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PRELIMINARY SOURCE ASSESSMENT
FOR HAZARDOUS WASTE AIR EMISSIONS
FROM TREATMENT, STORAGE AND
DISPOSAL FACILITIES (TSDFs)

Final Report

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1. SUMMARY AND CONCLUSIONS

This report presents a preliminary assessment of organic emissions from area sources at hazardous waste treatment, storage, and disposal facilities (TSDFs), and of the risks to the general public associated with these emissions. The types of potential emission sources which were studied are: drum storage and handling; tanker unloading; storage and treatment tanks; surface impoundments for treatment, storage, and disposal; land treatment facilities; landfills; fugitive emission sources associated with incineration and deep well injection; and distillation and other recovery operations. The study includes only fugitive emissions from incinerators; emissions from incinerator stacks were not included. The study also does not include fugitive dust emissions from waste piles or from excavation.

This preliminary assessment is based on emissions estimates for 39 TSDFs visited by EPA. Emissions for the selected facilities were quantified using empirical TSDF emissions models; and human exposures associated with these emissions were estimated using atmospheric dispersion modeling. Ranges of cancer risks were then calculated for the visited plants using a range of cancer risk factors for TSDF pollutants.

Nationwide emissions and cancer incidence for organic emissions from TSDF area sources were extrapolated from emissions and risks for the selected model plants. Two methods were used for this estimation. One was based on average impacts for various facility types at the model plants, and nationwide facility counts developed in a survey by Westat, Inc.¹ The second method used average impacts for model plants in various SIC groups, and plant counts from the Westat survey. Table 1-1 presents nationwide emissions and cancer incidence ranges aggregated by facility type, while Table 1-2 gives nationwide emissions and incidence aggregated by the SIC code of the TSDF. Maximum individual risk is also presented in the tables for various SIC codes and TSDF operation types. The maximum individual risk is the cancer risk over a 70-year lifetime for an individual exposed at the point of maximum ambient impact for the emission source.

As illustrated by the SIC code aggregation results given in Table 1-2, emissions and incidences could not be determined for TSDFs handling fabricated metal production waste (SIC 34) or electric equipment manufacturing waste (SIC 36). Organic emissions from each of these categories are probably significant because of due to use of solvents in cleaning parts made in both categories. Also, because of the urban locations of such facilities, risks and incidences associated with these emissions may be substantial. However, it is known that the model plant sample chosen to represent the industry is somewhat biased toward large, complex facilities, especially in the case of those facilities not classified by SIC. Thus, the impact estimates for the unspecified category in Table 1-2 may be overestimates.

TABLE 1-1. NATIONWIDE EMISSION AND RISK ESTIMATES AGGREGATED BY SOURCE TYPE

	Number of visited plants in category	Maximum individual risk for visited plants ^{a, b}	Number in category nation- wide	National estimate	
				total emissions (Gg/yr)	total annual incidence ^{a, c}
Drum handling	22	3 E-7 to 3 E-5	3577	10	0.04 to 4
Storage tanks	19	1 E-6 to 1 E-4	1428	20	0.07 to 7
Open treatment tanks and surface impoundment	20	4 E-5 to 4 E-3	1687	800	0.4 to 40
Land treatment	4	6 E-6 to 6 E-4	70	100	0.1 to 10
Landfills	5	1 E-6 to 1 E-4	199	20	0.004 to 0.4
Injection wells	1	4 E-9 to 4 E-7	87	0.05	0.00002 to 0.002
Incineration (area sources)	10	5 E-8 to 5 E-6	240	0.2	0.0002 to 0.02
Distillation and other recycling	13	9 E-7 to 9 E-5	392	5	0.03 to 3
			TOTALS ^d	960	0.6 to 64

^a Based on a unit risk factor range of 2 E-7 to 2 E-5 (probability of cancer incidence for exposure to 1 ug/m³ over a 70 year lifetime).

^b Maximum individual risk is the lifetime cancer risk to an individual exposed over a 70 year lifetime to the highest ambient concentration outside the plant boundary.

^c Annual incidence is the total cancer incidence for individuals living in the neighborhood of the facilities under study.

^d Columns may not add to totals because of rounding error.

TABLE 1-2. NATIONWIDE EMISSION AND RISK ESTIMATES AGGREGATED BY SIC CODES

	Number of visited plants in category	Maximum individual risk for visited plants ^{a,b}	Number in category nation- wide	National estimate	
				total emissions (Gg/yr)	total annual incidence ^{a,c}
Chemicals and allied products (SIC 28)	16	1 E-6 to 1 E-4	1249	50	<1 to 11
Fabricated metal products (SIC 34)	0	--	547	--	--
Electrical equipment (SIC 36)	0	--	540	--	--
Other metal-related products (SIC 33,35,37)	3	1 E-6 to 1 E-4	804	40	<1 to 10
All other manufacturing (SIC 20-27,29-32,38-39)	6	2 E-6 to 2 E-4	878	200	<1 to 9
Not otherwise specified	23	4 E-5 to 4 E-3	800	800	1 to 70
			TOTALS	1100	1 to 100

^a Based on a unit risk factor range of 2 E-7 to 2 E-5 (probability of cancer incidence for exposure to 1 ug/m³ over a 70 year lifetime).

^b Maximum individual risk is the lifetime cancer risk to an individual exposed over a 70 year lifetime to the highest ambient concentration outside the plant boundary.

^c Annual incidence is the total cancer incidence for individuals living in the neighborhood of the facilities under study.

^d Columns may not add to totals because of rounding error.

The results of the nationwide analysis of emissions and risks from TSD area sources are subject to a number of limitations. These result from uncertainties in the input data, and from simplifying assumptions made as part of the general methodology. Sources of uncertainty in inputs and in the study methodology include:

- o the use of 39 visited plants to represent the industry as a whole;
- o the use of models to estimate emissions and population exposures;
- o uncertainties associated with development of pollutant risk factors;
- o the unavailability of data or models to calculate emissions from some source types;
- o the use of default inputs where model inputs were not available; and
- o the use of literature sources for impoundment and open tank waste concentrations.

Appendix F provides a comparison of the national emission and incidence estimates presented in Table 1-1 with estimates based on mass balance calculations for the visited facilities. These mass balance calculations were made only for source types where such a method was applicable (i.e., impoundments, land treatment and landfills). Results were extrapolated and incidences were computed as in Tables 1-1 and 1-2, although the number of facilities used in the analysis was smaller due to the lack of waste throughput information for some facilities.

References for Section 1

1. Dietz, S., M. Emmet, R. DiGaetano, D. Tuttle, and C. Vincent (Westat, Inc.). National Survey of Hazardous Waste Generators and Treatment, Storage and Disposal Facilities Regulated Under RCRA in 1981. Prepared for U.S. Environmental Protection Agency: Office of Solid Waste. Washington, DC. April 1984. 318p.

2. INTRODUCTION

Air emissions from hazardous waste treatment, storage, and disposal facilities (TSDFs) recently have received a great deal of attention. The U. S. Environmental Protection Agency (EPA) Offices of Solid Waste, and Research and Development have conducted studies of potential sources of air emissions from hazardous waste TSDFs, and potential emission controls. The EPA Office of Air Quality Planning and Standards recently received primary responsibility for assessing emissions from TSDF area sources, and developing standards for these sources as appropriate.

This report presents a preliminary assessment of TSDF area sources and of the risks to the general public associated with these emissions. The types of potential emission sources which were studied are as follows:

- o drum storage and handling;
- o tanker unloading;
- o storage tanks;
- o treatment tanks;
- o surface impoundments for treatment, storage, and disposal;
- o land treatment facilities;
- o landfills;
- o area sources associated with incinerators;
- o deep well injection; and
- o distillation and other recovery operations.

Nationwide environmental impacts were estimated by extrapolating from impacts calculated for 39 TSDFs visited by EPA and its contractors. The 39 visited facilities are listed in Table 2-1. Section 3 of this report describes the techniques used to estimate emissions from the visited TSDFs. Techniques used to estimate risks from the model facilities are described in Section 4. Section 5 discusses the extrapolation techniques used to estimate nationwide emissions and risks, and presents the results of the nationwide assessment.

TABLE 2-1. LIST OF VISITED FACILITIES

1. ABCO Industries, Inc.	Roebuck, SC
2. ARCO-Cherry Point Refinery	Ferndale, WA
3. Allied Corporation Fibers and Plastics Co.	Philadelphia, PA
4. American Cyanamid Co.	Wallingford, CT
5. American Recovery Co., Inc.	Baltimore, MD
6. Amoco Chemical Corporation	Alvin, TX
7. Celanese Chemical Corporation	Bay City, TX
8. Chem-Security Systems, Inc.	Arlington, OR
9. E.I. DuPont deNemours, Chamber Works	Deepwater, TX
10. El Paso Products	Odessa, TX
11. Environmental Enterprises, Inc.	Cincinnati, OH
12. Environmental Protection Corporation	Bakersfield, CA
13. Fike Chemicals, Inc.	Nitro, WV
14. Fondessy/Aces	Oregon, OH
15. General Electric	Lynn, MA
16. Hamilton Standard Div., United Technologies	Windsor Locks, CT
17. IT Corporation	Rio Vista, CA
18. Liberty Solvents and Chemical Company, Inc.	Twinsburg, OH
19. Marisol, Inc.	Middlesex, NJ
20. Metropolitan Sewer District of Cincinnati	Cincinnati, OH
21. Mobil Joliet Refining Corporation	Joliet, IL
22. Morflex Chemical (formerly Pfizer)	Greensboro, NC
23. Occidental Chemical Corporation, Durez Resins	N. Tonawanda, NY
24. Rollins Environmental Services, Inc.	Baton Rouge, LA
25. S and W Waste, Inc.	South Kearny, NJ
26. SCA Chemical Services, Inc. (also listed as Earthline Co.)	Newark, NJ
27. SCA Services	Pinewood, SC
28. Seaboard Chemical Corporation	Jamestown, NC
29. Solvents Recovery Services	Linden, NJ
30. Southern Coating Co.	Sumter, SC
31. Tektronix, Inc.	Beaverton, OR
32. The Atchison, Topeka and Santa Fe Railway Co.	Somerville, TX
33. U.S. Pollution Control, Inc. Lone Mountain Facility	Waynoka, OK
34. Union Carbide Agricultural Products Co.	Woodbine, GA
35. Union Carbide Corp.	S. Charleston, WV
36. Union Carbide Agricultural Products	Institute, WV
37. CECOS International	Niagara Falls, NY
38. Chem-Waste Management	Kettleman City, CA
39. Gulf Coast Waste Disposal Authority	LaMarque, TX

3. CALCULATION OF EMISSIONS

Emissions from the 39 selected TSDFs were calculated using empirical emission models and emission factors. Appendix A lists estimated emissions for individual emission sources at the 39 selected TSDFs. Because many of the selected TSDFs made blanket claims of confidentiality, plant names are not given in the appendix. The emission source types, and the emission factors and models used to estimate emissions, are discussed below. Specific equations used in the emission models are given in Appendix B. The second and third portions of this section discuss sources of input data for the models and criteria used to select between different input data sources. Where possible, input data for the models were based on site visit observations or on published data; however, it was sometimes necessary to use default parameters. Default parameters used in the models are listed in Appendix C, while Appendix D gives sample emission calculations.

3.1 EMISSION MODELS

3.1.1 Drum Handling

Drum handling losses constitute emissions from drum filling (working losses) and fugitive losses during drum storage. Filling losses were computed after the method presented by Engineering-Science.¹ Fugitive loss factors were condensed into two categories in the E-S report: equipment leakage and spillage. For equipment leakage, an emission factor of 0.0017 lbs./drum was used. For drum spillage it was estimated that 50 gallons per 100,000 gallons stored are spilled, and that all of the spilled material is allowed to evaporate. These factors are considered to represent a conservative measure of loss.¹

3.1.2 Tanker Unloading

The unloading of volatile organics from tank trucks was quantified using two emission factors presented by Monsanto Research Corporation: one for unloading (0.36 g/kg handled) and one for spillage (0.095 g/kg handled).²

3.1.3 Tank Storage

Emissions from storage tanks containing organic liquids are estimated using equations presented in AP-42.³ For the tank designs of interest, fixed roof and floating roof, there are four primary sources of emissions: fixed roof breathing losses, fixed roof working losses, floating roof standing storage losses, and floating roof withdrawal losses.

Emissions from fixed roof tanks are the result of breathing and working losses. Breathing losses occur when the vapor in the tank expands due to temperature and/or barometric pressure changes. Expansion of the vapor in the tank results in the expulsion of organic vapors contained within the tank's vapor space through the pressure/vacuum relief valve.

Fixed roof working losses are the result of the combined filling and emptying losses. Losses due to filling result when an increase in liquid level increases the vapor space pressure within the tank. As the tank pressure approaches the pressure/vacuum valve relief pressure the valve cracks. The valve allows the vapors to be released thus reducing the tank pressure. Emptying losses occur as air is drawn into the tank during liquid removal. The air becomes saturated with organic vapor and expands releasing the vapor through the pressure/vacuum relief valves.

Standing storage and withdrawal losses are the primary sources of emissions from external and internal floating roof tanks. Standing storage losses result as air flows across the top of a floating roof and the tank wall. Withdrawal losses occur when organic liquid clings to the tank wall and is exposed to the atmosphere as the tank is emptied. Again, the emission rate will vary depending on the seal type used.

The equations presented in AP-42 for estimating emissions from storage tanks containing organic liquids were developed for tanks containing pure organic compounds. For tanks containing dilute mixtures of organics in heavy oil or water the equations are still valid; however the total pressure in the tank and the average vapor molecular weight must be calculated for a mixture

of organics. In calculating emissions from tanks containing mixtures, it was assumed that the tank vapor space was at equilibrium with the stored liquid. The stored liquid was also assumed to be an ideal solution.

