCDF concentration in the soil on a dry basis, g/g (C_{so})	$1.3x10^{-11}$	$7.56x10^{-10}$	$5.5x10^{-11}$	$1.39x10^{-9}$	104-Mill study data
Duration of exposure, s (T)	$2.21x10^{9}$	$2.21x10^{9}$	$2.21x10^{9}$	$2.21x10^{9}$	Abt 1989
Emission rate of 2378 TCDD/2378 TCDF from the soil surface, g/cm^2-s	$8.2x10^{-22}$	$4.8x10^{-20}$	$1.4x10^{-20}$	$3.5x10^{-18}$	Calculated

(continued)

TABLE 3-19 (continued)

Variable	2378 TCDD Low	2378 TCDD High	2378 TCDF Low	2378 TCDF High	Reference
Surface area, cm^2 (A)	$1.4x10^7$	$1.4x10^7$	$1.4x10^7$	$1.4x10^7$	See Table 3-21
Generation rate, g/s(G)	$1.1x10^{-14}$	$6.7x10^{-13}$	$1.9x10^{-12}$	4.910^{-11}	Calculated
Molecular weight, g/g-mole (M)	322	322	306	306	EPA 1989c
Equivalent side length of the area source perpendicular to the direction of the wind, m (L)	37.6	37.6	37.6	37.6	Appendix D
Mixing height of the vapors before inhalation by an individual, m (MH)	1.5	1.5	1.5	1.5	EPA 1988b
Average windspeed at the inhalation height, m (V)	2.2	2.2	2.2	2.2	EPA 1988b
Concentration of 2378 TCDD/2378 TCDF in the vapor, mg/m^3 (Cm)	$9.2x10^{-14}$	$5.4x10^{-12}$	$1.5x10^{-11}$	$3.9x10^{-10}$	Calculated
Exposure duration, h/day (ED)	8	8	8	8	See Table 3-21
Daily inhalation, mg/day (Iv)	$9.2x10^{-13}$	$5.4x10^{-11}$	$1.5x10^{-10}$	$3.9x10^{-9}$	Calculated

TABLE 3-20. ESTIMATED TOXICITY EQUIVALENTS AND PERCENT EXPOSURE DUE TO 2378 TCDD FOR LAND APPLICATION EQUIPMENT OPERATORS FROM VOLATILIZATION

Daily TEQ, mg/day (DTEQv)[a]		Lifetime average daily TEQ, mg/day-kg (LTEQv)[a]	
Low	High	Low	High
1.6×10^{-11} (0.6%)	4.5×10^{-10} (1%)	9.2×10^{-14} (0.6%)	3.0×10^{-12} (1%)

[a] Values in parentheses are percent exposure due to 2378 TCDD.

TABLE 3-21. ASSUMPTIONS AND UNCERTAINTIES IN ESTIMATING INHALATION EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR LAND APPLICATION EQUIPMENT OPERATORS FROM VOLATILIZATION

Uncertainty	Associated assumption	Reasonable possible variance of assumption	Effects on results
The open surface area where the workers would be exposed to 2378 TCDD and 2378 TCDF.	The daily application surface area was calculated assuming an average application depth of 5 in. (EPA 1979), a sludge specific gravity of 1.06 (Hammer 1975), and 209.5 tons processed (104-Mill *Study*). *See Appendix D* for calculation.	Reasonable range for application depth was 4 to 6 in (EPA 1979).	Exposure would range from 0.8 to 1.2 times the exposure level.
Inhalation exposure duration for land application equipment operators.	The duration of the exposure was assumed to be 8 hours since this would be the worst case exposure duration.	-	-

TABLE 3-22. ESTIMATED INHALATION EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR LAND APPLICATION EQUIPMENT OPERATORS FROM PARTICULATE MATTER

Variable	2378 TCDD		2378 TCDF		Reference
	Low	High	Low	High	
Concentration of particulate matter, mg/m³ (Cm)[a]	3.28	3.28	3.28	3.28	Calculated (see Appendix D)
Weight fraction of 2378 TCDD/ 2378 TCDF in the dry sludge, dry basis (WF)	1.3×10^{-11}	7.56×10^{-10}	5.5×10^{-11}	1.39×10^{-9}	104-Mill Study data
Exposure duration, h/day (ED)	8	8	8	8	Engineering judgment[b]
Daily inhalation, mg/day (Ip)	4.3×10^{-10}	2.5×10^{-8}	1.8×10^{-9}	4.6×10^{-8}	Calculated

[a] These calculations are below the OSHA nuisance dust standard of 15 mg/m³.

[b] The exposure duration was assumed to be 8 hours since this would be the worst-case exposure duration.

TABLE 3-23. ESTIMATED TOXICITY EQUIVALENTS AND PERCENT EXPOSURE DUE TO 2378 TCDD FOR LAND APPLICATION EQUIPMENT OPERATORS FROM PARTICULATE MATTER

Daily TEQ, mg/day (DTEQp)[a]		Lifetime average daily TEQ, mg/day-kg (LTEQp)[a]	
Low	High	Low	High
6.1×10^{-10} (19%)	2.9×10^{-8} (35%)	3.4×10^{-12} (19%)	2.0×10^{-10} (35%)

[a] Values in parentheses are percent exposure due to 2378 TCDD.

any types of gloves that are effective in limiting exposure to PCDDs and PCDFs. The same calculation procedure as that used to estimate dermal exposure for waste treatment plant operators and haulers/front-end loader operators was used to estimate dermal exposure levels for land application equipment operators.

The 2378 TCDD and 2378 TCDF concentrations for sludge from Table 2-5 are reported on a dry basis. Since the workers are handling wet sludge, this concentration was adjusted to a wet basis by adjusting for the estimated percent solids (30%) in the sludge. This corresponds to reducing the 2378 TCDD/2378 TCDF concentrations by a factor of 3.33.

Dermal exposure duration was based on engineering judgment. It was assumed that only the palms and fingers of both hands of the equipment operator would come in contact with the wet sludge. The density of dewatered sludge is 1058.8 mg/cm^3 and a liquid film thickness for the wet sludge was estimated to be 0.25 mm. Table 3-24 summarizes the variables and results for dermal exposure for land application equipment operators.

The relative toxicity of 2378 TCDF in respect to 2378 TCDD can be determined by calculating TEQ values. The percent exposure due to 2378 TCDD can also be calculated. Equations 9 and 10 are used to calculate these two variables. In these two equations, the daily inhalation exposure from volatilization (Iv) for 2378 TCDD and 2378 TCDF are replaced with the daily dermal exposure (DEW) for 2378 TCDD and 2378 TCDF. Table 3-25 presents the daily and lifetime average daily TEQ and percent exposure due to 2378 TCDD from dermal exposure for land application equipment operators. Table 3-26 presents the assumptions and uncertainties in the variables used to calculate the dermal exposures for land application equipment operators in Table 3-24.

TABLE 3-24. ESTIMATED DERMAL EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR LAND APPLICATION EQUIPMENT OPERATORS

Variable	2378 TCDD		2378 TCDF		Reference
	Low	High	Low	High	
2378 TCDD/2378 TCDF concentration of wet sludge, wet basis, ppt (DC)	3.9	227	16.5	417	See Table 3-26
Density of the sludge, mg/cm^3 (ρ)	1,058	1,058	1,058	1,058	EPA 1979
Liquid film thickness of the sludge, cm (FT)	0.025	0.025	0.025	0.025	See Table 3-10
Bioavailability factor for sludge, unitless (B)	0.15	0.15	0.15	0.15	EPA 1989d
Absorption coefficient of TCDD/TCDF through the skin, h^{-1} (AD)	0.012	0.012	0.012	0.012	EPA 1989d
Skin surface area, cm^2 (S)	250	300	250	300	See Table 3-26
Exposure duration, h/day (ED)	1	1	1	1	See Table 3-26
Dermal exposure, mg/day (DEW)	$4.7x10^{-11}$	$3.2x10^{-9}$	$2.0x10^{-10}$	$6.0x10^{-9}$	Calculated

TABLE 3-25. ESTIMATED TOXICITY EQUIVALENTS AND PERCENT EXPOSURE DUE TO 2378 TCDD FOR LAND APPLICATION EQUIPMENT OPERATORS FROM DERMAL EXPOSURE

Daily TEQ, mg/day (DTEQd)[a]		Lifetime average daily TEQ, mg/day-kg (LTEQd)[a]	
Low	High	Low	High
6.6×10^{-11} (19%)	3.8×10^{-9} (35%)	3.7×10^{-13} (19%)	2.6×10^{-11} (35%)

[a] Values in parentheses are percent exposure due to 2378 TCDD.

TABLE 3-26. ASSUMPTIONS AND UNCERTAINTIES IN ESTIMATING DERMAL EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR LAND APPLICATION EQUIPMENT OPERATORS

Uncertainty	Associated assumption	Reasonable possible variance of assumption	Effects on results
The 2378 TCDD/2378 TCDF concentration.	The TCDD/TCDF concentrations for sludge from Table 2-5 are reported on a dry basis. However, workers are handling wet sludge. This concentration was adjusted by the percent solids in the sludge. This corresponds to reducing the 2378 TCDD/2378 TCDF concentration by a factor of 3.33.	-	-
The skin surface area where the land application equipment operators would be exposed to 2378 TCDD and 2378 TCDF.	The exposed skin surface area was estimated by PEI to be 100 percent of palm and finger surfaces of both hands. The high and low represent the difference between the surface area of men's and women's hands. The exposed skin surface area is 250 cm^2 for females and 300 cm^2 for males (NCASI 1988).	The exposed skin surface area could potentially include exposure to both hands (front and back) and exposure to the forearms. Therefore, the skin surface area would increase to 2600 cm^2 (Popendorf 1982).	Exposure would range from 10 to 10.4 times greater exposure.
Dermal exposure duration for land application equipment operators.	The duration of the exposure was assumed to be 1 hour since the operator will not be in contact with wet sludge unless maintenance is required.	Reasonable range in the duration would be 0.5 to 2 hours.	Exposure would range from 0.5 to 2 times the exposure level.

3.1.2.3 Distribution of Sludge as a Saleable Product--

In heat-drying operations, which are used to dry the sludge so that it can be further processed into fertilizer, exposure to 2378 TCDD and 2378 TCDF may occur primarily through inhalation of particles entrained in the air during handling and conveying of the dried sludge to storage and distribution. Inhalation exposure will also occur in fertilizer manufacturing operations in which grinding, screening, and bagging of the dried sludge will produce particulate matter emissions. Dermal exposure to 2378 TCDD and 2378 TCDF may occur at the mills through cleanup and emergency maintenance, but is more likely in fertilizer manufacturing operations in which the sludge is much further processed. Dermal and inhalation exposures for this type of operation are not estimated because only one of the mills practices flash drying.

Equipment operators may be exposed to 2378 TCDD and 2378 TCDF by inhalation of particulate matter generated during composting operations. Particulate matter, which may be inhaled by the equipment operator, is generated during unloading of sludge, its placement in a window or pile, mixing bulking agents with the sludge, turning and mixing of the compost piles, removal of compost from piles and unloading at the screening operations, loading compost into the screens, and loading screened compost into piles and eventually into trucks for distribution. In addition, the equipment operators may inhale 2378 TCDD and 2378 TCDF which has volatilized from the wet sludge. It is estimated that the equipment operators may be exposed to 2378 TCDD and 2378 TCDF by inhalation throughout their 8-hour shift because their only job function is to operate equipment which is continuously in contact with the sludge/compost and operations are done in open areas.