3.1.4 Treatment Tanks

The emission factors for API separators were based on AP-42 emission factors for oil/water wastes. The value given is 0.6 kg of VOC emitted per 1000 liters wastewater throughput.⁴ Techniques used to estimate emissions for open aerated and non-aerated treatment tanks are the same as those used for aerated and non-aerated surface impoundments (below).

3.1.5 Surface Impoundments

The emission rate of a component from the liquid into the gas phase is given by the following equation:⁶

$$Q = K A (X_i - X_i^*) MW_i$$

where:

Q = emission rate (mass/time)

K = overall mass transfer coefficient (mole/length² time)

A = surface area of impoundment (length²)

X_i = mole fraction of i in liquid phase

X_i^* = mole fraction of i in gas phase

MW_i = molecular weight of component i (mass/mole)

It is reasonable to assume that the concentration of i in the gas phase is negligible compared to that in the liquid phase. Thus, the above equation becomes:

$$Q = K A X_i MW_i$$

The overall mass transfer coefficient, K is a combination of the individual mass transfer coefficients on the liquid and gas side. The following equation describes the relationship between the overall and individual mass transfer coefficients:

$$\frac{1}{K} = \frac{1}{k_L} + \frac{1}{K_{eq} k_g}$$

k_L = individual liquid phase mass transfer coefficient

k_g = individual gas phase mass transfer coefficient

K_{eq} = vapor liquid equilibrium constant

The vapor liquid equilibrium constant is the ratio of the molar vapor concentration to the molar liquid concentration at equilibrium for a particular compound. Methods have been proposed by a number of authors concerning the calculation of individual liquid and gas phase mass transfer coefficients (Table B-1). These methods constitute emission models for surface impoundments. There are differences in basic assumptions used to develop each model.

Quiescent Impoundments. A correlation proposed by Mackay and Matsugu (1973) was used to calculate the gas phase resistance (k_g) over a smooth liquid surface.⁵ This coefficient is a function of windspeed and effective diameter of the liquid surface.

Liquid phase mass transfer coefficients were based on one of three mass transfer theories presented in the literature:

- stagnant film theory,
- penetration or surface renewal theories, and
- boundary layer theory.

Stagnant film theory identifies k_L as a linear function of diffusivity. Penetration or surface renewal theories identify the dependency to be to the 0.5 power. Finally, the boundary layer theory states the dependency to be to

the two-third power. The exact dependence of k_L on diffusivity remains to be established.

In 1978 Cohen, et al., presented a liquid phase mass transfer coefficient developed from laboratory wind wave tank studies.⁵ Their equation was developed for benzene and toluene and indicated that k_L is dependent primarily on windspeed for velocities between 3 and 10 meters per second. Below 3 m/s, k_L was influenced by subsurface agitation, while at windspeeds above 10 m/s, k_L increases due to the presence of spray, bubble entrainment and white capping. Their equation, developed from stagnant film theory, suggested a linear dependency of k_L to diffusivity.

In 1964 Owens, et al, presented an equation based on reaeration stream studies.⁵ Unlike the wind velocity dependency analyzed by Cohen, Owens' correlations show k_L to be dependent on water velocity and depth. However, like the equation developed by Cohen, the Owens model also suggests a linear dependency of k_L to diffusivity.

Turbulent Impoundments. Estimating emission rates from aerated impoundments is more complex in the calculation of the overall mass transfer coefficient. In reality, only a small fraction of any impoundment is effectively aerated. As a result, both quiescent and turbulent mass transfer coefficients must be used. The first step involves the calculation of an overall mass transfer coefficient in the quiescent area of the impoundment from individual mass transfer coefficients as follows:⁵

$$K^Q = \frac{1}{k_L^Q} + \frac{1}{K_{eq} k_g^Q}$$

Likewise, an overall mass transfer coefficient on the turbulent side is also calculated:⁵

$$K^T = \frac{1}{k_L^T} + \frac{1}{K_{eq} k_g^T}$$

From these two overall mass transfer coefficients on the quiescent and turbulent side an actual overall mass transfer coefficient is obtained on a per area basis as follows:

$$K = \frac{A^T K^T + A^Q K^Q}{A^T + A^Q}$$

where $A^T + A^Q$ = Total area of impoundment.

The previous section addressed the models used to calculate k_L and k_g for the quiescent portion of the impoundment. The literature provides very little information on the calculation of individual turbulent mass transfer coefficients. Nonetheless, there are two correlations found, one on the gas and one on the liquid side, that correlate k_g and k_L to aeration parameters (Table B-2).

In 1977 Reinhardt developed an empirical expression to approximate the gas-phase mass transfer coefficient under mechanically aerated conditions. The correlation indicates that the dependency of k_g to diffusivity is linear.⁵

In the literature, the only relationship found to calculate the liquid phase mass transfer coefficient under agitated conditions was developed by Thibodeaux in 1978.⁵ Considerable research has been conducted on scale models with agitated water surfaces to determine the absorption rate of oxygen. These oxygen absorption rates, being liquid phase controlled, have been transformed to yield a liquid phase mass transfer coefficient under agitated conditions.

Disposal Impoundments. The above models for impoundments do not apply to drying impoundments for oily sludges. For these cases, the Hartley model was used to determine emissions.⁶ The Hartley model was developed to determine the evaporative loss of pure volatile compounds. The model assumes that the rate of mass transfer is controlled by resistance in the gas phase and is proportional to the saturated vapor concentration. The liquid phase resistance, which plays an important role for multicomponent liquid mixtures

containing volatile compounds, is completely ignored in the model development. The Hartley model calculates the flux rate of a component with respect to the flux rate of a known reference compound, usually water. Although the Hartley model represents a simple method of calculating air emissions it has several drawbacks.

For the case where a surface impoundment is allowed to dry, while occasionally being tilled, the land treatment model developed by Thibodeaux and Hwang was used to determine emissions.⁶ Because disposal operations are generally considered batch operations, emission rate estimates based on mass balance calculations have been favored where the necessary information has been provided. Having reasonable data about concentration and throughput provides upper limit emission estimates assuming no absorption on soil surfaces and no biological activity.

3.1.6 Land Treatment

The Thibodeaux-Hwang model estimates emissions from land-treatment facilities (Table B-3).⁶ The model assumes that the emission rate is controlled by diffusion of vapor through the air-filled pores of the soil. With the assumptions that the soil column is isothermal, that no vertical movement of waste occurs by capillary action, no adsorption of material occurs on soil particles and no biochemical oxidation occurs, the model describes the evaporation rate of a chemical species from a soil matrix. The model, as it appears in the literature, gives an instantaneous emission rate. Integration of the model with respect to time gives an average emission rate over a specified time range.

3.1.7 Covered Landfills

The Farmer model was used to estimate emissions from covered landfills (Table B-4). This model estimates emissions for cases where diffusion through air-filled pore spaces in the landfill cover is the rate limiting step. The model assumes: no degradation occurs from biological activity, no adsorption of the compound or transport in moving water occurs, and there is

no landfill gas production.⁶ The vapor concentration of a component in the waste is the driving force for diffusion. The addition of water to the soil will reduce the air-filled porosity, thus reducing the vapor flux from the soil surface because the diffusion rate through a liquid is generally several orders of magnitude less than diffusion through air.

3.1.7 Recycling, Deep Well Injection, and Incineration

Emissions from vents, pump seals, valves, flanges, relief valves, and other fugitive emission sources were calculated using published emission factors as follows:

- o for distillation vents, 1.65 g/kg throughput;⁷
- o for pumps in light liquid service, 98.8 g/hr-pump (assuming 2 seals/pump);⁸
- o for pumps in heavy liquid service, 42.8 g/hr-pump (assuming 2 seals/pump);⁸
- o for valves in liquid service: light liquid, 7.1 g/hr-valve;⁸ heavy liquid, 0.23 g/hr-valve;⁸
- o for valves in gas service, 5.6 g/hr-valve;⁸
- o for relief valves, 104 g/hr-valve;⁸
- o for flanges, 0.83 g/hr-flange;⁸
- o for open-ended lines, 1.7 g/hr-line;⁸ and
- o for sampling connections, 15 g/hr-connection.⁸

3.2 SOURCES OF FACILITY SPECIFICATIONS

Emissions from each TSDF and each operation within that facility were computed using the models and emission factors presented in the previous section. This section describes the process whereby input values were derived for the estimation process. These values were obtained from site visits, or from various literature sources when site data was unavailable.

3.2.1 Site Visits

Site visits to the 39 model TSDFs were made by EPA and its contractors. These visits assessed the processes involved in hazardous waste treatment, storage and disposal through review with plant personnel and inspection of the processes and operations. These visits provided the primary source of data for subsequent emission estimation, including physical specification of equipment and areas, operating practices and emission controls. Whenever available, values given by or derived from these visits were used preferentially to any other source.

3.2.2 Default Parameters

Where site data for certain parameters were unavailable or inadequate from the site visit reports, default values were used as applicable. These fell mainly into the area of physical specifications of equipment or operations (e.g., aerator specifications, impoundment depth). Generally, every attempt was made to accurately portray the plant's operation. Default parameters, values and references are provided in Appendix C.

3.3 SOURCES OF PROCESS STREAM COMPOSITION

Process stream composition is among the most important parameters for estimating emissions from all types of TSDFs. Process stream compositions were obtained or estimated using five basic sources. In order of preference, they are as follows:

- o analyses given or estimated by plant personnel and preliminary process testing results;⁹⁻¹²
- o waste codes obtained during visits with generic waste code analyses;
- o waste codes obtained from Part A data base with generic waste code analyses;
- o W-E-T model waste characterization;

- o Effluent Guidelines Document waste characterization for industry type; and
- o default waste concentrations.

3.3.1 Plant Estimates

Wherever possible compound specific waste composition data were based on site visit reports. Analyses estimated or given by plant personnel were assumed to be the best available wastestream information.

3.3.2 Preliminary Process Testing Results

For a limited number of sites with impoundments and open-top tanks, results from EPA sampling programs were available. These programs identified major organic constituents and estimated total organic carbon in an impoundment or open tank.

3.3.3 Waste Codes Obtained During Visits

Frequently EPA Waste Codes constituted the most detailed listing of wastestream specification available. For some EPA Waste Codes, typical compositions are available in the literature. References 13 to 15 provided proportional compositions necessary to estimate emissions.

3.3.4 Waste Code Obtained from Part A Data Base

The computerized RCRA Part A data base supplies the 15 largest volume waste codes and volumes by treatment type for each RCRA facility.¹⁴ These data were used in the same manner as waste codes obtained during visits (above).

3.3.5 W-E-T Model Waste Characterization

The W-E-T Model data base for hazardous wastes¹⁶ gives waste characterization for industry types or waste codes. When this source was

used, the EPA waste code associated with the process wastestream was located in the W-E-T data base. Then the organic composition of the model wastestream was substituted for the process wastestream.

3.3.6 Effluent Guidelines Documents

Effluent Guidelines Documents provide wastestream compositional data solely for priority pollutants by industry type. This source was used for acrylic polymer production wastestreams.¹⁸

3.3.7 Default Wastestream Compositions

Where wastestream data were unavailable for drums and storage tanks, their contents were assumed to be pure trichloroethylene. Trichloroethylene was selected as typical of waste code F001, which was selected based on the distribution of waste handled in tanks and drums from the Westat data base.^{1,17}

For surface impoundments and open top treatment tanks, where process stream composition data were not available from any of the above sources, emissions were based on model wastes. The total organic concentrations for the model wastes were selected based on preliminary analytical results for a number of impoundments and treatment tanks sampled by EPA. Preliminary analytical results for impoundments and open tanks are summarized in Table 3-1. The average concentration from Table 3-1, 47 ppm, was used in emission calculations where no process stream composition data were available.

3.4 SOURCES OF POLLUTANT PROPERTIES DATA

Most of the emission models discussed in Section 3.1 require physical parameters for pollutants. Parameters required include Henry's Law constants, diffusivities in air and water, vapor pressures, densities, and molecular weights. Generally such parameters were obtained from measurements or estimates given in literature sources.¹⁹⁻²⁰ However, gaps in physical properties data are common for many chemicals of environmental concern.

TABLE 3-1. SUMMARY OF ANALYTICAL RESULTS FOR IMPOUNDMENTS AND OPEN TANKS

=====			
Facility	TNMHC (ppb)	Facility	TNMHC (ppb)
-----		-----	
Treatment and Evaporation		Receiving and Holding	
Final clarifier	308	Primary clarifiers	4020
Waste water discharge	37100	Primary clarifier	35560
Final clarifiers	620	Primary clarifier overflow	195000
Secondary clarifier	2882	Oxidizing lagoon	654231
Primary aeration basin	370	Emergency holding pond	30470
Aeration basin	4120	Sludge holding pond	2480
Biomass basin	690	Leachate collection pond	5276
Bio basin; aeration tank	2812	Equalization Pond	41640
Evaporation pond	1810	Holding pond	1050
Evaporation pond	2250	Liquid waste holding pond	181000
Evaporation pond	2610	Liquid waste holding pond	14700
Evaporation pond	4760	Receiving pond	269000
Evaporation pond	6560	Neutralization pond	38700
Evaporation pond	8190	Equalization basin	6890
Evaporation pond	11000	Lagoon recycle from filters	79300
Evaporation pond	15600	Inlet canal	40920
Evaporation pond	18300	Neutralization tanks	115280
Reducing lagoon	3250		
Spray evaporation pond	8399	AVERAGE	100913
Evaporation pond	4500		
Evaporation pond	6500		
Evaporation pond	16000		
Evaporation pond	18800		
Evaporation pond	30000		
AVERAGE	8643		

Standard methods were used where necessary to estimate physical properties. For Henry's Law constant, Almgren's equation was used.²¹ Diffusivities in water were estimated using the Hayduk and Laudie method; and diffusivities in air were estimated using the Wilke and Lee method.²²

For model wastes discussed in Section 3.3.7, the physical parameters used were averages of parameters for chemicals which were estimated in previous ranking studies to represent large fractions of TSDF emissions.^{19,23} Chemicals ranking among the top ten in these studies are listed in Section 4.2. The Henry's Law constant used for model wastes was $0.01 \text{ atm-m}^3/\text{mol}$. Diffusivities were $0.07 \text{ cm}^2/\text{sec}$ for air, and $10^{-5} \text{ cm}^2/\text{sec}$ for water. The molecular weight used was 100 grams per mole.