Dermal exposure of equipment operators to the sludge/compost is minimal. It is estimated that the time of dermal exposure for the equipment operators is only 1 hour per shift because they are generally not in contact with the sludge/compost unless maintenance of the equipment is required.

The screen operators may be exposed to 2378 TCDD and 2378 TCDF via inhalation of particulate matter generated during screening of the compost. In addition, exposure may also occur from volatilization of 2378 TCDD and 2378 TCDF in the compost. It is estimated that the screen operators may be exposed via inhalation throughout their 8-hour shift because their major job function is to oversee screening operations which are generally conducted in an open area.

Dermal exposure of screen operators to the compost occurs during routine maintenance of the screen, such as unplugging, which occurs when the compost is too wet, and cleaning of any spilled material. It is estimated that the time of dermal exposure is 4 hours per shift assuming that screen cleaning and maintenance activities involve half of the 8-hour shift of the screen operators.

Compost haulers may be exposed to 2378 TCDD and 2378 TCDF through loading and unloading of the compost from the dump truck. After the dump truck is loaded with compost, the compost hauler transports it to farms or facilities which further process the compost, and unloads it. Exposure to 2378 TCDD and 2378 TCDF may occur through inhalation of particulate matter generated during compost loading and unloading, and from volatilization of 2378 TCDD and 2378 TCDF from the compost. Dermal exposure to 2378 TCDD and 2378 TCDF occurs during maintenance activities. It is estimated that these workers may be exposed through volatilization and inhalation of particulate matter for 4 hours per shift assuming loading and unloading activities involve half of the work time during an 8-hour shift. The compost hauler is assumed to spend the other half of his shift in transit. The time for dermal exposure for the compost haulers is estimated to be 1 hour per shift, because they will generally not be in contact with the compost unless maintenance is required. Compost is initially wet and then dried. As a worst case exposure assessment, the handling of dry material was used in dermal exposure calculations.

It was assumed that loading and unloading of the compost by the compost hauler is conducted daily throughout the year. It is possible that these operations could be seasonal, but PEI assumed, for worst-case conditions, that the operations were performed daily.

The following is an estimation of both inhalation and dermal exposures for equipment operators, screen operators, and compost haulers. The concentrations of 2378 TCDD and 2378 TCDF in sludge used in the exposure calculations for workers in composting operations are the low and high concentrations reported in the 104-Mill Study data for the sludges which are disposed of by distribution as a salable product corresponding to the calculated low and high TEQ. The mills which practice distribution of sludge as a salable product were identified in the 104-Mill Study data provided by EPA. Particulate matter emissions from compost handling operations were calculated using AP-42 equations and National Emission Data System (NEDS) emission factors, which are documented in Appendix E.

Particulate matter emissions from unloading and loading, screening, and mixing of sludge and compost were calculated using emission factors from

AP-42 (EPA 1985 and EPA 1988d) and NEDS (Stockton and Stelling 1987 and EPA 1988c). The emission factor for unloading and loading various materials is presented in Section 11.2.3 of AP-42 (EPA 1988d). This emission factor was used because the methodology to calculated PCDD/PCDF releases from particulate matter presented in EPA 1988b use particulate matter emission factors taken from AP-42 (EPA 1985 and EPA 1988d). The emission factors for screening and mixing of sludge and compost were taken from NEDS for conveying and screening of sand and aggregates. These emission factors were used as default emission factors because none exist for compost and sludge screening and mixing. The emissions from screening appeared to be overestimated by the emission factor used. In this instance, the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) of 15 mg/m^3 (8-hour time-weighted average) for nuisance dust was used for ambient particulate concentration.

Level of inhalation exposure--In composting operations, there are three job categories (equipment operators, screen operators, and compost haulers) potentially exposed to PCDDs and PCDFs through inhalation of vapors and particulate matter containing dioxin and dibenzofuran. All equipment operators and screen operators were assumed to be exposed for the entire 8 hours of their shift. Compost haulers were assumed to be exposed for half of their 8-hour shift (i.e., a total of 4 hours).

The same calculation procedures previously employed to estimate inhalation exposure to PCDDs and PCDFs by vaporization (using Equations 3 through 8) and particulate matter generation (using Equation 12) for waste treatment plant operators and sludge haulers/front-end loader operators were used to estimate inhalation exposure to equipment operators, screen operators, and compost haulers in composting operations. Appendix E presents the calculation of particulate emission rates (based on AP-42 emission factors), equivalent length of the area source, and particulate concentrations used in the exposure estimations. Table 3-27 summarizes the variables used to calculate inhalation exposure for the composting operation workers from volatilization of PCDDs and PCDFs from wet sludge/compost and presents subsequent exposure estimates.

The relative toxicity of 2378 TCDF in respect to 2378 TCDD can be determined by calculating TEQ values. In addition, the percent exposure due to 2378 TCDD can also be calculated. Using equations 9 and 10 these two variables are calculated. Table 3-28 presents the daily and lifetime average daily TEQ and percent exposure due to 2378 TCDD from volatilization from wet sludge/compost for composting operation workers. Table 3-29 presents the assumptions and uncertainties in the variables used to calculate the daily exposure for composting operation workers from volatilization in Table 3-27.

Table 3-30 summarizes the variables for inhalation of particulate matter generated from sludge/compost unloading and loading, turning, mixing, and screening operations. It presents estimated daily inhalation exposure to 2378 TCDD and 2378 TCDF for composting operation workers from particulate matter.

The relative toxicity of 2378 TCDF with respect to 2378 TCDD can be determined by calculating TEQ values. The percent exposure due to 2378 TCDD can also be calculated. Equations 9 and 10 are used to calculate these two variables. In these two equations, the daily inhalation exposure from volatilization (Iv) for 2378 TCDD and 2378 TCDF are replaced with the daily exposure from particulate matter (Ip) for 2378 TCDD and 2378 TCDF. Table 3-31 presents the daily and lifetime average daily TEQ and percent exposure due to 2378 TCDD from particulate matter for composting operation workers.

TABLE 3-27. ESTIMATED INHALATION EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR COMPOSTING OPERATION WORKERS FROM VOLATILIZATION

Variable	2378 TCDD Low	2378 TCDD High	2378 TCDF Low	2378 TCDF High	Reference
Henry's Law Constant, atm-m³/mole (Hc)	1.6×10^{-5}	1.6×10^{-5}	8.6×10^{-5}	8.6×10^{-5}	Abt 1989
Soil/water partition coefficient, mg/g in soil per mg/cm³ in water (Kd)	1.4×10^{6}	1.4×10^{6}	4900	4900	Abt 1989
Air/soil partition coefficient, mg/cm³ in air per mg/g in soil (K_{as})	4.7×10^{-10}	4.7×10^{-10}	7.2×10^{-7}	7.2×10^{-7}	Calculated
Molecular diffusivity of 2378 TCDD/2378 TCDF in air, cm²/s (Di)	0.047	0.047	0.048	0.048	Abt 1989
Effective porosity of soil, unitless (E)	0.25	0.25	0.25	0.25	Abt 1989
True density of soil g/cm³ (RHO_s)	2.65	2.65	2.65	2.65	Abt 1989
Intermediate variable to calculate rate of emission from the soil surface, cm²/s (ALPHA)	1.8×10^{-12}	1.8×10^{-12}	2.7×10^{-9}	2.7×10^{-9}	Calculated
Initial 2378 TCDD/2378 TCDF concentration in the soil on a dry basis, g/g (C_{so})	3.3×10^{-12}	1.01×10^{-10}	3.9×10^{-11}	1.57×10^{-9}	104-Mill study data
Duration of exposure, s (T)	2.21×10^{9}	2.21×10^{9}	2.21×10^{9}	2.21×10^{9}	Abt 1989
Emission rate of 2378 TCDD/2378 TCDF from the soil surface, g/cm²-s	2.1×10^{-22}	6.4×10^{-21}	9.7×10^{-20}	3.9×10^{-18}	Calculated

(continued)

TABLE 3-27 (continued)

Variable	2378 TCDD Low	2378 TCDD High	2378 TCDF Low	2378 TCDF High	Reference
Surface area, cm^2 (A)					
- Equipment operators	$6.5x10^8$	$6.5x10^8$	$6.5x10^8$	$6.5x10^8$	See Table 3-29
- Haulers	29,729	29,729	29,729	29,729	See Table 3-29
- Screen operators	177,600	177,600	177,600	177,600	See Table 3-29
Generation rate, g/s (G)					
- Equipment operators	$1.4x10^{-13}$	$4.1x10^{-12}$	$6.3x10^{-11}$	$2.5x10^{-9}$	Calculated
- Haulers	$6.2x10^{-18}$	$1.9x10^{-16}$	$2.9x10^{-15}$	$1.2x10^{-13}$	Calculated
- Screen operators	$3.7x10^{-17}$	$1.1x10^{-15}$	$1.7x10^{-14}$	$7.0x10^{-13}$	Calculated
Molecular weight, g/g-mole (M)	322	322	306	306	EPA 1989c
Equivalent side length of the area source perpendicular to the direction of the wind, m (L)					
- Equipment operators	254.4	254.4	254.4	254.4	Appendix E
- Haulers	2.44	2.44	2.44	2.44	Appendix E
- Screen operators	6	6	6	6	Appendix E
Mixing height of the vapors before inhalation by an individual, m (MH)	1.5	1.5	1.5	1.5	EPA 1988b
Average wind speed at the inhalation height, m (V)	2.2	2.2	2.2	2.2	EPA 1988b

(continued)

TABLE 3-27 (continued)

Variable	2378 TCDD Low	2378 TCDD High	2378 TCDF Low	2378 TCDF High	Reference
Concentration of 2378 TCDD/2378 TCDF in the vapor, mg/m³ (Cm)					
- Equipment operators	$1.6x10^{-13}$	$4.9x10^{-12}$	$7.5x10^{-11}$	$3.0x10^{-9}$	Calculated
- Haulers	$7.7x10^{-16}$	$2.4x10^{-14}$	$3.6x10^{-13}$	$1.4x10^{-11}$	Calculated
- Screen operators	$1.9x10^{-15}$	$5.7x10^{-14}$	$8.7x10^{-13}$	$3.5x10^{-11}$	Calculated
Exposure duration, h/day (ED)					
- Equipment operators	8	8	8	8	See Table 3-29
- Haulers	4	4	4	4	See Table 3-29
- Screen operators	8	8	8	8	See Table 3-29
Daily inhalation, mg/day (Iv)					
- Equipment operators	$1.6x10^{-12}$	$4.9x10^{-11}$	$7.5x10^{-10}$	$3.0x10^{-8}$	Calculated
- Haulers	$3.8x10^{-15}$	$1.2x10^{-13}$	$1.8x10^{-12}$	$7.2x10^{-11}$	Calculated
- Screen operators	$1.9x10^{-14}$	$5.7x10^{-13}$	$8.7x10^{-12}$	$3.5x10^{-10}$	Calculated

TABLE 3-28. ESTIMATED TOXICITY EQUIVALENTS AND PERCENT EXPOSURE DUE TO 2378 TCDD FOR COMPOSTING OPERATION WORKERS FROM VOLATILIZATION

Job category	Daily TEQ, mg/day (DTEQv)[a]		Lifetime average daily TEQ, mg/day-kg (LTEQv)[a]	
	Low	High	Low	High
Equipment operators	7.7×10^{-11} (0.2%)	3.1×10^{-9} (0.2%)	4.3×10^{-13} (0.2%)	2.1×10^{-11} (0.2%)
Haulers	1.8×10^{-13} (0.2%)	7.4×10^{-12} (0.2%)	1.0×10^{-15} (0.2%)	5.0×10^{-14} (0.2%)
Screen operators	8.9×10^{-13} (0.2%)	3.6×10^{-11} (0.2%)	5.0×10^{-15} (0.2%)	2.4×10^{-13} (0.2%)

[a] Values in parentheses are percent exposure due to 2378 TCDD.