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4. CALCULATION OF CANCER RISK AND INCIDENCE

The maximum individual cancer risk and the total annual cancer incidence were estimated for each of the visited facilities. The maximum individual risk is the risk of cancer over a 70-year lifetime for an individual exposed to the maximum pollutant concentration outside the plant boundary. The total annual incidence is the aggregate cancer risk for all individuals living in the vicinity of the plant.

In order to calculate maximum individual risk and total annual incidence, it is first necessary to calculate the maximum off-site pollutant concentration, and the total population exposure for each plant. Maximum risks and total annual incidences can then be calculated using the risk factor for the pollutant of concern.

4.1 CALCULATIONS OF PUBLIC EXPOSURES

4.1.1 General

The EPA's Human Exposure Model (HEM) was used to calculate public exposures to ambient air concentrations of pollutants emitted from stationary sources. The HEM contains (1) an atmospheric dispersion model, with included meteorological data, and (2) a population distribution estimate based on Bureau of Census data. The only input data needed to operate this model are source data, e.g., plant location, height of the emission release point, and temperature of the off-gases. Based on the source data, the model estimates the magnitude and distribution of ambient air concentrations of the pollutant in the vicinity of the source. The model is programmed to estimate these concentrations within a radial distance of 50 km (30.8 miles) from the source. If other radial distances are preferred, an over-ride feature allows the user to select the distance desired. The selection of 50 km (30.8 miles) as the programmed distance is based on modelling considerations, not on health effects criteria or EPA policy. The dispersion model contained in HEM is felt to be reasonably accurate within 50 km (30.8 miles).

4.1.2 Pollutant Concentrations Near a Source

The dispersion model within the HEM is a gaussian diffusion model that uses the same basic dispersion algorithm as the EPA's Climatological Dispersion Model. The algorithm has been simplified to improve computational efficiency.¹ The algorithm is evaluated for a representative set of input values as well as actual plant data, and the concentrations input into the exposure algorithm are arrived at by interpolation. Stability array (STAR) summaries are the principal meteorological input to the HEM dispersion model. The STAR data are standard climatological frequency-of-occurrence summaries formulated for use in U.S. EPA models and are available for major U.S. meteorological monitoring sites from the National Climatic Center, Asheville, NC. A STAR summary is a joint frequency-of-occurrence of wind speed, atmospheric stability, and wind direction, classified according to Pasquill's categories. The STAR summaries in HEM usually reflect 5 years of meteorological data for each of 314 sites nationwide. The model produces polar coordinate receptor grid points consisting of 10 downwind distances located along each of 16 radials which represent wind directions. Concentrations are estimated by the dispersion model for each of the 160 receptors located on this grid. The radials are separated by 22.5-degree intervals beginning with 0.0 degrees and proceeding clockwise to 337.5 degrees. The 10 downwind distances for each radial are 0.2, 0.5, 1.0, 2.0, 5.0, 10.0, 20.0, 30.0, 40.0 and 50.0 kilometers. The center of the receptor grid for each plant is assumed to be the plant center.

4.1.3 Population Living Near an Emission Source

To estimate the number and distribution of people residing within 50 km (30.8 miles) of each plant, the model contains for 1980, the Master Area Reference File (MARF) from the U.S. Census Bureau. This data base is broken down into enumeration district/block group (ED/BG) values. It contains the population centroid coordinates (latitude and longitude) and the 1980 population of each ED/BG in the United States (50 States plus the District of Columbia). The HEM identifies the population around each plant by using the

geographical coordinates of the plant. The HEM identifies, selects, and stores for later use those ED/BGs with coordinates falling within 50 km (30.8 miles) of plant center.

4.1.4 Population Exposure Determinations

The HEM uses the estimated ground level concentrations of a pollutant together with population data to calculate population exposure. For each of 160 receptors located around a plant, the concentration of the pollutant and the number of people estimated by the HEM to be exposed to that particular concentration are identified. The HEM multiplies these two numbers to produce exposure estimates and sums these products for each plant.

A two-level scheme has been adopted in order to pair concentrations and populations prior to the computation of exposure. The two level approach is used because the concentrations are defined on a radius-azimuth (polar) grid pattern with non-uniform spacing. At small radii, the grid cells are usually smaller than ED/BGs; at large radii, the grid cells are usually larger than ED/BGs. The area surrounding the source is divided into two regions, and each ED/BG is classified by the region in which its centroid lies. Population exposure is calculated differently for the ED/BGs located within each region. For ED/BG centroids located between 0.1 km (0.06 miles) and 3.5 km (2.2 miles) from the emission source, populations are divided between neighboring concentration grid points. There are 64 (4 x 16) polar grid points within this range. Each grid point has a polar sector defined by two concentric arcs and two wind direction radials. Each of these grid points and respective concentrations are assigned to the nearest ED/BG centroid identified from MED-X. Each ED/BG can be paired with one or many concentration points. The population associated with the ED/BG centroid is then divided among all concentration grid points assigned to it. The land area within each polar sector is considered in the apportionment.

For population centroids between 3.5 km (2.2 miles) and 50 km (30.8 miles) from the source, a concentration grid cell, the area

approximating a rectangular shape bounded by four receptors, is much larger than the area of a typical ED/BG. Since there is an approximate linear relationship between the logarithm of concentration and the logarithm of distance for receptors more than 2 km from the source, the entire population of the ED/BG is assumed to be exposed to the concentration that is logarithmically interpolated radially and arithmetically interpolated azimuthally from the four receptors bounding the grid cell. Concentration estimates for 96 (6 x 16) grid cell receptors at 10.0, 20.0, 30.0, 40.0, and 50.0 km from the source along each of 16 wind directions are used as reference points for this interpolation.

In summary, two approaches are used to arrive at coincident concentration/population data points. For the 64 concentration points within 3.5 km (2.2 miles) of the source, the pairing occurs at the polar grid points using an apportionment of ED/BG population by land area. For the remaining portions of the grid, pairing occurs at the ED/BG centroids themselves through the use of log-log and linear interpolation. For a more detailed discussion of the model used to estimate exposure, see reference 1.

4.2 RISK FACTORS

Maximum individual risk and annual incidence are calculated from population exposures using the unit risk factor for the pollutant of concern. The unit risk factor for a given pollutant is the probability of a cancer incidence for an individual exposed to $1 \mu\text{g}/\text{m}^3$ of the pollutant over a 70-year lifetime. Thus, the maximum individual risk for a plant is given by the product of (1) the unit risk factor for the pollutant emitted; and (2) the maximum concentration of the pollutant to which an individual is exposed. The annual incidence for a plant is given by the product of (1) the unit risk factor divided by 70; and (2) the population exposure in units of people- $\mu\text{g}/\text{m}^3$.

Unit risk factors have been established only for a small percentage of TSDF pollutants. For this reason, risks were not calculated for the 39 visited facilities on a pollutant-by-pollutant basis. Instead, for each plant, total pollutant exposures were calculated, and the range of cancer risks and incidences was calculated based on a range of unit factors. The risk factor range for TSDF pollutants was based on two ranking studies of TSDF pollutants.^{2,3} The top ten pollutants by emissions from the two ranking studies are given in Table 4-1, along with their unit risk factors, where available.⁴ These risk factors were developed based on animal studies and occupational epidemiological studies. (Epidemiological studies have not been conducted for TSDFs, but have been conducted for various manufacturing industries emitting TSDF pollutants.) The techniques used to develop unit risk factors are detailed in Appendix E.

The range of risk factors used for TSDFs was 2×10^{-7} to 2×10^{-5} (rounded to the nearest one significant figure). The upper end of the range was based on the unit risk factor for carbon tetrachloride, the highest-risk compound appearing on both rankings. The lower end of the range was based on the unit risk factor for methylene chloride.

TABLE 4-1. RISK FACTORS FOR THE TOP 10 CHEMICALS BY
EMISSIONS FROM GCA AND RTI RANKINGS

Compound	Ranking		Unit risk /ug/m3
	GCA	RTI	
Toluene	6	5	--
Methylene chloride	10	6	1.8E-7
Trichloroethylene	5	12	4.1E-6
Perchloroethylene	1	18	1.7E-6
Cyanide	18	1	--
1,1,1-trichloroethane	11	8	--
Benzene	21	2	6.9E-6
Carbon tetrachloride	4	19	1.5E-5
Acetonitrile	9	16	--
Methanol	2	--	--
Xylene	3	--	--
1,2-dichloroethane	--	3	7.0E-6
Formaldehyde	--	4	6.1E-6
Ethyl acetate	7	--	--
Vinyl chloride	--	8	--
Acetone	8	--	--
Ethylene oxide	--	10	3.6E-4

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5. NATIONWIDE EXTRAPOLATION

Nationwide emissions and cancer incidence for organic emissions from TSDF area sources were estimated from emissions and risks for the visited plants. Two methods were used for this estimation. Tables 5-1 and 5-2 present nationwide emissions and incidences aggregated by source type for pollutant unit risk factors of 10^{-5} and 10^{-7} , respectively. Tables 5-3 and 5-4 give nationwide emissions and incidences aggregated by the SIC code of the TSDF for unit risk factors of 10^{-5} and 10^{-7} . The unit risk factor for a given pollutant is defined as the probability of cancer incidence for an individual exposed to an average pollutant concentration of $1 \mu\text{g}/\text{m}^3$ over a 70-year lifetime. In addition to the national estimates, these tables give average emissions and incidences associated with the visited plants for each category of source or SIC. Maximum individual risk is also given for visited facilities and sources in the various SIC and source categories. The maximum individual risk is the cancer risk over a 70-year lifetime for an individual exposed at the point of maximum ambient impact for the emission source.

The results presented in Tables 5-1 through 5-4 are based on emissions, risks, and annual incidences for the individual visited facilities, calculated as described in Sections 3 and 4:

$$E_{s,f,c} = M_s [\text{source and waste specifications, meteorological data}]$$

$$I_{s,f,c} = \text{HEM} [\text{source specifications, meteorological data, population data, pollutant risk factor}] \cdot E_{s,f,c}$$

$$R_{s,f,c} = \text{HEM} [\text{source specifications, meteorological data, pollutant risk factor}] \cdot E_{s,f,c}$$

where $E_{s,f,c}$ = the emission estimate for all sources of type "s" at facility "f" in SIC category "c";

$I_{s,f,c}$ = the cancer incidence estimated to result from the emission, $E_{s,f,c}$, in the neighboring population;

TABLE 5-1. NATIONWIDE EMISSION AND RISK ESTIMATES AGGREGATED BY SOURCE TYPE
FOR A UNIT RISK FACTOR OF 2 E-5^a

	Number of visited plants in category	For visited plants			Number in category nation- wide	National estimate	
		Average emissions (Mg/yr)	Average annual incidence ^c	Maximum individual risk ^b		Total emissions (Gg/yr)	Total annual incidence ^c
Drum handling	22	3	1 E-3	3 E-5	3577	10	4
Storage tanks	19	10	5 E-3	1 E-4	1428	20	7
Open treatment tanks and surface impoundment	20	300	3 E-2	4 E-3	1687	800	40
Land treatment	4	1400	2 E-1	6 E-4	70	100	10
Landfills	5	100	2 E-3	1 E-4	199	20	0.4
Injection wells	1	1	2 E-5	4 E-7	87	0.05	0.002
Incineration (area sources)	10		8 E-5	5 E-6	240	0.2	0.02
Distillation and other recycling	13		8 E-3	9 E-5	392	5	3
TOTALS						960	64

^a The unit risk factor is the probability of cancer incidence for exposure to 1 ug/m^3 over a 70 year lifetime.

^b Maximum individual risk is the lifetime cancer risk to an individual exposed over a 70 year lifetime to the highest ambient concentration outside the plant boundary.

^c Annual incidence is the total cancer incidence for individuals living in the neighborhood of the facilities under study.

^d Columns may not add to totals because of rounding error.

TABLE 5-2. NATIONWIDE EMISSION AND RISK ESTIMATES AGGREGATED BY SOURCE TYPE
FOR A UNIT RISK FACTOR OF 2 E-7^a

	Number of visited plants in category	For visited plants			Number in category nation- wide	National estimate	
		Average emissions (Mg/yr)	Average annual incidence ^c	Maximum individual risk ^b		Total emissions (Gg/yr)	Total annual incidence ^c
Drum handling	22	3	1 E-5	3 E-7	3577	10	0.04
Storage tanks	19	10	5 E-5	1 E-6	1428	20	0.07
Open treatment tanks and surface impoundment	20	300	3 E-4	4 E-5	1687	800	0.4
Land treatment	4	1400	2 E-3	6 E-6	70	100	0.1
Landfills	5	100	2 E-5	1 E-6	199	20	0.004
Injection wells	1	1	2 E-7	4 E-9	87	0.05	0.00002
Incineration (area sources)	10		8 E-7	5 E-8	240	0.2	0.0002
Distillation and other recycling	13		8 E-5	9 E-7	392	5	0.03
TOTALS						960	0.64

^a The unit risk factor is the probability of cancer incidence for exposure to 1 ug/m^3 over a 70 year lifetime.

^b Maximum individual risk is the lifetime cancer risk to an individual exposed over a 70 year lifetime to the highest ambient concentration outside the plant boundary.

^c Annual incidence is the total cancer incidence for individuals living in the neighborhood of the facilities under study.