TABLE 3-29. ASSUMPTIONS AND UNCERTAINTIES IN ESTIMATING INHALATION EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR COMPOSTING OPERATION WORKERS FORM VOLATILIZATION

Uncertainty	Associated assumption	Reasonable possible variance of assumption	Effects on results
The open surface area where the equipment operator would be exposed to 2378 TCDD and 2378 TCDF.	Composting area was calculated using a land area requirement of 1 acre per 5 dry tons of sludge (EPA 1979) and 80.5 dry tons per day processed (104-Mill Study).	Reasonable range of a land application requirement is 1 acre/3 dry tons to 1 acre/5 dry tons.	Exposures would range from 0.6 to 1.0 times greater exposure.
The open surface area where the haulers would be exposed to 2378 TCDD and 2378 TCDF.	The open surface area of a dump truck was assumed to be 4 ft x 8 ft on a 6-yd^3 truck.	-	-
The open surface area where the screen operator would be exposed to 2378 TCDD and 2378 TCDF.	The open surface area of was based on the larger screen area of 17.5 m^2 (Kirk-Othmer 1981).	-	-
Inhalation exposure duration for equipment operator.	The duration of the exposure was assumed to be 8 hours since this would be the worst case exposure duration.	-	-

(continued)

TABLE 3-29 (continued)

Uncertainty	Associated assumption	Reasonable possible variance of assumption	Effects on results
Inhalation exposure duration for hauler.	The duration of the exposure was assumed to be 4 hours since the operator conducts loading operations for 1/2 the shift.	Reasonable range in the duration would be 2 to 8 hours.	Exposure would range from 0.5 to 2 times greater exposure.
Inhalation exposure duration for screen operator.	The duration of the exposure was assumed to be 8 hours since this would be the worst case exposure duration.	-	-

TABLE 3-30. ESTIMATED INHALATION EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR COMPOSTING OPERATION WORKERS FROM PARTICULATE MATTER

Variable	2378 TCDD		2378 TCDF		Reference
	Low	High	Low	High	
Concentration of particulate matter, mg/m³ (Cm)[a]					
- Equipment operators	2.36	2.36	2.36	2.36	Calculated (see Appendix E)
- Haulers	0.59	0.59	0.59	0.59	Calculated (see Appendix E)
- Screen operators	15	15	15	15	OSHA PEL for nuisance dust
Amount of 2378 TCDD/2378 TCDF in the dry sludge, dry basis (WF)	3.3×10^{-12}	1.01×10^{-10}	3.9×10^{-11}	1.57×10^{-9}	104-Mill Study data
Exposure duration, h/day (ED)					
- Equipment operators	8	8	8	8	Engineering judgment[b]
- Haulers	4	4	4	4	Engineering judgment[c]
- Screen operators	8	8	8	8	Engineering judgment[b]
Daily inhalation, mg/day (Ip)					
- Equipment operators	7.8×10^{-11}	2.4×10^{-9}	9.2×10^{-10}	3.7×10^{-8}	Calculated
- Haulers	9.7×10^{-12}	3.0×10^{-10}	1.2×10^{-10}	4.6×10^{-9}	Calculated
- Screen operators	4.9×10^{-10}	1.5×10^{-8}	5.9×10^{-9}	2.4×10^{-7}	Calculated

[a] These concentrations are below the OSHA nuisance dust standard of 15 mg/m³.

[b] The exposure duration was assumed to be 8 hours per day since this would be the worst case exposure duration.

[c] The haulers would be exposed to particulate matter during handling to the compost. Since the haulers spend approximately half of the shift loading and unloading compost, it was estimated the workers would be exposed to particulate matter for 4 hours per day.

TABLE 3-31. ESTIMATED TOXICITY EQUIVALENTS AND PERCENT EXPOSURE DUE TO 2378 TCDD FOR COMPOSTING OPERATION WORKERS FROM PARTICULATE MATTER

Job category	Daily TEQ, mg/day (DTEQp)[a]		Lifetime average daily TEQ, mg/day-kg (LTEQp)[a]	
	Low	High	Low	High
Equipment operators	1.7×10^{-10} (8%)	6.1×10^{-9} (6%)	9.5×10^{-13} (8%)	4.1×10^{-11} (6%)
Haulers	2.1×10^{-11} (8%)	7.6×10^{-10} (6%)	1.2×10^{-13} (8%)	5.1×10^{-12} (6%)
Screen operators	1.1×10^{-9} (8%)	3.9×10^{-8} (6%)	6.0×10^{-12} (8%)	2.6×10^{-10} (6%)

[a] Values in parentheses are percent exposure due to 2378 TCDD.

Level of dermal exposure--Dermal exposure levels to PCDDs and PCDFs was based on the assumption that the composting operation workers do not wear any types of gloves that are effective in limiting exposure to PCDDs and PCDFs. The workers are potentially in contact with both wet and dry compost. As a worst case, the workers were assumed to be handling dry compost. The same calculation procedure as used to estimate dermal exposure for waste treatment plant operators and haulers/front-end loader operators was used to estimate dermal exposure levels for the workers handling dry compost.

The 2378 TCDD and 2378 TCDF concentrations for compost from Table 2-5 are reported on a dry basis. Since the workers are assumed to be handling dry compost as a worst-case assumption, these values are used directly in Equation 14 for estimating dermal exposure to compost operators.

Dermal exposure duration was based on engineering judgment. It was assumed that only the palms and fingers of both hands of the equipment operator and compost hauler are in contact with the dry compost, whereas it is assumed that both the hands and forearms of the screen operator are in contact with the dry compost. The density of the compost is 513.2 mg/cm^3 and a liquid film thickness for the compost was estimated to be 0.25 mm. Table 3-32 summarizes the variables and results for dermal exposure for composting operation workers.

The relative toxicity of 2378 TCDF in respect to 2378 TCDD can be determined by calculating TEQ values. The percent exposure due to 2378 TCDD can also be calculated. Equations 9 and 10 are used to calculate these two variables. In these two equations, the daily inhalation exposure from volatilization (Iv) for 2378 TCDD and 2378 TCDF are replaced with the daily dermal exposure (DED) for 2378 TCDD and 2378 TCDF. Table 3-33 presents the daily and lifetime average daily TEQ and percent exposure due to 2378 TCDD from dermal exposure for composting operation workers. Table 3-34 presents

TABLE 3-32. ESTIMATED DERMAL EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR COMPOSTING OPERATION WORKERS

Variable	2378 TCDD		2378 TCDF		Reference
	Low	High	Low	High	
2378 TCDD/2378 TCDF concentration of dry compost, dry basis, ppt (DC)	3.3	101	39	1,570	104-Mill Study data
Density of the compost, mg/cm³ (ρ)	513.2	513.2	513.2	513.2	EPA 1979
Liquid film thickness of the compost, cm (FT)	0.025	0.025	0.025	0.025	See Table 3-10
Bioavailability factor for soil, unitless (B)	0.01	0.01	0.01	0.01	EPA 1989d
Absorption coefficient of TCDD/TCDF through the skin, h^{-1} (AD)	0.012	0.012	0.012	0.012	EPA 1989d
Skin surface area, cm² (S)					
- Equipment operators	250	300	250	300	See Table 3-34
- Haulers	250	300	250	300	See Table 3-34
- Screen operators	2,600	2,600	2,600	2,600	See Table 3-34
Exposure duration, h/day (ED)					
- Equipment operators	1	1	1	1	See Table 3-34
- Haulers	1	1	1	1	See Table 3-34
- Screen operators	4	4	4	4	See Table 3-34
Dermal exposure, mg/day (DED)					
- Equipment operators	1.3×10^{-12}	4.7×10^{-11}	1.5×10^{-11}	7.3×10^{-10}	Calculated
- Haulers	1.3×10^{-12}	4.7×10^{-11}	1.5×10^{-11}	7.3×10^{-10}	Calculated
- Screen operators	5.3×10^{-11}	1.6×10^{-9}	6.2×10^{-10}	2.5×10^{-8}	Calculated

TABLE 3-33. ESTIMATED TOXICITY EQUIVALENTS AND PERCENT EXPOSURE DUE TO 2378 TCDD FOR COMPOSTING OPERATION WORKERS FROM DERMAL EXPOSURE

Job category	Daily TEQ, mg/day (DTEQd)[a]		Lifetime average daily TEQ, mg/day-kg (LTEQd)[a]	
	Low	High	Low	High
Equipment operators	2.8×10^{-12} (8%)	1.2×10^{-10} (6%)	1.5×10^{-14} (8%)	8.0×10^{-13} (6%)
Haulers	2.8×10^{-12} (8%)	1.2×10^{-10} (6%)	1.5×10^{-14} (8%)	8.0×10^{-13} (6%)
Screen operators	1.2×10^{-10} (8%)	4.1×10^{-9} (6%)	6.4×10^{-13} (8%)	2.8×10^{-11} (6%)

[a] Values in parentheses are percent exposure due to 2378 TCDD.

TABLE 3-34. ASSUMPTIONS AND UNCERTAINTIES IN ESTIMATING DERMAL EXPOSURE TO 2378 TCDD AND 2378 TCDF FOR COMPOSTING OPERATION WORKERS

Uncertainty	Associated assumption	Reasonable possible variance of assumption	Effects on results
The skin surface area where the equipment operators and haulers would be exposed to 2378 TCDD and 2378 TCDF.	The exposed skin surface area was estimated by PEI to be 100 percent of palm and finger surfaces of both hands. The high and low represent the difference between the surface area of a men's and women's hands. The exposed skin surface area is 250 cm^2 for females and 300 cm^2 for males (NCASI 1988).	The exposed skin surface area could potentially include exposure exposure to both hands (front and back) and exposure to the forearms. Therefore, the skin surface area would increase to 2,600 cm^2 (Popendorf 1982).	Exposure would range from 10 to 10.4 times greater exposure.
The skin surface area where the screen operator would be exposed to 2378 TCDD and 2378 TCDF.	The exposed skin surface area was estimated by PEI to be both hands (front and back) and exposure to the forearms. Therefore, the skin surface area would be 2,600 cm^2 (Poppendorf 1982).	-	-
Dermal exposure duration for equipment operators and haulers.	The duration of the exposure was assumed to be 1 hour since the operators will not be in contact with dry compost unless maintenance is required.	Reasonable range in the duration would be 0.5 to 2 hours.	Exposure would range between 0.5 to 2 times greater exposure.

(continued)

TABLE 3-34 (continued)

Uncertainty	Associated assumption	Reasonable possible variance of assumption	Effects on results
Dermal exposure duration for screen operators.	The duration of the exposure was assumed to be 4 hours since the operators will spend half the shift on maintenance of the screen, cleanup of spills, and other maintenance activities.	Reasonable range in the duration would be 2 to 6 hours.	Exposure would range between 0.5 to 1.5 times greater exposure.

the assumptions and uncertainties in the variables used to calculate the dermal exposures for composting operation workers in Table 3-32.