^d Columns may not add to totals because of rounding error.

TABLE 5-3. NATIONWIDE EMISSION AND RISK ESTIMATES AGGREGATED BY SIC CODES
FOR A UNIT RISK FACTOR OF 2 E-5^a

	Number of visited plants in category	For visited plants			Number in category nation- wide	National estimate	
		Average emissions (Mg/yr)	Average annual incidence ^c	Maximum individual risk ^b		Total emissions (Gg/yr)	Total annual incidence ^c
Chemicals and allied products (SIC 28)	16	40	9 E-3	1 E-4	1249	50	10
Fabricated metal products (SIC 24)	0	--	--	--	547	--	--
Electrical equipment (SIC 36)	0	--	--	--	540	--	--
Other metal-related products (SIC 33,35,37)	3	50	1 E-2	1 E-4	804	40	10
All other manufacturing (SIC 20-27,29-32,38-39)	6	200	1 E-2	2 E-4	878	200	9
Not otherwise specified	23	1000	9 E-2	4 E-3	800	800	70
TOTALS ^d						1100	99

^a The unit risk factor is the probability of cancer incidence for exposure to 1 ug/m^3 over a 70 year lifetime.

^b Maximum individual risk is the lifetime cancer risk to an individual exposed over a 70 year lifetime to the highest ambient concentration outside the plant boundary.

^c Annual incidence is the total cancer incidence for individuals living in the neighborhood of the facilities under study.

^d Columns may not add to totals because of rounding error.

TABLE 5-4. NATIONWIDE EMISSION AND RISK ESTIMATES AGGREGATED BY SIC CODES
FOR A UNIT RISK FACTOR OF $2 \text{ E-}7$ ^a

	Number of visited plants in category	For visited plants			Number in category nation- wide	National estimate	
		Average emissions (Mg/yr)	Average annual incidence ^c	Maximum individual risk ^b		Total emissions (Gg/yr)	Total annual incidence ^c
Chemicals and allied products (SIC 28)	16	40	$9 \text{ E-}5$	$1 \text{ E-}6$	1249	50	0.1
Fabricated metal products (SIC 24)	0	--	--	--	547	--	--
Electrical equipment (SIC 36)	0	--	--	--	540	--	--
Other metal-related products (SIC 33,35,37)	3	50	$1 \text{ E-}4$	$1 \text{ E-}6$	804	40	0.1
All other manufacturing (SIC 20-27,29-32,38-39)	6	200	$1 \text{ E-}4$	$2 \text{ E-}6$	878	200	0.09
Not otherwise specified	23	1000	$9 \text{ E-}4$	$4 \text{ E-}5$	800	800	0.7
TOTALS ^d						1100	0.99

^a The unit risk factor is the probability of cancer incidence for exposure to 1 ug/m^3 over a 70 year lifetime.

^b Maximum individual risk is the lifetime cancer risk to an individual exposed over a 70 year lifetime to the highest ambient concentration outside the plant boundary.

^c Annual incidence is the total cancer incidence for individuals living in the neighborhood of the facilities under study.

^d Columns may not add to totals because of rounding error.

$R_{s,f,c}$ = the risk of cancer for an individual exposed to the maximum ambient concentration due to $E_{s,f,c}$;

M_s = the emission model for source type "s" (Chapter 3);

HEM = the human exposure model (Chapter 4); any [] denote parameters used in M_s or HEM.

Emissions, maximum individual risks, and annual cancer incidences for the visited plants are given in Appendix A. Because a number of the selected plants made confidentiality claims on some or all of the information used to estimate emissions, the emission and risk information given in Appendix A is not matched with plant names. The maximum individual risks presented for various source or SIC categories are simply the highest risks calculated for any visited source or facility in the category:

R_s^M = Maximum $R_{s,f,c}$ for any f or c

$R_{f,c}^T$ = $\sum_3 R_{s,f,c}$

R_c^M = Maximum $R_{f,c}^T$ for any f

where R_s^M = the highest individual risk for a visited source in category "s";

$R_{f,c}^T$ = the sum of the maximum individual risks for all sources at visited facility "f" in SIC "c"; and

R_c^M = the highest individual risk for a visited facility in SIC category "c".

The same basic methodology was used to develop national impact estimates from model plant impacts in the facility aggregation (Tables 5-1 and 5-2) and the SIC code aggregation (Tables 5-3 and 5-4). In the facility type aggregation, average emissions and annual incidences were first calculated for each basic type of operation used at the visited plants:

$$\overline{E}_s = \sum_{f,c} E_{s,f,c} / n_{s,f}$$

$$\overline{I}_s = \sum_{f,c} I_{s,f,c} / n_{s,f}$$

where \overline{E}_s = the average emission rate for source type "s" (i.e., drum handling, tank storage, etc.);

\overline{I}_s = the average annual cancer incidence due to emissions from a source of type "s";

$n_{s,f}$ = the number of visited facilities which included operations of type "s".

The total number of operations of each type nationwide was then obtained from the Westat survey of plants impacted by RCRA.¹ Total nationwide emissions were obtained for each source type by multiplying the average emissions for the source type from the visited plant calculations by the total number of facilities using that type of source nationwide. Annual cancer incidences were estimated similarly for each source type by taking the product of the average incidence for the source type and the nationwide number of facilities using the source type. Total nationwide emissions and incidences were then obtained by summing the national emissions and incidences for the various source categories:

$$E_s^T = \overline{E}_s \cdot N_s$$

$$I_s^T = \overline{I}_s \cdot N_s$$

$$s_E^T = \sum_s E_s^T$$

$$s_I^T = \sum_s I_s^T$$

where E_s^T = the total nationwide emission rate for source type "s";

I_s^T = the total annual cancer incidence due to emissions from source type "s";

N_s = the number of sources of type "s" nationwide;

s_E^T = the total nationwide aggregate emission estimate, by the source type method;

s_I^T = the total nationwide annual cancer incidence due to TSDF emissions, aggregated by the source type method.

For the aggregation by SIC code, emissions and incidences were first averaged for the various plants in each SIC code. Total impacts for each SIC code were calculated by multiplying the average emissions and incidences for the SIC categories by the nationwide numbers of plants falling into the categories. Again the total numbers of plants falling into the various SIC categories were obtained from the Westat survey.¹ Total nationwide impacts were obtained by summing the national impacts for the various SIC categories:

$$\overline{E}_c = \sum_{f,s} E_{s,f,c} / n_{f,c}$$

$$\overline{I}_c = \sum_{f,s} I_{s,f,c} / n_{f,c}$$

$$E_c^T = \overline{E}_c \cdot N_c$$

$$I_c^T = \overline{I}_c \cdot N_c$$

$$c_E^T = \sum_c E_c^T$$

$$c_I^T = \sum_c I_c^T$$

where \overline{E}_c = the average emission rate for a visited facility in SIC category "c";

\overline{I}_c = the average annual cancer incidence due to emissions from a facility in SIC category "c";

$n_{f,c}$ = the number of visited facilities in SIC category "c";

E_c^T = the total nationwide emission rate for TSDFs in SIC category "c";

I_c^T = the total annual cancer incidence due to emissions from TSDFs in category "c";

N_c = the number of facilities in SIC category "c" nationwide;

c_E^T = the total nationwide emission estimate, aggregated by the SIC category method;

c_I^T = the total nationwide annual cancer incidence due to TSDF emissions, aggregated by the SIC category method.

As Tables 5-1 and 5-2 show, the national estimates made using the two aggregation techniques are similar. As illustrated by the SIC code aggregation results given in Table 5-2, emissions and incidences could not be determined for fabricated metal production facilities (SIC 34) or electrical equipment manufacturers (SIC 36). Organic emissions from each of these categories may be significant because of the use of solvents in cleaning parts made in both categories.

Appendix F provides a comparison of the national emission and incidence estimates presented in Table 5-1 with estimates based on mass balance calculations for the visited facilities. These mass balance calculations were made only for source types where such a method was applicable (i.e., impoundments, land treatment and landfills). Results were extrapolated and incidences were computed as in Tables 5-1 and 5-2, although the number of facilities used in the analysis was smaller due to the lack of waste throughput information for some facilities.

References for Section 5

1. Dietz, S., M. Emmet, R. DiGaetano, D. Tuttle, and C. Vincent (Westat, Inc.). National Survey of Hazardous Waste Generators and Treatment, Storage and Disposal Facilities Regulated Under RCRA in 1981. Prepared for U.S. Environmental Protection Agency: Office of Solid Waste. Washington, DC. April 1984. 318p.

6. UNCERTAINTIES AND LIMITATIONS

The results of the nationwide analysis of emissions and risks from TSDF area sources are subject to a number of limitations. These result from uncertainties in the input data, and from simplifying assumptions made as part of the general methodology. In addition, the emission models and dispersion models used in the study are subject to some uncertainty.

A major assumption in the analysis was that the sample of visited facilities is representative of the nationwide TSDF population. In fact, a study of the visited plants showed the sample to be biased in some respects.¹ A major bias is that the sample does not cover some SIC categories. Also, the model plant group is somewhat biased toward large, complex facilities, especially for plants unspecified by SIC. Thus, the average volume treated among the visited TSDFs is much larger than the average estimated by the Westat survey for the total TSDF population.² Although these biases may cancel one another, they indicate a high degree of uncertainty in the SIC code impact aggregation.

It should be noted that the national emissions estimates include only emission sources covered by the Resource Conservation and Recovery Act (RCRA). Many hazardous waste treatment, storage, and disposal operations are currently exempt from RCRA requirements, although they do emit air pollutants. (For instance, small facilities and some open tanks are exempt from RCRA). In fact, some non-RCRA sources were studied at the visited facilities, and emissions calculations for these were used in making estimates of emissions for similar RCRA sources. The use of non-RCRA source data in estimating RCRA source emissions is not expected to bias the national estimates substantially. However, the exclusion of non-RCRA sources from the national aggregations certainly results in an underestimate of overall TSDF emissions.

In addition, the study methodology involved the tacit assumption that the sources for which emission factors or models have been developed are the major emission sources. Some sources, especially transfer and handling points, were not included in this study because of the unavailability of emission models or emission factors. This lack of emissions data for some sources may also have resulted in an underestimate of nationwide impacts for these sources.

The use of default parameters for model inputs is another potential source of uncertainty, although these were used only where no data were available. For surface impoundments or open tanks, another major source of uncertainty is in the waste concentrations which were input to emission models. Waste analyses were not available for most plants, thus analyses were typically based on estimates in the literature for generic waste types.

The emission models used in this study are empirical models, and many have undergone preliminary verification studies; however any model is subject to some uncertainty. In addition, some of the models were extended to cases for which they have not been verified. For instance, the unverified Hartley land disposal model was extended to cover disposal surface impoundments in some cases, while the Thibodeaux-Hwang land treatment model was extended to cover disposal surface impoundments in other cases.

References for Section 6

1. Memo from Andrew Baldwin, GCA/Technology Division, to William Battye GCA/Technology Division. Case Study Facility Group Representativeness. September 26, 1984. 16p.
2. Dietz, S., M. Emmet, R. DiGaetano, D. Tuttle, and C. Vincent (Westat, Inc.). National Survey of Hazardous Waste Generators and Treatment, Storage and Disposal Facilities Regulated Under RCRA in 1981. Prepared for U.S. Environmental Protection Agency: Office of Solid Waste. Washington, DC. April 1984. 318p.

APPENDIX A
EMISSIONS AND RISKS
FOR MODEL PLANTS

PLANT #	SIL CODE	FACILITY	EMISSIONS (kg/yr)	INDIVIDUAL RISK WITH UNIT FACTOR OF 2.0E-7	INDIVIDUAL RISK WITH UNIT FACTOR OF 2.0E-5	ANNUAL INCIDENCE AT UNIT RISK OF 2.0E-7	ANNUAL INCIDENCE AT UNIT RISK OF 2.0E-5	POPULATION (7.1.8c)
1	45	Drum Filling	8.00E+00	6.35E-06	6.35E-06	8.50E-05	8.50E-05	
1	45	Distillation	5.19E+01	4.12E-07	4.12E-05	5.71E-04	5.71E-02	
1	45	Tanker Unloading	9.65E+00	7.82E-06	7.82E-06	1.06E-04	1.06E-02	
1	45	Storage Tanks	2.29E+01	1.82E-07	1.82E-05	2.52E-04	2.52E-02	
		TOTAL	9.27E+01	7.36E-07	7.36E-05	1.02E-03	1.02E+01	1.27E+07 URBAN
2	28	Drum Storage	2.00E+01	1.12E-06	1.12E-07	6.00E-06	6.00E-06	
2	28	Distillation	3.60E+00	2.01E-06	2.01E-06	1.06E-06	1.06E-04	
		TOTAL	3.80E+00	2.12E-06	2.12E-06	1.14E-06	1.14E-04	5.33E+05 URBAN
3	35	Drum Storage	3.17E+01	3.46E-06	3.46E-07	6.56E-07	6.56E-05	
3	35	Wastewater Treatment	1.29E+02	1.41E-06	1.41E-04	3.46E-04	3.46E-02	
3	35	Distillation	1.07E+00	1.17E-06	1.17E-06	2.66E-06	2.96E-04	
		TOTAL	1.30E+02	1.42E-06	1.42E-04	3.52E-04	3.52E-02	1.73E+06 URBAN
4	49	Distillation	2.74E+00	1.19E-08	1.19E-06	0.00E+00	0.00E+00	
4	49	Drum Unloading	4.00E+01	1.74E-06	1.74E-07	0.00E+00	0.00E+00	
4	49	Impoundments	1.48E+00	6.42E-09	6.42E-07	0.00E+00	0.00E+00	
4	49	Storage Tanks	3.60E+01	1.56E-09	1.56E-07	0.00E+00	0.00E+00	
		TOTAL	4.98E+00	2.16E-08	2.16E-06	0.00E+00	0.00E+00	2.60E+04 RURAL
5	28	Wastewater Treatment	4.70E+01	2.66E-07	2.66E-05	1.41E-05	1.41E-03	
		TOTAL	4.70E+01	2.66E-07	2.66E-05	1.41E-05	1.41E-03	4.52E+05 URBAN
6	28	Impoundment	1.90E+00	2.96E-09	2.96E-07	1.14E-06	1.14E-04	
6	28	Incineration	6.00E+01	9.42E-10	9.42E-08	3.60E-07	3.60E-05	
		TOTAL	2.50E+00	3.93E-09	3.93E-07	1.50E-06	1.50E-04	3.63E+05 URBAN
7	28	Incineration	1.21E+00	3.93E-09	3.93E-07	1.45E-06	1.45E-04	
7	28	Wastewater Treatment	4.80E+01	1.56E-07	1.56E-05	5.76E-05	5.76E-03	
		TOTAL	4.92E+01	1.60E-07	1.60E-05	5.91E-05	5.91E-03	3.96E+05 RURAL
8	37	Drum Storage	1.90E+01	1.47E-08	1.47E-06	2.47E-07	2.47E-05	
8	37	Incineration	6.00E+01	4.64E-08	4.64E-06	7.80E-07	7.80E-05	
8	37	Storage Tanks	3.50E+03	2.71E-10	2.71E-08	4.55E-09	4.55E-07	
8	37	Distillation	4.25E+00	3.29E-07	3.29E-05	5.53E-06	5.53E-04	
		TOTAL	5.04E+00	3.90E-07	3.90E-05	6.56E-06	6.56E-04	1.66E+06 URBAN
9	45	Landtreatment	1.18E+03	5.94E-06	5.94E-04	7.06E-04	7.06E-02	
		TOTAL	1.18E+03	5.94E-06	5.94E-04	7.06E-04	7.06E-02	7.55E+05 URBAN
10	25	Drum Storage	4.92E+00	3.02E-07	3.02E-05	1.10E-05	1.10E-03	
10	25	Storage Tanks	1.42E+01	7.67E-07	7.67E-05	3.40E-05	3.40E-03	
10	25	Distillation	1.42E+01	8.65E-07	8.65E-05	3.14E-05	3.14E-03	
10	25	Impoundment	1.60E+01	9.71E-07	9.71E-05	3.52E-05	3.52E-03	
		TOTAL	5.14E+01	2.93E-06	2.97E-04	1.12E-04	1.12E-02	5.77E+05 TOTAL
11	16	Drum Storage	5.41E+00	2.39E-06	2.39E-06	3.25E-06	3.25E-04	
11	16	Wastewater Treatment	2.28E+02	1.01E-06	1.01E-04	1.37E-04	1.37E-02	
		TOTAL	2.33E+02	1.03E-06	1.03E-04	1.40E-04	1.40E-02	1.15E+06 URBAN

12	49	Impoundments	1.31E+03	2.22E-07	2.22E-05	0.00E+00	0.00E+00		
12	49	Drum Storage	3.20E+01	5.38E-09	5.38E-07	0.00E+00	0.00E+00		
12	49	Landfill	4.16E+02	8.79E-08	8.99E-06	0.00E+00	0.00E+00		
12	49	Storage Tanks	4.09E+01	6.87E-09	6.87E-07	0.00E+00	0.00E+00		
		TOTAL	1.81E+03	3.04E-07	3.04E-05	0.00E+00	0.00E+00	9.14E+04	RURAL
17	26	Distillation	1.33E+01	2.33E-07	2.33E-05	9.94E-05	9.94E-03		
17	28	Drum Storage	3.39E+00	2.68E-08	2.68E-06	1.15E-05	1.15E-03		
13	28	Storage Tanks	5.41E+01	4.30E-07	4.30E-05	1.84E-04	1.84E-02		
13	28	Tanker Unloading	6.20E+00	4.92E-08	4.92E-06	2.11E-05	2.11E-03		
		TOTAL	9.30E+01	7.36E-07	7.38E-05	3.1E-04	3.1E-02	6.21E+06	URBAN
14	28	Storage Tanks	1.20E+00	5.64E-09	5.64E-07	1.08E-06	1.08E-04		
14	28	Distillation	1.71E+01	8.04E-08	8.04E-06	1.54E-05	1.54E-03		
14	28	Incineration	6.00E-01	2.86E-07	2.86E-07	5.40E-07	5.40E-05		
14	28	Drum Storage	1.39E+00	1.14E-08	1.14E-06	2.15E-06	2.15E-04		
14	28	Wastewater Treatment	3.72E+01	1.75E-07	1.75E-05	3.35E-05	3.35E-03		
		TOTAL	5.85E+01	2.75E-07	2.75E-05	5.26E-05	5.26E-03	6.25E-05	RURAL
15	29	Wastewater Treatment/API	5.00E-01	1.15E-09	1.15E-07	1.00E-07	1.00E-05		
15	29	Impoundment	8.54E+02	1.99E-06	1.99E-04	1.71E-04	1.71E-02		
15	29	Landtreatment	1.53E+01	3.52E-08	3.52E-06	3.06E-06	3.06E-04		
		TOTAL	8.70E+02	2.03E-06	2.03E-04	1.74E-04	1.74E-02	1.07E+05	RURAL
16	28	Wastewater Treatment/API	6.80E-01	3.17E-08	3.17E-06	8.16E-06	8.16E-04		
16	28	Distillation	1.65E+01	7.69E-07	7.69E-05	1.98E-04	1.98E-02		
16	28	Drum Storage	4.00E-02	1.86E-09	1.86E-07	4.80E-07	4.80E-05		
16	28	Storage Tanks	3.20E+00	1.41E-07	1.41E-05	3.84E-05	3.84E-03		
		TOTAL	2.04E+01	9.43E-07	9.43E-05	2.45E-04	2.45E-02	4.90E+06	URBAN
17	28	Storage Tanks	4.50E-02	2.16E-10	2.16E-08	9.00E-08	9.00E-06		
17	28	Distillation	1.52E+00	7.28E-09	7.28E-07	3.04E-06	3.04E-04		
17	28	Impoundments	2.20E+02	1.05E-06	1.05E-04	4.39E-04	4.39E-02		
17	28	Drum Storage	6.00E-02	2.87E-10	2.87E-08	1.20E-07	1.20E-05		
		TOTAL	2.21E+02	1.06E-06	1.06E-04	4.42E-04	4.42E-02	2.19E+06	URBAN
18	49	Tanker Unloading	4.30E-01	4.14E-09	4.14E-07	3.83E-06	3.83E-04		
18	49	Storage Tanks	9.19E+00	8.69E-08	8.69E-06	8.18E-05	8.18E-03		
18	49	Drum Unloading	9.20E-01	8.35E-09	8.35E-07	8.19E-06	8.19E-04		
		TOTAL	1.05E+01	9.99E-08	9.99E-06	9.38E-05	9.38E-03	2.63E+06	URBAN
20	NA	Impoundment	2.10E+01	6.38E-09	6.38E-07	2.10E-06	2.10E-04		
		TOTAL	2.10E+01	6.38E-09	6.38E-07	2.10E-06	2.10E-04	1.64E+05	URBAN
21	28	Incineration	6.00E-01	1.42E-10	1.42E-08	6.00E-08	6.00E-06		
21	28	Landfill	6.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00		
		TOTAL	6.00E-01	1.42E-10	1.42E-08	6.00E-08	6.00E-06	9.47E+04	RURAL
22	42	Impoundment	3.46E+02	6.30E-08	6.30E-06	0.00E+00	0.00E+00		
		TOTAL	3.46E+02	6.30E-08	6.30E-06	0.00E+00	0.00E+00	1.07E+04	RURAL
23	NA	Wastewater Treatment	6.47E+02	2.05E-06	2.05E-04	1.16E-03	1.16E-01		
23	NA	Drum Storage	2.10E+00	8.75E-09	8.75E-07	3.83E-06	3.83E-04		
23	NA	Incineration	1.21E+00	1.84E-09	1.84E-07	2.18E-06	2.18E-04		
		TOTAL	6.50E+02	2.06E-06	2.06E-04	1.17E-03	1.17E-01	3.43E+06	URBAN

24	28	Injection Well	6.00E-01	3.75E-09	3.75E-07	1.80E-07	1.80E-05		
24	28	Drum Filling	1.80E-03	1.13E-11	1.13E-09	5.40E-10	5.40E-08		
24	28	Storage Tanks	1.73E+00	1.08E-08	1.08E-06	5.15E-07	5.15E-05		
24	28	Incineration	1.21E+00	7.55E-09	7.56E-07	3.83E-07	3.83E-05		
			*****	*****	*****	*****	*****		
		TOTAL	3.54E+00	2.21E-08	2.21E-06	1.06E-06	1.06E-04	2.11E+05	URBAN
25	29	Storage Tank	9.30E-02	6.64E-10	6.64E-08	2.38E-07	2.38E-05		
25	29	Drum Storage	1.80E+00	1.21E-08	1.21E-06	4.32E-06	4.32E-04		
			*****	*****	*****	*****	*****		
		TOTAL	1.90E+00	1.27E-08	1.27E-06	4.56E-06	4.56E-04	1.77E+06	URBAN
26	49	Landtreatment	3.10E+02	1.74E-07	1.74E-05	6.20E-05	6.20E-03		
26	49	Landfill	8.30E-02	4.66E-11	4.66E-09	1.86E-05	1.86E-06		
			*****	*****	*****	*****	*****		
		TOTAL	3.10E+02	1.74E-07	1.74E-05	6.20E-05	6.20E-03	3.18E+05	RURAL
27	28	Drum Storage	2.90E-01	2.20E-08	2.20E-07	8.70E-08	8.70E-06		
27	28	Wastewater Treatment	4.10E+00	3.12E-08	3.12E-06	1.23E-06	1.23E-04		
27	28	Impoundment	7.30E-08	5.55E-16	5.55E-14	2.19E-14	2.19E-12		
			*****	*****	*****	*****	*****		
		TOTAL	4.39E+00	3.34E-08	3.34E-06	1.32E-06	1.32E-04	4.68E+05	URBAN
28	17	Landtreatment	4.01E+03	4.50E-06	4.50E-04	6.42E-03	6.42E-01		
			*****	*****	*****	*****	*****		
		TOTAL	4.01E+03	4.50E-06	4.50E-04	6.42E-03	6.42E-01	8.35E+05	RURAL
29	35	Storage Tanks	1.77E+00	5.17E-09	5.17E-07	4.60E-06	4.60E-04		
29	35	Drum Storage	3.10E+00	9.05E-09	9.05E-07	8.06E-06	8.06E-04		
			*****	*****	*****	*****	*****		
		TOTAL	4.87E+00	1.42E-08	1.42E-06	1.27E-05	1.27E-03	3.63E+06	URBAN
31	49	Impoundments	4.00E+00	1.49E-09	1.49E-07	2.00E-06	2.00E-04		
			*****	*****	*****	*****	*****		
		TOTAL	4.00E+00	1.49E-09	1.49E-07	2.00E-06	2.00E-04	1.20E+06	RURAL
32	28	Drum Storage	2.60E-01	1.43E-08	1.43E-06	9.10E-07	9.10E-05		
32	28	Distillation	3.52E+00	1.94E-07	1.94E-05	1.23E-05	1.23E-03		
32	28	Storage Tanks	1.87E+01	1.03E-06	1.03E-04	6.53E-05	6.53E-03		
			*****	*****	*****	*****	*****		
		TOTAL	2.24E+01	1.24E-06	1.24E-04	7.85E-05	7.85E-03	2.50E+06	RURAL
33	49	Tanker Unloading	1.72E+00	5.95E-08	5.95E-06	3.27E-06	3.27E-04		
33	49	Incineration	6.00E-01	2.08E-08	2.08E-06	1.14E-06	1.14E-04		
			*****	*****	*****	*****	*****		
		TOTAL	2.32E+00	8.03E-08	8.03E-06	4.41E-06	4.41E-04	1.67E+06	URBAN
34	29	Drum Storage	9.00E-03	3.82E-11	3.82E-09	1.26E-08	1.26E-06		
34	29	Wastewater Treatment/API	2.30E+00	2.75E-09	2.75E-07	3.22E-06	3.22E-04		
34	29	Treatment Tanks	1.19E+00	5.05E-09	5.05E-07	1.67E-06	1.67E-04		
			*****	*****	*****	*****	*****		
		TOTAL	3.50E+00	1.48E-08	1.48E-06	4.90E-06	4.90E-04	1.51E+06	RURAL
35	02	Distillation	3.06E+00	2.75E-08	2.75E-06	2.75E-08	2.75E-06		
35	02	Tank Storage	1.51E+00	1.33E-08	1.33E-06	1.33E-08	1.33E-06		
35	02	Incineration	1.24E+00	1.12E-08	1.12E-06	1.12E-08	1.12E-06		
			*****	*****	*****	*****	*****		
		TOTAL	5.81E+00	5.20E-08	5.20E-06	5.20E-08	5.20E-06	1.12E+06	URBAN
36	49	Landfill	1.91E+02	1.23E-06	1.23E-04	9.07E-05	9.07E-07		
36	49	Wastewater Treatment	5.53E+05	3.76E-08	3.76E-03	2.76E-07	2.76E-01		
36	49	Incineration	6.00E-01	4.08E-09	4.08E-07	3.00E-07	3.00E-05		
36	49	Storage Tank	5.45E+00	3.71E-08	3.71E-06	2.72E-06	2.72E-04		
			*****	*****	*****	*****	*****		
		TOTAL	5.71E+02	3.89E-05	3.89E-03	2.82E-03	2.66E-01	5.40E+05	URBAN