3.2 PERSONAL PROTECTIVE EQUIPMENT AND CONTROLS

Use of protective equipment such as protective clothing or gloves, eye shields, and respirators for minimizing exposure to PCDDs and PCDFs during sludge handling and disposal operations was not mentioned in the literature. In general, respirators are never worn during these operations; however, their use is recommended during composting operations (EPA 1979). Protective clothing and gloves may be worn during sampling and maintenance activities but are only used for the prevention of soiling of employee clothes rather than prevention of exposure to PCDDs and PCDFs by dermal contact (Fisher 1989). The gloves, however, are not effective in limiting exposures to PCDDs and PCDFs.

Use of control equipment to minimize worker exposure to dioxins was not mentioned in the literature. Particulate control devices such as scrubbers, electrostatic precipitators and fabric filters are used to control particulate emissions from drying and incineration operations. These controls, however, are used to meet National Ambient Air Quality Standards (NAAQS) for particulate matter rather than to protect workers. Landfilling and composting operations may use water to control dust during dry conditions; workers may also be supplied with respirators during such conditions (EPA 1979). Watering may reduce particulate matter emissions by 50 percent. Control equipment for worker protection such as hoods and enclosed operations may be used when sludge is further processed such as in conveying, grinding, and bagging of compost and dried sludge prior to or during fertilizer manufacture. Because of the unknown extent of utilization and efficiency of any associated control equipment, no reductions were computed for inhalation or dermal exposure levels for PCDDs and PCDFs.

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

PCDDs and PCDFs are present in primary and secondary sludges formed during wastewater treatment operations at pulp and paper mills, thereby resulting in a potential for worker exposure to these chemicals in the processing and commercial use of pulp and paper mill sludge. Two studies have quantified their presence in sludge: the 5-Mill and 104-Mill studies. Results from the 5-Mill Study showed that concentrations in primary, secondary, and combined dewatered sludge ranged from 17 to 710 ppt for 2378 TCDD and 32 to 10,900 ppt for 2378 TCDF, with the largest concentrations reported in secondary sludge samples. Results from the 104-Mill Study showed that concentrations corresponding to the calculated low and high TEQ in combined dewatered sludges ranged from 0.7 to 1390 ppt for 2378 TCDD and 3.0 to 17,100 ppt for 2378 TCDF. It also showed that concentration in non-dewatered sludges ranged from 6 to 4500 ppq for 2378 TCDD and 6 to 14,000 ppq for 2378 TCDF.

Workers involved in pulp and paper mill sludge processing and commercial use of the sludge may be exposed to 2378 TCDD and 2378 TCDF via three major routes: 1) dermal contact with wet or dry sludge and compost during maintenance of equipment and performance of job functions; 2) inhalation of particulate matter generated by sludge and compost handling during sludge processing, landfilling, land application, and composting operations involving unloading, loading, spreading, burying, or screening of the materials; and 3) inhalation of 2378 TCDD and 2378 TCDF volatilized from the sludge and/or compost.

Although considerable data have been collected on concentrations of 2378 TCDD and 2378 TCDF for pulp, sludge, and wastewaters in the pulp and paper industry, no inhalation or dermal exposure data for 2378 TCDD and 2378 TCDF are currently available. This in part because of the lack of a validated sampling and analytical method for measuring worker exposure to these chemicals. PEI resorted to modeling techniques based on a number of assumptions in order to estimate inhalation and dermal exposure to 2378 TCDD and 2378 TCDF. A range (i.e., low and high values) of exposure and risk estimates are presented for each industry/worker scenario and exposure route.

The model used in this report for estimating exposures to 2378 TCDD/2378 TCDF vapors utilizes a mass balance approach to estimate worker exposures from an area source for specific activities. It should be noted that the inhalation exposure estimates do not include any quantitative reductions in volatilization of 2378 TCDD and 2378 TCDF due to binding with organic matter and from interference due to other chemicals present in the sludge or compost because of a lack of available data regarding these effects; thus, the inhalation exposure values should be interpreted as worst-case estimates.

Data were not available on the amount of particulates generated during sludge handling operations such as loading/unloading, spreading, compacting, plowing into the soil, and composting. Appendices B through E present the methodology and assumptions used in estimating the amount of particulates generated during sludge processing/handling, landfilling operations, land application, and composting operations; the widely used AP-42 emission factors were utilized for these estimates. In addition, no data were available on the amount of 2378 TCDD and 2378 TCDF in the particulates; therefore, it was assumed that the concentration of 2378 TCDD and 2378 TCDF in the sludge was equal to that in the particulates. This approach again assumes a worst-case exposure level for 2378 TCDD and 2378 TCDF.

There were no data available on dermal exposures for workers handling pulp and paper mill sludge. PEI estimated dermal exposure based on a CPSC model. This model considers the partitioning of PCDD/PCDF from the appropriate matrix (e.g., soil, sludges, paper) to a liquid (i.e., waste, skin soil, urine, blood) and percutaneous absorption of PCDDs and PCDFs from the liquid. This model pertains to the handling of sludge/soil. PEI assumed worst case exposure durations when no data on the duration of exposure were available.

Table 4-1 summarizes the 2378 TCDD and 2378 TCDF daily inhalation and dermal exposure levels estimated in this report for workers involved in processing and commercial usage of pulp and paper mill sludge. Table 4-2 summarizes daily toxicity equivalents, lifetime average daily toxicity equivalents, and the percentage exposure due to 2378 TCDD estimated in this report for workers involved in processing and commercial usage of pulp and paper mill sludge. Appendix F presents the methodology for the calculation of average and population risks for workers involved in the processing and commercial use of pulp and paper mill sludge. Table 4-3 summarizes the average and population risks estimated in this report based on lifetime average daily toxicity equivalents for workers involved in processing and commercial usage of pulp and paper mill sludge.

There are several data needs for developing more refined estimates on worker exposure to PCDDs and PCDFs for pulp and paper mill sludge processing and commercial use. Some areas in which additional information is needed include the following: 1) characterization of worker activities; 2) the

TABLE 4-1. SUMMARY OF 2378 TCDD AND 2378 TCDF DAILY INHALATION AND DERMAL EXPOSURE ESTIMATES FOR WORKERS INVOLVED IN PROCESSING AND COMMERCIAL USAGE OF PULP AND PAPER MILL SLUDGE

			Daily exposure values (mg/day/worker)					
			2378 TCDD		2378 TCDF			
Job category	No. of workers	Exposure type	Low	High	Low	High	Duration of exposure (h/day)	Frequency of exposure (days/yr)
Sludge handling/processing - Sludge haulers/front-end loader operators	400	Inhalation-volatilization	8.1×10^{-16}	1.6×10^{-12}	1.4×10^{-13}	7.9×10^{-10}	4	250
		Inhalation-particulate matter	5.9×10^{-14}	1.2×10^{-10}	2.6×10^{-13}	1.5×10^{-9}	4	250
		Dermal	2.5×10^{-12}	6.0×10^{-9}	1.1×10^{-11}	7.3×10^{-8}	1	250
- Waste treatment plant operators	1300	Inhalation-volatilization	2.1×10^{-15}	4.1×10^{-12}	3.5×10^{-13}	2.0×10^{-9}	4	250
		Inhalation-particulate matter	8.3×10^{-15}	1.7×10^{-11}	3.6×10^{-14}	2.0×10^{-10}	1	250
		Dermal	5.2×10^{-11}	1.0×10^{-7}	2.2×10^{-10}	1.3×10^{-6}	2	250
Landfilling operations - Equipment operators	400	Inhalation-volatilization	1.9×10^{-14}	1.9×10^{-11}	3.2×10^{-12}	1.2×10^{-8}	8	250
		Inhalation-particulate matter	4.3×10^{-12}	4.4×10^{-9}	1.9×10^{-11}	6.8×10^{-8}	8	250
		Dermal	2.5×10^{-12}	3.1×10^{-9}	1.1×10^{-11}	4.7×10^{-8}	1	250
Land application operations - Equipment operators	20	Inhalation-volatilization	9.2×10^{-13}	5.4×10^{-11}	1.5×10^{-10}	3.9×10^{-9}	8	250
		Inhalation-particulate matter	4.3×10^{-10}	2.5×10^{-8}	1.8×10^{-9}	4.6×10^{-8}	8	250
		Dermal	4.7×10^{-11}	3.2×10^{-9}	2.0×10^{-10}	6.0×10^{-9}	1	250
Composting operations - Equipment operators	150	Inhalation-volatilization	1.6×10^{-12}	4.9×10^{-11}	7.5×10^{-10}	3.0×10^{-8}	8	250
		Inhalation-particulate matter	7.8×10^{-11}	2.4×10^{-9}	9.2×10^{-10}	3.7×10^{-8}	8	250
		Dermal	1.3×10^{-12}	4.7×10^{-11}	1.5×10^{-11}	7.3×10^{-10}	1	250

(continued)

TABLE 4-1 (continued)

Job category	No. of workers	Exposure type	Daily exposure values (mg/day/worker)				Duration of exposure (h/day)	Frequency of exposure (days/yr)
			2378 TCDD		2378 TCDF			
			Low	High	Low	High		
- Compost haulers	50	Inhalation-volatilization	$3.8x10^{-15}$	$1.2x10^{-13}$	$1.8x10^{-12}$	$7.2x10^{-11}$	4	250
		Inhalation-particulate matter	$9.7x10^{-12}$	$3.0x10^{-10}$	$1.2x10^{-10}$	$4.6x10^{-9}$	4	250
		Dermal	$1.3x10^{-12}$	$4.7x10^{-11}$	$1.5x10^{-11}$	$7.3x10^{-10}$	1	250
- Screen operators	20	Inhalation-volatilization	$1.9x10^{-14}$	$5.7x10^{-13}$	$8.7x10^{-12}$	$3.5x10^{-10}$	8	250
		Inhalation-particulate matter	$4.9x10^{-10}$	$1.5x10^{-8}$	$5.9x10^{-9}$	$2.4x10^{-7}$	8	250
		Dermal	$5.3x10^{-11}$	$1.6x10^{-9}$	$6.2x10^{-10}$	$2.5x10^{-8}$	4	250

TABLE 4-2. SUMMARY OF DAILY TOXICITY EQUIVALENTS, LIFETIME AVERAGE DAILY TOXICITY EQUIVALETS, AND PERCENTAGE EXPOSURE DUE TO 2378 TCDD FOR WORKERS INVOLVED IN PROCESSING AND COMMERCIAL USAGE OF PULP AND PAPER MILL SLUDGE

Job category	No. of workers	Exposure type	Toxicity equivalents per worker[a] Daily TEQ, mg/day Low	High	Lifetime average daily TEQ, mg/day-kg Low	High	Duration of exposure (h/day)	Frequency of exposure (days/yr)
Sludge handling/processing - Sludge haulers/front-end loader operators	400	Inhalation-volatilization	1.5×10^{-14} (0.6)	8.0×10^{-11} (0.2)	8.2×10^{-17}	5.4×10^{-13}	4	250
		Inhalation-particulate matter	8.5×10^{-14} (19)	2.6×10^{-10} (8)	4.8×10^{-16}	1.8×10^{-12}	4	250
		Dermal	3.6×10^{-12} (19)	1.3×10^{-8} (8)	2.0×10^{-14}	9.0×10^{-11}	1	250
- Waste treatment plant operators	1300	Inhalation-volatilization	3.7×10^{-14} (0.6)	2.0×10^{-10} (0.2)	2.1×10^{-16}	1.4×10^{-12}	4	250
		Inhalation-particulate matter	1.2×10^{-14} (19)	3.7×10^{-11} (8)	6.6×10^{-17}	2.5×10^{-13}	1	250
		Dermal	7.4×10^{-11} (19)	2.3×10^{-7} (8)	4.2×10^{-13}	1.6×10^{-9}	2	250
Landfilling operations - Equipment operators	400	Inhalation-volatilization	3.4×10^{-13} (0.6)	1.2×10^{-9} (0.2)	1.9×10^{-15}	8.0×10^{-12}	8	250
		Inhalation-particulate matter	6.2×10^{-12} (19)	1.1×10^{-8} (6)	3.5×10^{-14}	7.5×10^{-11}	8	250
		Dermal	3.6×10^{-12} (19)	7.7×10^{-9} (6)	2.0×10^{-14}	5.2×10^{-11}	1	250
Land application operations - Equipment operators	20	Inhalation-volatilization	1.6×10^{-11} (0.6)	4.5×10^{-10} (1)	9.2×10^{-14}	3.0×10^{-12}	8	250
		Inhalation-particulate matter	6.1×10^{-10} (19)	2.9×10^{-8} (35)	3.4×10^{-12}	2.0×10^{-10}	8	250
		Dermal	6.6×10^{-11} (19)	3.8×10^{-9} (35)	3.7×10^{-13}	2.6×10^{-11}	1	250
Composting operations - Equipment operators	150	Inhalation-volatilization	7.7×10^{-11} (0.2)	3.1×10^{-9} (0.2)	4.3×10^{-13}	2.1×10^{-11}	8	250
		Inhalation-particulate matter	1.7×10^{-10} (8)	6.1×10^{-9} (6)	9.5×10^{-13}	4.1×10^{-11}	8	250
		Dermal	2.8×10^{-12} (8)	1.2×10^{-10} (6)	1.5×10^{-14}	8.0×10^{-13}	1	250

(continued)

TABLE 4-2 (continued)

Job category	No. of workers	Exposure type	Toxicity equivalents per worker[a] Daily TEQ, mg/day Low	High	Lifetime average daily TEQ, mg/day-kg Low	High	Duration of exposure (h/day)	Frequency of exposure (days/yr)
- Compost haulers	50	Inhalation-volatilization	1.8×10^{-13} (0.2)	7.4×10^{-12} (0.2)	1.0×10^{-15}	5.0×10^{-14}	4	250
		Inhalation-particulate matter	2.1×10^{-11} (8)	7.6×10^{-10} (6)	1.2×10^{-13}	5.1×10^{-12}	4	250
		Dermal	2.8×10^{-12} (8)	1.2×10^{-10} (6)	1.5×10^{-14}	8.0×10^{-13}	1	250
- Screen operators	20	Inhalation-volatilization	8.9×10^{-13} (0.2)	3.6×10^{-11} (0.2)	5.0×10^{-15}	2.4×10^{-13}	8	250
		Inhalation-particulate matter	1.1×10^{-9} (8)	3.9×10^{-8} (6)	6.0×10^{-12}	2.6×10^{-10}	8	250
		Dermal	1.2×10^{-10} (8)	4.1×10^{-9} (6)	6.4×10^{-13}	2.8×10^{-11}	4	250

[a] Values in parentheses are percent exposures due to 2378 TCDD.

TABLE 4-3. SUMMARY OF AVERAGE AND POPULATION RISKS BASED ON LIFETIME AVERAGE DAILY TOXICITY EQUIVALENTS FOR WORKERS INVOLVED IN PROCESSING AND COMMERCIAL USAGE OF PULP AND PAPER MILL SLUDGE

			Estimated risk[a]			
			Average risk, unitless		Population risk cases/yr	
Job category	No. of workers	Exposure type	Low	High	Low	High
Sludge handling/processing						
- Sludge haulers/front-end loader operators	400	Inhalation-volatilization	2×10^{-11} (0.6)	2×10^{-7} (0.2)	8×10^{-10}	5×10^{-6}
		Inhalation-particulate matter	1×10^{-10} (19)	5×10^{-7} (8)	4×10^{-9}	2×10^{-5}
		Dermal	6×10^{-9} (19)	3×10^{-5} (8)	2×10^{-7}	8×10^{-4}
- Waste treatment plant operators	1300	Inhalation-volatilization	2×10^{-12} (0.6)	9×10^{-9} (0.2)	2×10^{-11}	9×10^{-8}
		Inhalation-particulate matter	2×10^{-11} (19)	7×10^{-8} (8)	2×10^{-10}	7×10^{-7}
		Dermal	1×10^{-7} (19)	4×10^{-4} (8)	1×10^{-6}	4×10^{-3}
Landfilling operations						
- Equipment operators	400	Inhalation-volatilization	5×10^{-10} (0.6)	2×10^{-6} (0.2)	5×10^{-9}	2×10^{-5}
		Inhalation-particulate matter	1×10^{-8} (19)	2×10^{-5} (6)	1×10^{-7}	2×10^{-4}
		Dermal	6×10^{-9} (19)	1×10^{-5} (6)	6×10^{-8}	1×10^{-4}
Land application operations						
- Equipment operators	20	Inhalation-volatilization	3×10^{-8} (0.6)	9×10^{-7} (1)	1×10^{-8}	4×10^{-7}
		Inhalation-particulate matter	1×10^{-6} (19)	6×10^{-5} (35)	5×10^{-7}	3×10^{-5}
		Dermal	1×10^{-7} (19)	7×10^{-6} (35)	5×10^{-8}	4×10^{-6}
Composting operations						
- Equipment operators	150	Inhalation-volatilization	1×10^{-7} (0.2)	6×10^{-6} (0.2)	5×10^{-7}	2×10^{-5}
		Inhalation-particulate matter	3×10^{-7} (8)	1×10^{-5} (6)	1×10^{-6}	4×10^{-5}
		Dermal	4×10^{-9} (8)	2×10^{-7} (6)	2×10^{-8}	9×10^{-7}
- Compost haulers	50	Inhalation-volatilization	3×10^{-10} (0.2)	1×10^{-8} (0.2)	4×10^{-10}	2×10^{-8}
		Inhalation-particulate matter	3×10^{-8} (8)	1×10^{-6} (6)	4×10^{-8}	2×10^{-6}
		Dermal	4×10^{-9} (8)	2×10^{-7} (6)	5×10^{-9}	3×10^{-7}
- Screen operators	20	Inhalation-volatilization	1×10^{-9} (0.2)	7×10^{-8} (0.2)	7×10^{-10}	3×10^{-8}
		Inhalation-particulate matter	2×10^{-6} (8)	7×10^{-5} (6)	9×10^{-7}	4×10^{-5}
		Dermal	2×10^{-7} (8)	8×10^{-6} (6)	9×10^{-8}	4×10^{-6}

[a] Values in parentheses are percent risk due to 2378 TCDD.

number of workers in different job categories; 3) the potential for worker exposure in the various sludge processing and disposal operations; 4) the frequency and duration of potential dermal and inhalation exposure to PCDDs and PCDFs from pulp and paper mill sludge processing and use; and 5) the extent of use and effectiveness of personal protective equipment and engineering controls in this industry. This information is also needed for operations which may not be affiliated with pulp and paper mills such as composting operations and processing of dried sludge for fertilizer manufacture. Most of the estimates regarding types and numbers of workers and duration of exposure used in this report were based upon parallels with municipal sludge-handling operations and engineering judgment.

There are some ongoing as well as planned studies which may clarify some of the uncertainties and fill some data gaps in this report. The 104-Mill Study has been completed; however, the data that was collected needs to be analyzed with respect to plant operating parameters such as sludge and pulp production rates, type of wood used (e.g., softwood, hardwood), pulping technology used (e.g. Kraft, sulfite), and quantity of bleaching chemical used. PEI is awaiting authorization to receive Toxic Substances Control Act (TSCA) Confidential Business Information (CBI) in order to perform additional analyses on data from the 104-Mill Study. The 25 Bleach Line Study by NCASI is expected to be completed in early 1990 and will provide 2378 TCDD and 2378 TCDF concentration data for sludges in addition to effluent, bleach plant filtrates, and intermediate and final pulps. Site visits to pulp and paper manufacturing operations as well as to affiliated or non-affiliated disposal or commercial sludge processing sites would also provide additional insight on the potential for exposure to workers when performing different activities.

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APPENDIX A

104-MILL STUDY: 2378 TCDD AND 2378 TCDF CONCENTRATIONS IN SLUDGE ON A DRY BASIS

Company & Location	Sludge (ppt)[a]	
	2378 TCDD	2378 TCDF
Alabama River Pulp		
Claiborne, AL	68.0	342.0
	73.0	393.0
	81.0	373.0
Alaska Pulp Corp.		
Sitka, AK	4.7	42.0
Appleton Papers, Inc.		
Roaring Springs, PA	5.0	113.0
Badger Paper Mills, Inc.		
Peshtigo, WI	36.0[b]	1800.0[b]
Boise Cascade Corp.		
Jackson, AL	18.0	147.0
	18.0	169.0
DeRidder, LA	280.0[b]	440.0[b]
St. Helens, OR	4.2	25.0
Rumford, ME	105.0	674.0
Wallula, WA	70.0	1490.0
International Falls, MN	24.0	380.0
	37.0	680.0
	710.0	10,900.0
Bowater Corp.		
Catawba, SC	620.0[b]	880.0[b]
Calhoun, TN	4500.0[b]	14,000.0[b]
Brunswick Pulp/Paper		
Brunswick, GA	33.0	62.0
Buckeye Cellulose (P&G)		
Perry, FL	12.0	40.0
Oglethorpe, GA	2.6	3.0
	2.6	6.1
Champion Intl. Corp.		
Lufkin, TX	17.0	32.0
	18.0	34.0
	36.0	78.0
Courtland, AL	215.0	923.0
Quinnesec, MI	95.0	735.0
Cantonment, FL	14.0	21.0
Houston, TX	106.0	144.0
Canton, NC	172.0	260.0

Company & Location	Sludge (ppt)[a]	
	2378 TCDD	2378 TCDF
Chesapeake Corp.		
West Point, VA	14.0	47.0
Consolidated Papers, Inc.		
Wisconsin Rapids, WI	54.0	330.0
	69.0	556.0
	134.0	679.0
Container Corp. of America		
Brewton, AL	16.0	34.0
Federal Paper Board Co.		
Augusta, GA	680.0[b]	1400.0[b]
Riegelwood, NC	2.9	3.3
	3.8	5.2
Gaylord Container		
Antioch, CA	101.0	1570.0
Georgia-Pacific Corp.		
Bellingham, WA	19.0	584.0
Crossett, AR	168.0	1680.0
	190.0[b]	710.0[b]
Palatka, FL	92.0[b]	410.0[b]
Woodland, ME	0.9[c]	7.3
Zachary, LA (Port Hudson)	17.0	421.0
Gilman Paper Co.		
St. Marys, GA	220.0[b]	610.0[b]
International Paper Co.		
Bastrop, LA	140.0	677.0
Erie, PA	0.7[c]	3.0
	0.9	3.1
Georgetown, SC	62.0	161.0
Jay, ME	180.0	760.0
Mobile, AL	108.0	617.0
Moss Point, MS	161.0	1020.0
Natchez, MS	14.0	78.0
Pine Bluff, AR	185.0	2940.0
Selma, AL	680.0[b]	2900.0[b]
Texarkana, TX	71.0	1000.0
	86.0	387.0
Ticonderoga, NY	59.0	267.0
	306.0	2470.0