37	28	Distillation	3.30E+00	2.71E-08	2.71E-06	1.96E-06	1.96E-04		
37	28	Storage Tanks	2.70E-01	2.22E-09	2.22E-07	1.62E-07	1.62E-05		
			*****	*****	*****	*****	*****		
		TOTAL	3.57E+00	2.93E-08	2.93E-06	2.14E-06	2.14E-04	5.15E+05	USE-
38	42	Storage Tanks	1.02E+01	8.10E-08	8.10E-06	1.12E-04	1.12E-02		
38	42	Crus Storage	5.30E+00	4.21E-08	4.21E-06	5.93E-05	5.83E-03		
			*****	*****	*****	*****	*****		
		TOTAL	1.55E+01	1.23E-07	1.23E-05	1.71E-04	1.71E-02	1.18E+07	USE+
39	28	Crus Storage	1.94E+00	1.54E-08	1.54E-06	2.13E-05	2.13E-03		
			*****	*****	*****	*****	*****		
		TOTAL	1.94E+00	1.54E-08	1.54E-06	2.13E-05	2.13E-03	1.30E+07	USE+
40	NA	Landfill	7.50E-01	3.92E-10	3.92E-08	2.25E-07	2.25E-05		
40	NA	Incubement/Mining Pit	1.58E+02	8.26E-08	8.26E-06	4.74E-05	4.74E-03		
			*****	*****	*****	*****	*****		
		TOTAL	1.59E+02	8.30E-08	8.30E-06	4.76E-05	4.76E-03	2.47E+05	PLF-

APPENDIX B

EMISSION MODEL EQUATIONS

TABLE B-1. SUMMARY OF EMPIRICAL RELATIONSHIPS TO DETERMINE THE INDIVIDUAL LIQUID AND GAS PHASE MASS TRANSFER COEFFICIENTS FOR A NONAERATED IMPOUNDMENT¹

Liquid Phase Coefficient (k_L):

$$[1] \quad k_L = \left(11.4 \text{ Re}^{\ast 0.195} - 5 \right) \left(\frac{\text{MW}_{\text{benzene}}}{\text{MW}_i} \right)^{0.5} \quad (\text{Cohen, Cocchio and Mackay, 1978})$$

for $0.11 < \text{Re}^{\ast} \leq 102$, where k_L is in cm/hr and

$$\text{Re}^{\ast} = \frac{7.07 \times 10^{-3} (Z_{10}) (U_{10})^{1.25}}{\text{Va} \exp(56.6/U_{10}^{0.25})}$$

if $\text{Re}^{\ast} < 0.11$, then $k_L = 2.4$ cm/hr

where;

Re^{\ast} = roughness Reynolds number

$\text{MW}_{\text{benzene}}$ = molecular weight of benzene (78.1 g/g-mole)

MW_i = molecular weight of compound i (g/g-mole)

U_{10} = wind velocity (cm/s) measured at height Z_{10} (10 m) above the water surface (cm)

Va = air kinematic viscosity (cm²/sec)

$$[2] \quad k_L = (1.3 \text{ Re}^{\ast 0.195} - 0.57) \left(\frac{D_{i, \text{H}_2\text{O}}}{D_{\text{TOL}, \text{H}_2\text{O}}} \right) \quad (\text{Cohen, et al. as presented by Hwang, 1982})$$

where;

k_L is in lb-mol/ft²-hr. (Note: This equation is a modified form of equation 1 to obtain the k_L value in units of lb-mol/ft²-hr).

Re^{\ast} = roughness Reynolds number (determined as above)

$D_{i, \text{H}_2\text{O}}$ = diffusion coefficient of compound i in water (cm²/sec)

$D_{\text{TOL}, \text{H}_2\text{O}}$ = diffusion coefficient of toluene in water (cm²/sec)

TABLE B-1. (CONTINUED)

$$[3] \quad k_L = 3.12 (1.024)^{\theta-20} U_o^{0.67} H_o^{-0.85} \left(\frac{D_{i,H_2O}}{D_{O_2,H_2O}} \right) \quad \text{(Owens, Edwards and Gibbs, 1964, as presented by Hwang, 1982)}$$

where;

k_L is in lb-mol/ft²-hr

θ = temperature (°C)

U_o = surface velocity, ft/sec, normally 0.035 x wind speed (ft/sec) for natural surface, and 0.1 ft/sec for outside region of effect of aerators in the biological treatment.

H_o = effective depth of surface impoundment (ft)

D_{O_2,H_2O} = diffusion coefficient of oxygen in water (cm²/sec)

Gas Phase Coefficient (k_G):

$$[1] \quad k_G = 0.0958 U_{air}^{0.78} N_{sc}^{-0.67} d_e^{-0.11} \frac{\rho_{air}}{MW_{air}} \quad \text{(MacKay and Matsugu, 1973)}$$

where;

k_G is in lb-mol/ft²-hr

U_{air} = wind speed (m/hr)

N_{Sc} = gas Schmidt number = $\mu_g / \rho_g D_{i,air}$

μ_g = absolute gas viscosity (g/cm-sec)

ρ_g = density of gas (g/cm³)

$D_{i,air}$ = diffusion coefficient of compound i in air (cm²/sec)

d_e = effective diameter of the quiescent area of the impoundment
 $(m) = \left(\frac{4A_c}{\pi} \right)^{0.5}$

A_c = area of convective (natural) zone of impoundment surface (m²)

ρ_{air} = density of air (lb/ft³)

MW_{air} = molecular weight of air (28.8 lb/lb-mole)

TABLE B-2. THIBODEAUX, PARKER AND HECK MODEL FOR SURFACE IMPOUNDMENTS ²

Type of Model: Predictive
 Basis: Mass transport calculations based on the two-film resistance theory

Form: $E_i = M_i K_{iL}(X_i - X_i^*)$
 and, for each volatile component i

$$K_{iL} = (K_{iL}^t A_t + K_{iL}^n A_n) / (A_t + A_n)$$

$$\frac{1}{K_{iL}^t} = \frac{1}{k_{iL}^t} + \frac{1}{H_i k_{ig}^t}$$

$$\frac{1}{K_{iL}^n} = \frac{1}{k_{iL}^n} + \frac{1}{H_i k_{ig}^n}$$

<u>Symbol</u>	<u>Symbol/Parameter Definition</u>	<u>Typical Precision^a</u>	<u>Source of Input Parameter</u>
A_t, A_n	Surface areas of the turbulent and natural zones, respectively, (cm ²)	±25%	Measured
E_i	Flux of component i from the impoundment surface, (g/cm ² -s)	Unk	—
H_i	Henry's law constant in mole fraction form, $H = y/x$	Unk	Literature data or estimation
k_{ig}^t, k_{ig}^n	Individual gas phase mass transfer coefficients for the turbulent and natural zones, respectively, (mol/cm ² -s)	Unk	Calculated from empirical correlations*
K_{iL}	Overall liquid-phase mass transfer coefficient for component i, (mol/cm ² -s)	Unk	Calculation

k_{iL}^t, k_{iL}^n	Individual liquid phase mass transfer coefficients for the turbulent and natural zones, respectively, (mol/cm ² -s)	Unk	Calculated from empirical correlations*
K_{iL}^t, K_{iL}^n	Overall liquid phase mass transfer coefficients for the turbulent (aerated) and natural (un-aerated) zones of the impoundment, respectively, (mol/cm ² -s)	Unk	Calculated
M_i	Molecular weight of component i, (g/g-mol)	0%	Literature data
X_i	Mole fraction of component i in the aqueous phase	<u>+2%</u>	Calculated from concentration measurements
X_i^*	Mole fraction of component i in equilibrium with the mole fraction of component i in the air, y_i . If y_i is assumed to be negligibly small, $X_i^* = 0$.	<u>+2%</u>	Calculated from measured concentrations in the atmosphere

Empirical Correlation for Individual Mass Transfer Coefficients are:

$$k_{iL}^t = \frac{0.823 J (\text{POWER}) \alpha (1.024)^{\theta-20}}{a_v V} \left(\frac{D_{iw}}{D_{O_2w}} \right)^{1/2} \quad (a)$$

$$k_{iG}^t = 1.35 \times 10^{-5} \frac{\rho_g D_{i,\text{air}}}{d} N_{Re}^{1.42} N_P^{0.40} N_{Sc}^{0.5} N_{Fr}^{-0.21} \quad (b)$$

N_{Re} = Reynolds Number, $d^2 \omega \rho_g / \mu_g$

N_P = Power Number, $P_{rg} / \rho_L d^5 \omega^3$

N_{Sc} = Schmidt Number, $\mu_g/D_{i,air} \rho_g$

N_{Fr} = Froude Number, dw^2/g

$$k_{iL}^n = (3.421 \times 10^{-4})(1.024)^{\theta-20} U_o^{0.67} H_o^{-0.85} \left(\frac{D_{iw}}{D_{o2w}} \right) \quad (c)$$

$$k_{iG}^n = 0.482 U_{air}^{0.78} N_{Sc}^{-0.67} d_e^{-0.11} \left(\frac{\rho_g}{MW_{air}} \right) \quad (d)$$

<u>Symbol</u>	<u>Symbol/Parameter Definition</u>	<u>Typical Precision</u>	<u>Source of Input Parameter</u>
J	oxygen-transfer rating of surface aerator; normally in the range of about 2-4 lb O ₂ /hp-hr	-	Estimated
POWER	total power input to aerators in aerated surface impoundment, Hp	±10%	Measured
α	correction factor for wastewater/clean water oxygen transfer (0.80 to 0.85)	-	Estimated
θ	water temperature, (°C)	±1%	Measured
D _{iw}	diffusion coefficient for component i in water, cm ² /sec	±15%	Laboratory data or estimated
D _{o2w}	diffusion coefficient for oxygen in water, (cm ² /sec)	±15%	Laboratory data or estimated
a _v	surface area per unit of volume of surface impoundment, (ft ² /ft ³)	±10%	Calculated
V	volume of surface impoundment in region affected by aeration, (ft ³)	±25%	Estimated
ρ _g	density of air, (g/cm ³)	Unk	Literature

$D_{i,air}$	diffusion coefficient for component "i" in air, (cm^2/sec)	$\pm 15\%$	Laboratory data or estimated from correlations
d	diameter of aerator turbine or impeller, (ft) (cm in Eq. for k_{iG} and N_{Re})	$\pm 1\%$	Measured
w	rotational speed of turbine impellor, (rad/sec)	$\pm 10\%$	Measured
μ_g	viscosity of air, (g/cm-sec)	Unk	Literature
P_r	power to impeller,	$\pm 10\%$	Calculated
g	acceleration of gravity 32.2 ft/sec^2	$\pm 0\%$	Literature
L	density of liquid, (g/cm^3)	$\pm 2\%$	Laboratory data or literature
U_o	surface velocity, (m/sec)	$\pm 10\%$	Measurements and calculated
H_o	effective depth of surface impoundment, (m)	$\pm 10\%$	Measured or estimated
U_{air}	wind speed, (m/sec)	$\pm 10\%$	Measured
d_e	effective diameter of quiescent area of surface impoundment, (m)	$\pm 25\%$	Calculated
MW_{air}	molecular weight of air, (g/g-mole)	$\pm 0\%$	Literature
A_c	non-aerated impoundment area (m^2)	$\pm 10\%$	Measurements and calculations

^aIn many cases these are rough estimates. Values can be refined with future data. Unk = unknown.

TABLE B-3. THIBODEAUX-HWANG MODEL FOR VOLATILE ORGANIC EMISSIONS FROM LANDTREATMENT OPERATIONS 2

Basis: Emission rate is controlled by diffusion rate of vapor through the air-filled pores of the landtreated soil.

Form:

$$E_i = \frac{D_{ei} C_{ig}}{h_s^2 + \left(\frac{2 D_{ei} t A (h_p - h_s) C_{ig}}{M_{io}} \right)^{1/2}}$$

$$C_{ig} = \frac{H_c C_{io}}{\left(1 + \frac{H_c D_{ei} Z_o}{D_{wi} A_s f(y)} \right)}$$

and

$$f(y) = (h_p^2 + h_p h_s - 2h_s^2)/6$$

Symbol	Symbol/Parameter Definition	Typical Precision	Source of Input Parameter
A	surface area over which waste is applied, cm ²	± 2%	measured
A _s	interfacial area per unit volume of soil for the oily waste, cm ² /cm ³	-	calculated
C _{ig}	effective wet zone pore space concentration of component i, g/cm ³	-	calculated
C _{io}	concentration of component i in oil, g/cm ³	± 25%	calculated
D _{ei}	effective diffusivity of component i in the air-filled soil pore spaces, cm ² /s	± 25%	published data; estimation
d _p	soil clump diameter, cm	-	average calculated from measurements or estimated

(Continued)

TABLE B-3. (CONTINUED)

D_{wi}	effective diffusivity of compound i in the oil, cm^2/s	$\pm 5\%$	published data; estimation
E_i	flux of component i from the soil surface, $\text{g}/\text{cm}^2\text{-sec}$	-	calculated
$f(y)$	$(h_p^2 + h_p h_s - 2h_s^2)/6$ accounts for the lengthening dry zone	-	calculated
H_c	Henry's Law constant in concentration form, $\text{cm}^3 \text{ oil}/\text{cm}^3 \text{ air}$	$\pm 15\%$	published data or measurement
h_p	depth of soil contaminated or wetted with landtreated waste, cm	$\pm 10\%$	measured
M_{io}	initial mass of component i incorporated into the zone $(h_p - h_s)$, g	$\pm 5\%$	measured
t	time after application, sec		measured
y	height of wetted soil remaining after partial drying, cm	-	measured
w_f	weight fraction oil in film form in soil	-	calculated
Z_o	oil layer diffusion length, cm	-	calculated or estimated
f	fraction of oil in film form	-	estimated
ρ_p	soil clump density, g/cm^3	$\pm 10\%$	measured or estimated
$\bar{\rho}_w$	waste-oil density, g/cm^3	$\pm 10\%$	measured or estimated

TABLE B-4. FARMER MODEL FOR VOLATILE ORGANIC EMISSIONS FROM COVERED LANDFILLS²

Basis: Emission rate is assumed to be mass transfer controlled by diffusion of gases through the air-filled soil pores.