Company & Location	Sludge (ppt)[a]	
	2378 TCDD	2378 TCDF
ITT-Rayonier, Inc.		
Fernandina Beach, FL	4.7	32.0
Hoquiam, WA	4.8	25.0
Jesup, GA	3.0	2.4
Port Angeles, WA	47.0	65.0
James River Corp.		
Berlin, NH	98.0	2170.0
	104.0	2930.0
Camas, WA	12.0	105.0
Clatskanie, OR	19.0	100.0
	89.0	810.0
Green Bay, WI	35.0	250.0
Old Town, ME	12.0	34.0
St. Francesville, LA	96.0	243.0
Butler, AL	330.0[b]	1100.0[b]
Kimberly-Clark Corp.		
Coosa Pines, AL	3800.0[b]	9200.0[b]
Leaf River Forest Products (Great Northern Nekoosa)		
New Augusta, MS	212.0	413.0
	756.0	1300.0
Lincoln Pulp/Paper		
Lincoln, ME	48.0	223.0
Longview Fibre Co.		
Longview, WA	69.0	437.0
Mead Corp.		
Chillicothe, OH	3.3	39.0
Escanaba, MI	125.0	574.0
Kingsport, TN	1.5[c]	25.0
Nekoosa Papers, Inc. (Great Northern Nekoosa)		
Ashdown, AR	13.0	30.0
Nekoosa and Port Edwards, WI	109.0	1300.0
Pentair, Inc.		
Park Falls, WI	9.4	90.0
	11.0	73.0

Company & Location	Sludge (ppt)[a]	
	2378 TCDD	2378 TCDF
Pope & Talbot, Inc.		
Halsey, OR	31.0	106.0
Potlatch Corp.		
Cloquet, MN	5.0	25.0
Lewiston, ID	78.0	639.0
McGhee, AR	91.0	433.0
P.H. Glatfelter Co.		
Spring Grove, PA	93.0	238.0
Procter & Gamble Co.		
Mehoopany, PA	6.0[b]	6.0[b]
Scott Paper Co.		
Hinckley, ME	6.9	29.0
	33.0	106.0
	39.0	149.0
	67.0	330.0
Mobile, AL	9.5	18.0
Westbrook, ME	13.0	55.0
Simpson Paper Co.		
Anderson, CA	278.0	6740.0
Tacoma, WA	29.0	106.0
	39.0	101.0
Stone Container Corp.		
Missoula, MT	55.0[b]	150.0[b]
Panama City, FL	3.6	16.0
Temple-Eastex, Inc.		
Evadale, TX	16.0	49.0
Union Camp Corp.		
Eastover, SC	6.9	13.0
Franklin, VA	3.6	6.0
Wausau Paper Mills Co.		
Brokaw, WI	3.2	68.0
	4.1	56.0

Company & Location	Sludge (ppt)[a]	
	2378 TCDD	2378 TCDF
Westvaco Corp.		
Covington, VA	119.0	799.0
Luke, MD	80.0	471.0
Wickliffe, KY	9.4	46.0
Weyerhaeuser Co.		
Cosmopolis, WA	12.0	61.0
Longview, WA	25.0	80.0
	35.0	89.0
New Bern, NC	213.0	1600.0
	373.0	1920.0
Plymouth, NC	1390.0	17,100.0
Rothschild, WI	58.0	150.0
Willamette, Ind.		
Hawesville, KY	52.0[b]	810.0[b]
	83.0[b]	380.0[b]

NOTE: Information furnished by United States Environmental Protection Agency, Washington, D.C., based on 104-Mill Survey; updated results provided in computer diskette form. Concentrations reported on a dry basis.

[a] Concentration in ppt unless otherwise noted.

[b] Concentrations in ppq; sludge is non-dewatered.

[c] Concentration of non-detectable samples was assumed to be half the detection limit.

APPENDIX B

EXPOSED POPULATION AND PARTICULATE MATTER EMISSIONS CALCULATIONS FOR SLUDGE HANDLING/ PROCESSING OPERATIONS

Sludge Formation/Processing

Range from 1 to 5, use average of three waste treatment personnel

104 mills bleach pulp using chlorine

$\frac{3 \text{ employees}}{\text{mill}} \times 104 \text{ mills} = 312 \text{ people/shift}$

312 people/shift x 4 shifts = 1248 people (use 1300 people)

Sludge Handling: These personnel not included in waste treatment (sludge formation/processing) personnel just listed.

Total sludge produced from 104-Mill Study = 2,959,152.4 tons/yr

Average sludge production per mill per day = $\frac{2{,}959{,}152.4 \text{ tons}}{(104 \text{ mills})(365 \text{ days/yr})}$
= 78 dry tons/day

Assume: Two shifts of haulers, 5 tons of sludge per 6-yd^3 dump truck, 1-h round trip

$$\frac{78 \text{ tons/day}}{5 \text{ tons/trip}} = \frac{15.6 \text{ trips}}{1 \text{ h/trip}} = \frac{15.6 \text{ h}}{2 \text{ shifts}} = 7.8 \text{ h/shift}$$

Therefore, 1 hauler/shift
Also assume one front-end loader operator/shift

Number of employees for sludge transportation = $\frac{2 \text{ people}}{\text{shift}} \times \frac{2 \text{ shifts}}{\text{day}}$
x 104 mills = 416 (use 400)

Total number of sludge-processing employees = 1300 + 400 = 1700

Convert dry tons/day to tons dewatered sludge/day = $\frac{78 \text{ dry tons/day}}{0.3^*}$
= 260 tons/day

Particulate Emission Sources

1) Dewatered sludge loading into storage pile, 260 tons/day

2) Loading from pile into dump truck by front-end loader, 260 tons/day

From AP-42 Section 11.2.3 (EPA 1988d): $E = k(0.0032)\frac{\left(\frac{U}{5}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.2}}$ lb/ton

* 30% solids.

U = 8.95 mph (suggested default from EPA 1988b.)
M = 70% (moisture content of dewatered sludge)
k = 0.74 for particulate <30 μm, 0.35 for particulate <10 μm

$$E = k(0.0032)\ \frac{\left(\frac{8.95}{5}\right)^{1.3}}{\left(\frac{70}{2}\right)^{1.2}}$$

For particulate <30 μm, k = 0.73 E = 0.000071 lb/ton
For particulate <10 μm, k = 0.35 E = 0.000034 lb/ton

Dewatered Sludge Loading/Unloading Emissions - Two sources

Particulate <30 μm = 0.000071 lb/ton x 260 tons/day x 2 sources
= 0.037 lb/day
Particulate <10 μm = 0.000034 lb/ton x 260 tons/day x 2 sources
= 0.018 lb/day

1) Hauler/Front-End-Loader Operator

Particulate Source 2

TSP = 0.037 lb/day ÷ 2 sources = 0.018 lb/day

$$\text{Total particulate emissions per shift} = \frac{0.018 \text{ lb/day}}{2 \text{ shifts/day}} = \frac{0.009 \text{ lb}}{\text{shift}}$$

$$\text{Outside concentration, mg/m}^3 = \frac{Q}{(L)(MH)(V)}$$

Q = emission rate, mg/s

$$Q = \frac{0.009 \text{ lb}}{8 \text{ h}} \times \frac{453.6 \text{ g}}{1 \text{ lb}} \times \frac{1000 \text{ mg}}{\text{g}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 0.14 \text{ mg/s}$$

L = length of treated area
MH = mixing height (suggested default from EPA 1988b = 1.5 m)
V = wind speed at mixing height (suggested default from EPA 1988b = 2.2 m/s)

Assumed surface area of 6-yd^3 dump truck 32 ft^2, assume length is 2 times width.

$$L(0.5L) = 32$$
$$L^2 = 64$$
$$L = 8 \text{ ft} \times \frac{0.3048 \text{ m}}{1 \text{ ft}} = 2.44 \text{ m}$$

$$\text{Outside concentration} = \frac{0.14 \text{ mg/s}}{(2.44 \text{ m})(1.5 \text{ m})(2.2 \text{ m/s})} = 0.017 \text{ mg/m}^3$$

2) <u>Treatment Plant Personnel</u>

Particulate Source 1

TSP = 0.037 lb/day ÷ 2 sources = 0.018 lb/day

$$\text{Total particulate emissions per shift} = \frac{0.018\ \text{lb/day}}{3\ \text{shifts/day}} = \frac{0.006\ \text{lb}}{\text{shift}}$$

$$\text{Outside concentration, mg/m}^3 = \frac{Q}{(L)(MH)(V)}$$

$$Q = \frac{0.006\ \text{lb}}{8\ \text{h}} \times \frac{453.6\ \text{g}}{1\ \text{lb}} \times \frac{1000\ \text{mg}}{\text{g}} \times \frac{1\ \text{h}}{3600\ \text{s}} = 0.094\ \text{mg/s}$$

L = assume length of sludge pile 10 ft = 3 m
MH = 1.5 m (default)
V = 2.2 m/s (default)

$$\text{Outside concentration, mg/m}^3 = \frac{0.094\ \text{mg/s}}{(3\ \text{m})(1.5\ \text{m})(2.2\ \text{m/s})} = 0.0095\ \text{mg/m}^3$$

APPENDIX C

EXPOSED POPULATION AND PARTICULATE MATTER EMISSIONS CALCULATIONS FOR LANDFILLING OPERATIONS

Total sludge produced at 60 mills that landfill sludge = 1,641,416.8 dry tons/yr

Mill average daily production = $\frac{1,641,416.8 \text{ tons/yr}}{365 \text{ days/yr} \times 60 \text{ mills}}$

= 75.0 dry tons/day

Convert dry tons/day to dewatered tons/day (30% solids)

$= \frac{75.0 \text{ dry tons/day}}{0.3} = 250 \text{ tons/day}$

From Table 19-6 of EPA 1979: Average pieces of equipment for disposal by landfilling 250 wet tons/day sludge (Scheme 4) is 3

Assume each piece of equipment has its own operator.

2 overlapping shifts/day at landfill

Number of workers per landfill = $\frac{3 \text{ operators}}{\text{shift}} \times 2 \text{ shifts} = 6 \text{ operators}$

Total number of workers = 6 operators x 60 mills that landfill sludge = 360 operators (use 400 operators)

Particulate Emission Sources

1) Dewatered sludge unloading from dump truck into landfill, 250 tons/day
2) Spreading dewatered sludge, 250 tons/day
3) Compacting dewatered sludge, 250 tons/day
4) Cover with excavated soil - No dioxin particulate from this source

Unloading Operations

From AP-42 Section 11.2.3 (EPA 1988d):

$$E = k(0.0032)\ \frac{\left(\frac{U}{5}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.2}} \quad \text{lb/ton}$$

U = 8.95 mph (default)
M = 70% moisture
k = 0.74 for particulate <30 μm, 0.35 for PM-10 (particulate <10 μm)

$$E = k(0.0032)\ \frac{\left(\frac{8.95}{5}\right)^{1.3}}{\left(\frac{70}{2}\right)^{1.2}}$$

For particulate <30 µm, k = 0.74 E = 0.000071 lb/ton
For particulate <10 µm, k = 0.35 E = 0.000034 lb/ton

Unloading Emissions

Particulate <30 µm = 0.000071 lb/ton x 250 tons/day = 0.018 lb/day
Particulate <10 µm = 0.000034 lb/ton x 250 tons/day = 0.0085 lb/day

Spreading and Compacting

From EPA 1988b: Spreading assumed similar to agricultural tilling.

Assume both spreading and compacting similar to agricultural tilling.

From AP-42 Section 11.2.2:

$E = k(48)(S)^{0.6}$ lb/acre
k = 1 for TSP, 0.33 for <30 µm, 0.21 for <10 µm
S = silt content of soil, in this case dewatered sludge

Assume all solids (30% in dewatered sludge) are fine particles, thus S = 30%.

Determine daily acreage of sludge application. Dewatered sludge specific gravity = 1.06 (from Hammer 1975).

$$\frac{250 \text{ tons}}{\text{day}} \times \frac{2000 \text{ lb}}{\text{ton}} \times \left(\frac{1 \text{ ft}^3}{62.4 \text{ lb}} \times \frac{1}{1.06}\right) \times \left(\frac{1 \text{ yd}}{3 \text{ ft}}\right)^3 = 280 \text{ yd}^3\text{/day}$$

Sludge application rate - from EPA 1979, Table 19-3. Dry sludge application rate approximately 5700 yd^3/acre.

$$\frac{280 \text{ yd}^3 \text{ sludge}}{\text{day}} \times \frac{1 \text{ acre}}{5700 \text{ yd}^3 \text{ sludge}} = 0.05 \text{ acres/day}$$

Spreading and Compacting Emissions

$E = k(4.8)(30)^{0.6}$ lb/acre

For Total Suspended Particulates (TSP), k = 1 E = 36.9 lb/acre
For particulate <30 µm, k = 0.33 E = 12.2 lb/acre
For PM-10, k = 0.21 E = 7.76 lb/acre

Spreading Emissions

TSP = 36.9 lb/acre x 0.05 acre/day = 1.84 lb/day
Particulate <30 µm = 12.2 lb/acre x 0.05 acre/day = 0.61 lb/day
PM-10 = 7.76 lb/acre x 0.05 acre/day = 0.39 lb/day

Compacting Emissions

Same as spreading
TSP = 1.84 lb/day
Particulate <30 μm = 0.61 lb/day
PM-10 = 0.39 lb/day

$$\text{Total particulate emissions per shift} = \frac{0.018 + 1.84 + 1.84}{2 \text{ shifts}}$$

$$= 1.85 \text{ lb/8-h shift}$$

$$\text{Outside concentration, mg/m}^3 = \frac{Q}{(L)(MH)(V)}$$

where Q = emission rate, mg/s
L = length of one side of treated area, m
MH = mixing height (assumed to be 1.5 m from EPA 1988b)
V = wind speed at mixing height (assumed to be 2.2 m/s from EPA 1988b)

$$Q = \frac{1.85 \text{ lb}}{8 \text{ h}} \times \frac{453.6 \text{ g}}{1 \text{ lb}} \times \frac{1000 \text{ mg}}{\text{g}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 29.1 \text{ mg/s}$$

L = assume application area (0.05 acre) is square

$$L^2 = 0.05 \text{ acre} \times \frac{43{,}560 \text{ ft}^2}{\text{acre}} = 2178 \text{ ft}^2$$

$$L = 46.7 \text{ ft} \times \frac{0.3048 \text{ m}}{1 \text{ ft}} = 14.2 \text{ m}$$

$$\text{Outside concentration} = \frac{29.1 \text{ mg/s}}{(14.2 \text{ m})(1.5 \text{ m})(2.2 \text{ m/s})} = 0.62 \text{ mg/m}^3$$

APPENDIX D

EXPOSED POPULATION AND PARTICULATE MATTER EMISSIONS CALCULATIONS FOR LAND APPLICATION OF SLUDGE

Total sludge produced at seven mills that practice land application of sludge = 160,582.5 dry tons/yr

Mill average daily sludge production = $\frac{160{,}582.5 \text{ dry tons/yr}}{365 \text{ days/yr} \times 7 \text{ mills}}$
= 62.8 dry tons/yr

Convert dry tons/day to dewatered tons/day (30% solids)

$$\frac{62.8 \text{ dry tons/day}}{0.3} = 209.5 \text{ tons/day}$$

Number of workers: assume 1 shift
1 person to spread
1 person to till

Total number of workers exposed = $\frac{2 \text{ people}}{\text{shift}}$ x 1 shift x 7 mills = 14 (use 20)

Particulate Emission Sources

1) Dewatered sludge unloading from dump truck onto land, 209.5 tons/day
2) Spreading dewatered sludge, 209.5 tons/day
3) Plowing dewatered sludge into soil, 209.5 tons/day

Unloading Operations

From AP-42 Section 11.2.3 (EPA 1988d):

$$E = k(0.0032) \frac{\left(\frac{U}{5}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.2}} \quad \text{lb/ton}$$

U = 8.95 mph (default)
M = 70% moisture
k = 0.74 for particulate <30 μm; 0.35 for PM-10

For particulate <30 μm, E = 0.000071 lb/ton
For particulate <10 μm, E = 0.000034 lb/ton

Unloading Emissions

Particulate <30 μm = 0.000071 lb/ton x 209.5 tons/day = 0.015 lb/day
Particulate <10 μm = 0.000034 lb/ton x 209.5 tons/day = 0.0071 lb/day

Spreading and Plowing

From EPA 1988b: Spreading assumed similar to tilling, plowing is same as tilling.

From AP-42 Section 11.2.2:

$E = k(4.8)(S)^{0.6}$ lb/acre
k = 1 for TSP, 0.33 for <30 μm, 0.21 for PM-10
S = silt content of soil; in this case, assume equal to solids content of dewatered sludge - 30%

Determine daily average of sludge appliation.

Dewatered sludge specific gravity = 1.06, from Hammer 1975
Depth of application average of 5 in. from Table 19-11 of EPA 1979

$$209.5 \text{ tons} \times \frac{2000 \text{ lb}}{\text{ton}} \times \left(\frac{1 \text{ ft}^3}{62.4 \text{ lb}} \times \frac{1}{1.06}\right) = 6334.7 \text{ ft}^3$$

$$\frac{6334.7 \text{ ft}^3}{5 \text{ in.} \times \frac{1 \text{ ft}}{12 \text{ in.}}} = 15{,}203.2 \text{ ft}^2 \times \frac{1 \text{ acre}}{43{,}560 \text{ ft}^2} = 0.35 \text{ acre/day}$$

Spreading and Plowing Emissions

$E = k(4.8)(30)^{0.6}$ lb/acre

For TSP, k = 1 E = 36.9 lb/acre
For particulate <30 μm, k = 0.33 E = 12.2 lb/acre
For PM-10, k = 0.21 E = 7.76 lb/acre

Spreading Emissions

TSP = 36.9 lb/acre x 0.35 acre/day = 12.9 lb/day
Particulate <30 μm = 12.2 lb/acre x 0.35 acre/day = 4.27 lb/day
PM-10 = 7.76 lb/acre x 0.35 acre/day = 2.72 lb/day

Plowing Emissions

Same as spreading

TSP = 12.9 lb/day
Particulate <30 μm = 4.27 lb/day
PM-10 = 2.72 lb/day

Total particulate emissions = 0.015 + 12.9 + 12.9 = 25.9 lb/day

$$\text{Outside concentration (mg/m}^3) = \frac{Q}{(L)(MH)(V)}$$

MH = 1.5 m (default)
V = 2.2 m/s (default)

$$Q = \frac{25.8 \text{ lb}}{8 \text{ h}} \times \frac{453.6 \text{ g}}{1 \text{ lb}} \times \frac{1000 \text{ mg}}{\text{g}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 406.4 \text{ mg/s}$$

L = assume application area (0.35 acre/day) is square

$$L^2 = \left(0.35 \text{ acre} \times \frac{43{,}560 \text{ ft}^2}{\text{acre}}\right) = 15{,}246 \text{ ft}^2$$

$$L = 123.5 \text{ ft} \times \frac{0.3045 \text{ m}}{\text{ft}} = 37.6 \text{ m}$$

$$\text{Outside concentration, mg/m}^3 = \frac{406.4 \text{ mg/s}}{(37.6 \text{ m})(1.5 \text{ m})(2.2 \text{ m/s})} = 3.28 \text{ mg/m}^3$$

APPENDIX E

EXPOSED POPULATIONS AND PARTICULATE MATTER EMISSIONS CALCULATIONS FOR COMPOSTING OPERATIONS

Total sludge produced at the seven mills which distribute and market sludge 205,636 dry tons/yr

$$\text{Mill average daily sludge production} = \frac{205{,}636 \text{ dry tons/yr}}{365 \text{ days/yr} \times 7 \text{ mills}}$$

$$= 80.5 \text{ dry tons/day}$$

From EPA 1979, composting operation processing 80 to 120 dry tons/day employed 20 operators and mechanics (excluding sludge haulers).

Outside company, however, handled compost; therefore add screening personnel and haulers of dried compost.

Hauling: Screened compost density 865 lb/yd^3, assume 6-yd^3 dump truck

$$865 \text{ lb/yd}^3 \times 6 \text{ yd}^3 \times \frac{1 \text{ ton}}{2000 \text{ lb}} = 2.6 \text{ tons compost/load}$$

Convert 80.5 dry tons/day to tons/day shipped compost (60% solids)

$$= \frac{80.5}{0.6} = 134.2 \text{ tons/day compost}$$

$$\frac{134.2 \text{ tons/day}}{2.6 \text{ tons/load}} = 52 \text{ trips}$$

Assume 1 h round trip → $\dfrac{52 \text{ trips} \times 1 \text{ h}}{8 \text{ h/shift}}$ = 6.5 haulers (use 7 haulers)
8-h shift
8 h/day operation

Screening: Assume 2 operators

Total Population Exposed

Operators and mechanics	20 x 7 = 140	Use 150
Haulers of dried, screened sludge	7 x 7 = 49	Use 50
Screening operators	2 x 7 = 14	Use 20
	182	220

220 people exposed who work 1 shift/day

Particulate Emission Sources

1) Unloading dewatered sludge from dump truck
2) Loading into front-end loader (FEL) and dumping into windrow/pile
3) Mixing bulking agent and dewatered sludge
4) Turning and mixing of compost piles (assume daily)
5) Removing piles and unloading at screening operations into piles by FEL
6) Removal from storage pile by FEL and placement in screens (dried compost)
7) Screening of compost
8) Loading of screened compost into piles for distribution
9) Unloading from pile by FEL and loading into dump truck
10) Unloading from dump truck onto farmland

Unloading and Loading Operations

From AP-42 Section 11.2.3 (EPA 1988d):

$$E = k(0.0032)\frac{\left(\frac{U}{5}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.2}} \quad \text{lb/ton}$$

E = emission factor, lb/ton
k = particle size multiplier; 0.74 for <30 μm; 0.35 for <10 μm
U = mean wind speed, mph
M = material moisture content, %

Assume mean wind speed of 4 m/s = 8.95 mph (default from EPA 1988b)

Moisture content dewatered sludge = 70%
Finished compost moisture content = 55% (prior to drying) from EPA 430/9-81-001 Composting Processes to Stabilize and Disinfect Municipal Sewage Sludge, p. 29.
Dried compost moisture content = 40% from EPA 1979

Emission Factor for Unloading/Loading Dewatered Sludge

$$E = k(0.0032)\frac{\left(\frac{8.95}{5}\right)^{1.3}}{\left(\frac{70}{2}\right)^{1.2}}$$