Form:

$$E_i = K_D D_i C_s A \frac{(P_a)^{10/3}}{(P_t)^2} \left(\frac{1}{L} \right) \left(\frac{W_i}{W} \right)$$

$$C_s = \frac{P_i M_i}{RT}$$

$$P_t = 1 - \left(\frac{B}{\rho_s} \right)$$

$$\theta = \left(\frac{W_w}{W} \right) \left(\frac{B}{\rho_w} \right)$$

$$P_a = P_c - \theta$$

<u>Symbol</u>	<u>Symbol/Parameter Definition</u>	<u>Precision</u>	<u>Input Parameter</u>
A	Surface area of the landfill (cm ₂)	±0.1%	File data or direct measurement
B	Soil bulk density (g/cm ₃)	±8%	Varies from 1 to 2 g/cc. Need direct measurement for accuracy.
C _s	Saturation vapor concentration (g/m ₃)	.05%	Calculated from gas law and species vapor pressure.

(Continued)

TABLE B-4. (CONTINUED)

$D_{i,air}$	Diffusion coefficient of the species of interest in air (cm^2/sec)	$\pm 5\%$	Calculated value from literature or ratio to a compound with a known D by molecular weight.
E_i	Mass emission rate (g/sec)	-	--
K_D	Codisposal factor. Use 1.0 for isolated toxic waste disposal and 6.0 for toxic waste codisposed with biologically degradable wastes.	$\pm 10\%$ -2%	Literature
L	Depth of soil cover (cm)	$\pm 17\%$	File data or measurement
M_i	Molecular weight of the species (g/mole)	-	Literature
P_a	Air-filled porosity (dimensionless)	$\pm 30\%$	Calculated
P_i	Vapor pressure of the species in interest (mm Hg)	5%	Literature or direct measurement.
ρ_s	Soil particle density (g/cm^3)	$\pm 8\%$	Recommends 2.65 g/cm^3 for most mineral material.
P_t	Soil porosity (dimensionless)	$\pm 13\%$	Can be estimated based on soil bulk density and soil particle density.
ρ_w	Density of water (g/cm^3)	$\pm 2\%$	Literature
R	Gas constant $62,300 \frac{\text{mm Hg} \cdot \text{cm}^3}{^\circ\text{K} \cdot \text{mole}}$	-	Given

(Continued)

TABLE B-4. (CONTINUED)

W_i/W	Weight fraction of the species of interest in the disposed waste (g/g)	$\pm 20\%$	Direct measurement.
W_w/W	Weight fraction of water in the soil cover	$\pm 5\%$	Direct measurement.
T	Temperature ($^{\circ}\text{K}$)	$\pm 1^{\circ}\text{K}$	Direct measurement.
θ	Volume fraction of water in the soil cover (g/g)	$\pm 17\%$	Direct measurement.

REFERENCES FOR APPENDIX B

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2. Farino, W., P. Spawn, M. Jasinski, and B. Murphy (GCA/Technology Division). Evaluation and Selection of Models for Estimating Air Emissions from Hazardous Waste Treatment, Storage and Disposal Facilities. Prepared for U.S. Environmental Protection Agency: Office of Solid Waste. Washington, DC. May 1983. Chapters 4, 6 and 7.

APPENDIX C

DEFAULT PARAMETERS FOR EMISSION MODELS

APPENDIX C. DEFAULT PARAMETERS FOR EMISSION MODELS

Model	Parameters	Default Value	Reference (default)	Comment
Drum handling - working loss	Saturation factor	0.2	1 (p 5-6)	Assumed bottom filling
	Vapor pressure	NA	--	Compound specific
	Molecular Weight	NA	--	Compound specific
	Temperature	25°C	--	Assumed
Fixed-roof tank: AP-42	Tank diameter	based on capacity	--	$2x [v/(23.5 \cdot \text{height})]^{0/5}$ where height is in 8' intervals, or manufacturer's specifications
	Average vapor space height	0.5 (height) in ft	1 (p. 5-12)	Average of national estimates for large (0.75) and small (0.25) facilities.
	Average diurnal temperature change	20°F	2 (p. 7-3)	
	Paint factor	1.0	--	White, good condition tank. Best case.
	Adjustment for small diameter	NA	--	
	Product factor	NA	--	Compound specific
	Turnover factor	NA	--	
	Annual throughput	NA	--	
Surface Impoundments: Cohen, Cocchio, Mackay, Owens				
Aerated	Air temperature	25°C	--	Assumed
	Water temperature	25°C	--	Assumed
	Liquid density	1 g/cm ³	--	Density of water
	Wind speed	variable	--	Closest available STAR aerometric data
	Height of wind speed measure	1000 cm	--	Assumed
	Effective depth	410 cm	4	
	Surface area	NA	--	Site specific
	Turbulent area fraction	0.2%	3 (p. 38)	
	Aerator parameters			
	diameter of impeller	60 cm	2 (p. 4-25)	
	rotational speed	126 radians/second	2 (p. 4-25)	
	volume affected	50-1124 m ³	2 (p. 4-25)	Based on aerators required
	power to impeller	5-100 Hp	2 (p. 4-25)	Based on turbulent area required
	total power to aerators	NA	--	Based on turbulent area required
	oxygen transfer rating	3 lb O ₂ /hr-hp	3 (p. 37)	Typical range 2-4
	correction factor for oxygen transfer	0.825	3 (p. 37)	Typical range 0.8 - 0.85

(continued)

APPENDIX C. DEFAULT PARAMETERS FOR EMISSION MODELS (continued)

Model	Parameters	Default Value	Reference (default)	Comment
Non-aerated	See Aerated Impoundments, except			
	Effective depth	226 cm	4	
	treatment	194 cm	4	
	storage	30 cm	4	
Landtreatment	disposal			
Thibodeaux	Initial concentration of component	NA	--	Wastestream specific
	Soil contamination depth	23 cm	3 (p. 17)	
	Depth of subsurface injection	NA	--	Site specific
	Duration of waste on ground	NA	--	Site specific
	Surface area of application	NA	--	Site specific
	Fxn of oil in film form	1.0	3 (p. 17)	
	Initial mass of component	NA	--	Site specific
	Soil clump or particle diameter	0.005 cm	3 (p. 17)	
	Soil clump density	2.65 g/cm ³	3 (p. 17)	
	Oil density	0.78 g/cm ³	3 (p. 17)	
	Bulk density of soil	1.5 g/m ³	2 (p. 6-4)	
	Porosity of soil	0.43	2 (p. 6-3)	
Hartley	Evaporative rate	34.78 g/cm ² -mo	5	Kings County, CA
	Relative humidity	0.25	5	Kings Co., CA for West Coast or Texas
		0.6	3 (p. 12)	Other sites
	Vapor pressure	NA	--	Compound specific
	Molecular weight	NA	--	Compound specific
	Vapor pressure (water)	Constant	--	23.756 mm Hg @ 25°C
	Molecular weight (water)	Constant	--	18

(continued)

APPENDIX C. DEFAULT PARAMETERS FOR EMISSION MODELS (continued)

Model	Parameters	Default Value	Reference (default)	Comment
Landfill (covered): Farmer	Air temperature	25°C	--	Assumed
	Surface area	NA	--	Site specific
	Depth of soil cover	30 cm	3 (p. 22)	
	Bulk density	1.5 g/cm ³	2 (p.5-7)	
	Soil particle density	2.65 g/cm ³	3 (p. 22)	
	Weight frn of water	0.2	3 (p. 22)	
	Weight frn of component in waste	NA	--	Wastestream specific
Incinerator fugitives	Source inventory	2 pumps	--	Engineering judgment
		1 relief valve	--	Engineering judgment
Deep well injection fugitives	Source inventory	2 pumps	--	Engineering judgment
		1 relief valve		
Recycling fugitives	Source inventory	2 light liquid pumps	--	Engineering judgment
		1 heavy liquid pump	--	Engineering judgment
		27 gas valves	6	
		35 light liquid valves	6	
		17 heavy liquid valves	6	
		2 safety relief valves	--	Engineering judgment
		21 open-ended lines	6	
		5 sampling connections	6	
		120 flanges	6	

References for Appendix C

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APPENDIX D

SAMPLE CALCULATIONS

DRUM STORAGE AND HANDING

Drum storage losses are considered as working losses and fugitive losses.

In the case of working losses

$$L_W(\text{lbs}/1000 \text{ gallons}) = 12.46 \frac{\text{SPM}}{T}$$

where,

S = saturation factor,

P = vapor pressure of contents in PSIA,

M = molecular weight of contents,

T = temperature in degrees Rankin.

For the drums handled at facility #18, the following values were used:

S = 0.2 (assumes bottom filling, see Appendix C),

P = 2.5 PSIA (vapor pressure of trichloroethylene; the drum contents had to be assumed, see Appendix C)

M = 131 (molecular weight of trichloroethylene)

T = 536.4°R (25°C)

Throughput = 100 drums weekly, or 260,000 gallons yearly @50 gallons per drum. Substituting into the equation yields 1.532 lbs/1000 gallons or 0.18 Mg/year.

Fugitive losses stem from equipment leakage and spillage. These factors, respectively, are 0.0017 lbs/drum and 50 gallons per 100,000 gallons. Again substituting the throughput figures, this yields 8.84 lbs/yr and 130 gallons/yr, respectively. At a density of 1.5 g/ml (trichloroethylene), the latter figure translates to 0.738 Mg/yr. Total fugitive losses are 0.74 Mg/yr.

Total drum storage losses total 0.92 Mg/yr.

TANK UNLOADING¹

Two factors are used in estimating emissions from tanker unloading:

0.095 g/kg handled for spillage, and
0.36 g/kg handled for unloading.

At facility #13, approximately 1.4×10^7 kg/yr are unloaded from tankers.
Using the factors above,

spillage = 1.3 Mg/yr emitted, and
unloading = 5.0 Mg/yr emitted.

FIXED-ROOF STORAGE TANKS²

Fixed roof tank breathing losses can be estimated from:

$$L_B = (2.26 \times 10^{-2})M [P/(14.7-P)]^{0.68} D^{1.73} H^{0.51} T^{0.50} F_P C K_C$$

where: L_B = fixed roof breathing loss (lb/yr)

M = molecular weight of vapor in storage tank (lb/lb mole)

P = true vapor pressure at bulk liquid conditions (PSIA)

D = tank diameter (ft)

H = average vapor space height, including roof volume correction (ft)

T = average ambient diurnal temperature change (°F)

F_P = paint factor (dimensionless)

C = (adjustment factor for small diameter tanks (dimensionless)

K_C = product factor (dimensionless).

For a tank at facility #18 storing toluene, the relevant values are as follows:

M = 92 (toluene)

P = 0.56 PSIA (toluene at 25°C)

D = 11.4 (given)

H = 16.3 (assumed half full, on average)

T = 20°F (see Appendix C)

F_P = 1.33 (light gray tank, given)

C = 0.6 adjustment for small diameter)

K_C = 1.0 (all organic liquids except crude oil)

Substituting these values yields a breathing loss estimate at 105 Kg.

Fixed roof tank working losses can be estimated from:

$$L_W = 2.40 \times 10^{-2} MPK_N K_C \quad (2)$$

where: L_W = fixed roof working loss (lb/10³ gal throughput)

M = molecular weight of vapor in storage tank (lb/lb mole)

P = true vapor pressure at bulk liquid conditions (PSIA)

K_N = turnover factor dimensionless)

K_C = product factor (dimensionless).

The fixed roof working loss (L_W) is the sum of the loading and unloading losses. Special tank operating conditions may result in losses which are significantly greater or lower than the estimates provided by Equation 2.

For the toluene tank at facility #18, the values are as follows:

M = 92 (toluene)

P = 0.56 PSIA (toluene at 25°C)

K_N = 1 (less than 36 turnovers per year)

K_C = 1

Throughput = 34,605 ga/yr.

Substituting, losses are 0.56 kg/1000 gallons or 19.4 kg/year.

Total loss of toluene from this tank is therefore estimated at 124.4 kg/yr.

TREATMENT TANKS - OIL/WATER SEPARATORS

Oil/water separators were treated as uncontrolled emitters. An emission factor (Reference 3) of 0.6 kg per 1000 liters throughput was used. At facility #15, emissions were calculated using a throughput of 806,250 liters annually for the API separator. This actually is the sludge volume generated by the separator and is therefore an underestimate. No total throughput was available. Using this data, emissions are calculated as 0.5 Mg per year for the API separator.

DISPOSAL IMPOUNDMENTS AND LAND SPREADING

The Hartley model for landtreatment emissions is:⁴

$$E_a = E_w / (1 - RH) [P_a M_a^{0.5} / P_w M_w^{0.5}] (A) (W_i / W)$$

where:

E_a = emission of chemical a in g/month

A = surface area (cm^2)

W_i / W = weight fraction of a in waste

E_w = evaporate rate of water (g/cm^2 - month)

M_w = molecular weight of water

P_w = vapor pressure of water (mm Hg)

RH = relative humidity

P_a = vapor pressure of a (mm/g)

M_a = molecular weight of a

For facility #9, the appropriate values for these variables are given below. The site is in Texas and landtreats K wastes. Typical waste code compositional breakdowns were used to determine the organics and their concentrations.