Converting dry tons/day to tons dewatered sludge/day (30% solids)

$$\frac{80.5 \text{ tons/day}}{0.3} = 268.3 \text{ tons/day}$$

For particulate <30 μm, k = 0.74 — E = 0.000071 lb/ton
For particulate <10 μm, k = 0.35 — E = 0.000045 lb/ton

Emission Factor for Unloading/Loading Finished Compost

$$E = k(0.0032)\frac{\left(\frac{8.95}{5}\right)^{1.3}}{\left(\frac{55}{2}\right)^{1.2}}$$

Converting dry tons/day to finished compost, tons/day (45% solids)

$$\frac{80.5 \text{ tons/day}}{0.45} = 178.9 \text{ tons/day}$$

For particulate <30 μm, k = 0.74 — E = 0.000095 lb/ton
For particulate <10 μm, k = 0.35 — E = 0.000045 lb/ton

Emission Factor for Unloading/Loading Dried Compost

$$E = k(0.0032)\frac{\left(\frac{8.95}{5}\right)^{1.3}}{\left(\frac{40}{2}\right)^{1.2}}$$

Converting dry tons/day to final dried compost, tons/day (60% solids)

$$\frac{80.5 \text{ tons/day}}{0.6} = 134.2 \text{ tons/day}$$

For particulate <30 μm, k = 0.74 — E = 0.00014 lb/ton
For particulate <10 μm, k = 0.35 — E = 0.000066 lb/ton

Dewatered Sludge Unloading/Loading Emissions

1) Unloading from dump truck, 268.3 tons/day
2) Loading onto pile by FEL, 268.3 tons/day

Particulate <30 μm = 0.000071 lb/ton x (2 sources x 268.3 tons/day) = 0.038 lb/day
Particulate <10 μm = 0.000034 lb/ton x (2 sources x 268.3 tons/day) = 0.018 lb/day

Finished Compost Unloading/Loading Emissions

5) Removing piles and unloading at screening operations prior to drying 178.9 tons/day

Particulate <30 μm = 0.000095 lb/ton x 178.9 tons/day = 0.017 lb/day
Particulate <10 μm = 0.000045 lb/ton x 178.9 tons/day = 0.0081 lb/day

Dried Compost Unloading/Loading Emissions

6) Removal from storage piles after drying and placement in screens, 134.2 tons/day
8) Loading of screened compost into piles for distribution, 134.2 tons/day
9) Unloading from pile by FEL and loading into dump truck, 134.2 tons/day
10) Unloading from dump truck onto farmland, 134.2 tons/day

Particulate <30 μm = 0.00014 lb/ton x (4 sources x 134.2 tons/day) = 0.075 lb/day
Particulate <10 μm = 0.000066 lb/ton x (4 sources x 134.2 tons/day) = 0.035 lb/day

Screening Operation

7) Screening of compost, 178.9 tons/day

Use PM-10 emission factor from NEDS for SCC Code 3-05-025-11, Sand/Gravel Screening

PM-10 emission factor: 0.12 lb/ton

PM-10 = 0.12 lb/ton x 178.9 tons/day = 21.5 lb/day

For TSP, use AP-42 Appendix C.2, Table C.2-2, Category 3

51% <10 μm

$$TSP = \frac{21.5}{0.51} = 42.1 \text{ lb/day}$$

Mixing and Turning Operations

3) Mixing bulking agent and dewatered sludge, 268.3 tons/day
4) Turning and mixing of compost piles, 268.3 tons/day

Use TSP emission factor from NEDS for SCC Code 3-05-025-03, Sand/Gravel Material Transfer and Conveying

TSP emission factor: 0.029 lb/ton

For PM-10 use AP-42 Appendix C.2, Table C.2-2, Category 3

PM-10 51% <10 μm

TSP = 0.089 lb/ton x (2 sources x 268.3 tons/day) = 15.6 lb/day
PM-10 = 0.51(15.6 lb/day) = 7.94 lb/day

Controls: Watering of piles during dusty conditions will reduce particulate emissions by approximately 50%.

Total Particulate Emissions

1) Screening Operators - Screening operations (Source 7) TSP = 42.1 lb/day (8-h shift)

$$\frac{42.1\ \text{lb}}{8\ \text{h}} \times \frac{453.6\ \text{g}}{1\ \text{lb}} \times \frac{1000\ \text{mg}}{\text{g}} \times \frac{1\ \text{h}}{3600\ \text{s}} = 663.1\ \text{mg/s}$$

$$\text{Outside concentration (mg/m}^3) = \frac{Q}{(L)(MH)(V)}$$

MH = 1.5 m (default)
V = 2.2 m/s (default)
Q = 663.1 mg/s
L = from Kirk-Othmer 1981 - Supplement Volume, length-to-width ratio of screen is 2:1; largest screen area is 17.76 m^2

Screen area = 17.76 m^2 = L (0.5L)
35.52 = L^2
5.96 = L
6 m = L

$$\text{Outside concentration (mg/m}^3) = \frac{663.1\ \text{mg/s}}{(6\ \text{m})(1.5\ \text{m})(2.2\ \text{m/s})} = 33.5\ \text{mg/m}^3$$

2) Equipment Operators

Particulate Sources 1 through 6, 8, and 9

TSP	Sources 1 and 2	= 0.038 lb/day
	Sources 3 and 4	= 15.6 lb/day
	Source 5	= 0.017 lb/day
	Sources 6, 8, 9	= 0.056 lb/day
	Total	= 15.7 lb/day (8-h shift)

$$\frac{15.7\ \text{lb}}{8\ \text{h}} \times \frac{453.6\ \text{g}}{1\ \text{lb}} \times \frac{1000\ \text{mg}}{1\ \text{g}} \times \frac{1\ \text{h}}{3600\ \text{s}} = 1978.2\ \text{mg/s}$$

$$\text{Outside concentration (mg/m}^3) = \frac{Q}{(L)(MH)(V)}$$

MH = 1.5 m (default)
V = 2.2 m/s (default)
Q = 1978.2 mg/s
L = assume area is square

Area assumed to be 16 acres based on EPA 1979, p. 12-24 cites actual composting area is 1 acre per 5 dry tons of sludge. Average dry tons/day handled is 80.5 dry tons. Dividing by 5 gives 16 acres.

$$L^2 = 16 \text{ acres} \times \frac{43{,}560 \text{ ft}^2}{\text{acre}} = 696{,}960 \text{ ft}^2$$

$$L = 834.8 \text{ ft} \times \frac{0.3048 \text{ m}}{\text{ft}} = 254.4 \text{ m}$$

$$\text{Outside concentration (mg/m}^3) = \frac{1978.2 \text{ mg/s}}{(254.4 \text{ m})(1.5 \text{ m})(2.2 \text{ m/s})} = 2.36 \text{ mg/m}^3$$

3) Compost Haulers

Particulate Sources 9 and 10

TSP Sources 9 and 10 = 0.038 lb/day (8-h shift)

$$\frac{0.038 \text{ lb}}{8 \text{ h}} \times \frac{453.6 \text{ g}}{1 \text{ lb}} \times \frac{1000 \text{ mg}}{1 \text{ g}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 4.79 \text{ mg/s}$$

$$\text{Outside concentration (mg/m}^3) = \frac{Q}{(L)(MH)(V)}$$

Q = 4.79 mg/s
MH = 1.5 m (default)
V = 2.2 m/s (default)
L = assume length of dump truck container is 2 x width and assume surface area of 6-yd³ dump truck is 32 ft²

$$L\,(0.5L) = 32$$
$$L^2 = 64$$
$$L = 8 \text{ ft} \times \frac{0.3048 \text{ m}}{1 \text{ ft}} = 2.44 \text{ m}$$

$$\text{Outside concentration} = \frac{4.79 \text{ mg/s}}{(2.44 \text{ m})(1.5 \text{ m})(2.2 \text{ m/s})} = 0.59 \text{ mg/m}^3$$

APPENDIX F

RISK ASSESSMENT METHODOLOGY

RISK ASSESSMENT

This section presents the methodology for the calculation of risk to 2378 TCDD and 2378 TCDF. Unit risk is used to compare the relative potencies of carcinogens. Potency is defined as the linear portion of a given dose-response curve which is used to calculate the unit risk factors. On a curve, the upper confidence limit for the extra risk calculated at low doses is always linear. The slope (q*) is taken as the upper-bound of the potency of the chemical (TCDD) in inducing cancer at low doses. The 95% upper confidence limit of dose-response functions for the linear slope factor q* of 2378 TCDD is 0.156 kg-d/ng or $1.56 \times 10^{+5}$ $(mg/kg/day)^{-1}$. The derivation of this factor is described in EPA 1984.

During the development of the slope factor an absorption factor of 55 percent was applied. The equation for calculation of average risk and population risk are presented in Equations F-1 and F-2, respectively.

AVGRISK = LTEQ x PF / AF Equation F-1

POPRISK = AVGRISK x POP / YEAR Equation F-2

Where:

AVGRISK = average risk for the lifetime average daily toxicity equivalents, unitless
LTEQ = lifetime average daily TEQ, mg/day-kg
PF = potency factor, kg-day/mg
AF = absorption factor, unitless

POPRISK = population risk for the lifetime average daily toxicity equivalents, cases/year
POP = number of workers in the population
YEAR = number of years in a lifetime, years

The lifetime average daily toxicity equivalents (TEQ) which were used in Equation F-1 were presented in tables from Section 3. Three types of lifetime average daily TEQ were calculated in Section 3 for inhalation exposure from volatilization, inhalation exposure from particulate matter, and dermal exposure. The potency factor used in the equation was 0.156 kg-day/ng (EPA 1984). The absorption factor (AF) was estimated to be 0.55 (Farland 1987).

Table F-1 summarizes the variables for the estimated average risk and population risk for workers involved in sludge handling/processing, landfilling, land application, and composting operations. The average risk and population risks are summarized in Table 4-3. The following is an example calculation for calculating average risk and population risk.

Lower limit for average risk for haulers/front-end loader operators handling/processing sludge from volatilization

$$AVGRISK = 8.2\times10^{-17} \text{ mg/day-kg} \times 1.56\times10^{5} \text{ day/kg-mg} /0.55$$
$$= 2\times10^{-11}$$

Lower limit for population risk for haulers/front-end loader operators handling/processing sludge from volatilization

$$POPRISK = 2\times10^{-11} \times 1300 \text{ workers/40 years}$$
$$= 8\times10^{-10} \text{ cases/year}$$

TABLE F-1. VARIABLES FOR ESTIMATING AVERAGE RISKS AND POPULATION RISKS

Variable	Value	Reference
Potency factor, kg-day/mg (PF)	$1.56 \times 10^{+5}$	EPA 1984
Absorption factor, unitless (AF)	0.55	EPA 1988b

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EPA Contract Officer: Paul Quillen
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16. Abstract (Limit: 200 words)

This report assesses potential worker exposures and risks to 2378 TCDD and 2378 TCDF in the processing and commercial use of pulp and paper mill sludge. The report identifies the job categories in each operation and examines worker exposure via the following three exposure pathways: 1) inhalation of volatilized 2378 TCDD/2378 TCDF, 2) inhalation of particulates containing 2378 TCDD/2378 TCDF, and 3) dermal contact with pulp and paper mill sludge.

Since no available personnel exposure monitoring data is available, various modeling techniques and assumptions are used to estimate exposures. A range (low and high values) of exposure and risk estimates are presented for each industry/worker scenario and exposure route. The "low" and "high" exposures and risks are estimated based on the lowest and highest dioxin TEQ concentrations, as reported in the 104-Mill Study, and typical to reasonable worst-case assumptions, respectively.

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