$A = 3.2 \times 10^8 \text{ cm}^2$ (given)

$E_w = 34.78 \text{ g}/\text{cm}^2$ - month (California data, see Appendix C)

$M_w = 18 \text{ g}/\text{mole}$ (given)

$P_w = 23.756 \text{ mm Hg @} 25^\circ\text{C}$ (given)

$RH = 25\%$ (California data, see Appendix B)

<u>Volatile organic</u>	<u>Pa(mmHg)</u>	<u>Ma</u>	<u>Wi/W</u>	<u>Emission</u> (mg/yr)
Benz(a)pyrene	7.5×10^{-9}	252	7.4×10^{-8}	0.0
Cyanide (as HCN)	726	27	1.7×10^{-4}	1140
Phenol	0.34	92	7.4×10^{-5}	7.2
Oil (as crude)	6.0×10^{-3}	189	9.0×10^{-2}	13.2

Results of substituting the values are tabulated above. Each chemical constituent is treated separately. Total emissions from landtreatment at the site are 1160 Mg/yr.

SOLVENT RECOVERY STILL

Input

Facility Number 3

Throughput: About 1000 gal/yr of solvent is processed, principally freon-113 and trichloroethylene. It is assumed that 50 percent of the solvent is freon-113, and 50 percent is trichloroethylene. This corresponds to about 2760 kg/yr of trichloroethylene and 2950 kg/yr 1,1,2-trichloro-1,2,2-trifluoroethane (freon-113).

Process Fugitive Emission Sources:

2 light liquid pumps	-	98.8	g/hr-pump (assuming 2 seals/pump)
1 heavy liquid pump	-	42.8	g/hr-pump (assuming 2 seal/pump)
27 gas valves	-	5.6	g/hr valve
35 light liquid valves		7.1	g/hr-valve
17 heavy liquid valves	-	0.23	g/hr-valve
2 safety relief valves	-	104	g/hr-line
21 open ended lines		1.7	g/hr-line
5 sampling connections	-	15	g/hr-connection
120 flanges	-	0.83	g/hr-flange

Note: The numbers of pumps and relief valves were estimated based on a recovery operation configuration comprising a batch distillation column with a condenser and with no tank storage (solvent is pumped directly to and from drums). The numbers, relief valve inventories, and standard ratios of process valves to pumps, etc., are taken from Reference 5. Emission factors for process fugitive sources are also from this reference. The solvent still is assumed to be operated about 1000 hrs/yr.

Other Emission factors:⁶

Still condenser vent:	1.65 g/kg
Drum loading:	0.36 g/kg
Spillage:	0.10 g/kg

Calculated Emission

Process Fugitive:	0.96 Mg/yr total VOC
	0.48 Mg/yr trichloroethylene
	0.48 Mg/yr 1,1,2-trichloro- 1,2,2-trifluoroethane
Still condenser vent:	0.012 Mg/yr total VOC
drum loading; and	0.0058 Mg/yr trichloroethylene
spillage	0.0062 Mg/yr 1,1,2-trichloro- 1,2,2-trifluoroethane
Totals:	0.97 Mg/yr total VOC
	0.49 Mg/yr trichloroethylene
	0.49 Mg/yr 1,1,2-trichloro- 1,2,2-trifluoroethane

INJECTION WELLS

Emissions from the associated pumps and valves in a deep well injection unit were estimated as follows. Two pumps (two seals per pump) and one relief valve, all in light liquid service, were assumed per unit. Total operation time was assumed to be 2000 hours per year. Emission factors for these sources were taken from Reference 5.

98.8 g/hour - pump, and
104 g/hour - valve.

For example, the injection well at facility #21 was treated in this manner. Multiplying the 2000 hours by the emission factors yields 0.395 Mg per two pumps and 0.208 Mg per valve. Total emissions for the unit are therefore 0.60 Mg per year.

INCINERATORS

For the purposes of estimating fugitive emissions associated with incinerators, there were several assumptions made in all cases. Two pumps (two seals per pump) and one relief valve, all in light liquid service, were assumed per unit. Emission factors for these sources were taken from Reference 5:

98.8 g/hour - pump, and
104 g/hour - valve.

Incinerators were assumed to operate 2000 hours per year in each case. For example, the incinerator at facility #14 was treated in this manner. Emissions for the two pumps are 0.395 Mg per year, and for the valve losses are 0.298 Mg. Total emissions for the unit are therefore 0.60 Mg per year.

SURFACE IMPOUNDMENTS

Non-Aerated (Facility #11, model wastestream - see Section 3.3.7)

$$K_G = 2.920 U_{air}^{0.78} N_{Sc}^{-0.67} d_e^{-0.11} \text{ (cm/hr) (MacKay)}^7$$

$$U_{air} = \text{wind speed (meters/hr)} = 15,000 \text{ m/hr}$$

$$N_{Sc} = \frac{M_{air}}{P_{air} D_{i,air}} = \text{Schmidt Number (dimensionless)}$$

$$M_{air} = 4.5686 \times 10^{-7} T + 1.7209 \times 10^{-4}$$

$$= 4.5686 \times 10^{-7} (25.^\circ\text{C}) + 1.7209 \times 10^{-4} = 1.835 \times 10^{-4} \text{ g/cm} \cdot \text{sec}$$

$$P_{air} = MW_{air} / (.08206 (T+273) \times 1000)$$

$$= 28.8 / (.08206 (298) \times 1000) = 1.178 \times 10^{-3} \text{ g/cm}^3$$

$$D_{i,air} = .07 \text{ cm}^2/\text{sec}$$

$$N_{Sc} = 1.835 \times 10^{-4} / (1.178 \times 10^{-3} (.07)) = 2.225$$

$$d_e = (4A / 3.14)^{0.5} = \text{effective diameter (meters)}$$

$$= 4((1.17 \times 10^3 \text{ m}^2) / 3.14)^{0.5} = 38.6 \text{ meters}$$

$$k_G = 2.920 (15,000)^{0.78} (2.225)^{-0.67} (38.6)^{-0.11}$$

$$= 2.920 (1808.64) (.585) (.669)$$

$$= 2066.88 \text{ cm/hr}$$

$$k_L = (11.4 R_{Re}^{.195} - 5) (78.1 / MW_L)^{0.5} \text{ (Cohen, Cocchio, Mackay)}^7$$

$$R_{Re} = \frac{7.07 \times 10^{-3} Z U^{1.25}}{V_a \exp(56.6 / U^{.25})} = \text{Roughness Reynolds \#}$$

$$Z = \text{height of measurement} = 10 \text{ meters} = 1000 \text{ cm}$$

$$U = \text{windspeed} = 15,000 \text{ m/hr} = 416.67 \text{ cm/sec}$$

$$V_a = M_{air} / P_a = \frac{1.835 \times 10^{-4} \text{ g/cm} \cdot \text{sec}}{1.178 \times 10^{-3} \text{ g/cm}^3} = .1558 \text{ cm}^2/\text{sec}$$

$$R_{Re} = \frac{7.07 \times 10^{-3} (1000) (416.67)^{1.25}}{.1558 \text{ EXP } (56.6/(416.67)^{.25})}$$

$$= 8.54 \times 10^4 = .31$$

$$2.759 \times 10^5$$

$$k_L = (11.4/.31)^{.195 - 5} (78/100)^{0.5}$$

$$= 4.07 (.884) = 3.60 \text{ cm/hr}$$

Overall Mass Transfer Coefficient

$$\frac{1}{k} = \frac{1}{k_L} + \frac{1}{Hk_G}$$

H = Henry's law const

$$= \frac{1}{3.60} + \frac{1}{.01 (2066.88)}$$

$$= .278 + .048$$

$$= 3.07 \text{ cm/hr}$$

Emission Rate

$$Q = K (\text{cm/hr}) \text{ ppm} \times 10^{-6} (\text{g/cm}^3) \text{ Area } (\text{cm}^2)$$

$$= 3.07 (40 \times 10^{-6}) (1.171 \times 10^7)$$

$$= 1.438 \times 10^3 \text{ g/hr}$$

$$1.438 \times 10^3 \text{ g/hr} \times \frac{\text{Mg}}{10^6 \text{g}} \times \frac{24 \text{ hr}}{\text{day}} \times \frac{365 \text{ day}}{\text{yr}}$$

$$= 12.60 \frac{\text{Mg}}{\text{yr}}$$

Aerated (Facility #11, model wastestream - see Section 3.3.7)

Natural side--

$$k_G = 2.920 U_{\text{air}}^{0.78} N_{\text{Sc}}^{-0.67} d_e^{-0.11} \text{ cm/hr} \quad (\text{MacKay})^7$$

$$N_{\text{air}} = 15,000 \text{ m/hr}$$

$$N_{\text{Sc}} = 2.225$$

$$d_e = (4A/3.14)^{0.5} = 4 ((2.770 \times 10^2/3.14))^{0.5} = 18.78 \text{ meters}$$

$$\begin{aligned} k_G &= 2.920 (15,000)^{0.78} (2.225)^{-0.67} (18.78)^{-0.11} \\ &= 2.920 (1808.64) (.585) (.724) \\ &= 2236.8 \text{ cm/hr} \end{aligned}$$

$$k_L = (11.4 R_{Re}^{.195} - 5) (78.1/MW_i)^{0.5} \quad (\text{Cohen, Cocchio, Mackay})^7$$

$$= 3.60 \text{ cm/hr}$$

Convective Side--

$$k_G^T = 1.90 \times 10^{-4} Re^{1.42} NP^{.4} Sc^{.5} FR^{-.21} \frac{Pair Di, air}{d}$$

$$Re = \frac{d^2 w Pair}{Mair} = \text{Reynolds \#}$$

$$NP = Pr gc/P_1 (d/30.48)^5 W^3 = \text{Powers \#}$$

$$N_{Sc} = \frac{Mair}{Di, air Pair} = \text{Schmidt \#}$$

$$N_{Fr} = \frac{dw^2}{gc} = \text{Froude \#}$$

$$d = \text{impelled diameter} = 60 \text{ cm}$$

$$w = \text{rotational speed of impeller} = 126 \text{ rad/sec}$$

$$Pair = 1.178 \times 10^{-3} \text{ g/cm}^3 = \text{density air (at } 25^\circ\text{C)}$$

$$Mair = 1.835 \times 10^{-4} \text{ g/cm sec} = \text{viscosity air (} 25^\circ\text{C)}$$

$$Pr = \text{power to impeller} = 4.5 \text{ Hp}$$

$$gc = \text{grav. const.}$$

$$P_1 = \text{density of water} = 1\text{g/cc or } 62.37 \text{ lb/ft}^3$$

$$Di, air = .07 \text{ cm}^2/\text{sec}$$

$$Re = 2.91 \times 10^6$$

$$NP = 6.88 \times 10^{-4}$$

$$SL = 2.225$$

$$FR = 9.53 \times 10^5$$

$$k_G^T = 3.28 \text{ cm/hr}$$

$$K_{LT} = 1.509 \times 10^3 \text{ J (POWR)} \propto (1.024)^{\theta-20} (Diw/2.41 \times 10^{-5})^{.5} / (AV/30.48)V \text{ (Ref. 7)}$$

$$J = O_2 \text{ Transfer Rating} = 3 \text{ lb } O_2/\text{Hp}\cdot\text{hr}$$

$$POWR = \text{Total Power to Aerator} = 5\text{Hp}$$

$$\alpha = \text{correction factor for } O_2 \text{ Transfer} = .825$$

$$\theta = \text{Temperature} = 25^\circ\text{C}$$

$$A_V = \text{surface to volume ratio (meters}^{-1}\text{)} = \frac{100}{\text{depth (cm)}} = .244$$

$$V = \text{volume affected by aeration} = 50 \text{ m}^3$$

$$k_L^T = 3643 \text{ cm/hr}$$

$$K = \frac{1}{k_L} + \frac{1}{K_{eq} k_G}$$

$$K_{eq} = \frac{HP_1 MW_{air}}{RT \text{ Pair } ((\text{ppm } (MW_i) - (1-\text{ppm}) MW_1) \times 10^{-6})}$$

$$H = \text{Henry's Law Const} = .01 \text{ atm m}^3/\text{mole}$$

$$R = 8.2 \times 10^{-5} \text{ m}^3 \cdot \text{atm/mol K}$$

$$P_1 = 1 \text{ g/cm}^3$$

$$MW_{air} = 28.8 \text{ g/mole}$$

$$\text{Pair} = 1.178 \times 10^{-3} \text{ g/cm}^3$$

$$\text{ppm}_i = 40$$

$$MW_i = 100 \text{ g/mole}$$

$$MW_1 = 18.0 \text{ g/mole}$$

$$K_{eq} = 555.9$$

$$K^T = \frac{1}{k_L^T} + \frac{1}{K_{eq} K_G^T}$$

$$= \frac{1}{3643} + \frac{1}{(555.9)(3.28)}$$

$$= 1215.16 \text{ cm/hr}$$

$$K^N = \frac{1}{k_L^N} + \frac{1}{K_{eq} K_G^N}$$

$$= \frac{1}{3.60} + \frac{1}{(555.9)(2236.8)}$$

$$= 3.60 \text{ cm/hr}$$

$$K_{OVERALL} = fK^T + (1-f)K^N$$

$$f = \text{fraction aerated} = .058$$

$$= .058 (1215.16) + (1-058) (3.60)$$

$$= 70.48 + 3.39$$

$$K = 73.87 \text{ cm/hr}$$

Emission Rate

$$Q = K (\text{ppm} \times 10^{-6}) \text{ Area (cm}^2\text{)}$$

$$= 73.87 (40 \times 10^{-6}) (2.770 \times 10^6)$$

$$= 8185 \text{ g/hr}$$

$$8185 \text{ g/hr} \times 8.76 \times 10^{-3} = 71.70 \frac{\text{Mg}}{\text{yr}}$$

LAND TREATMENT (Thibodeaux-Hwang Model)⁷ (Facility #40, methylene chloride)

$$Q = \text{Dei}(f)/tA(\text{hp}-\text{hs}) (\text{h}_s^2 + 2 \text{ Dei } A (\text{hp}-\text{hs}) \text{ Cig } t/f\text{Mio})^{.5} \times 315.36$$

$$\text{De}_i = \text{Di} \text{P}^{1.33}$$

$$\text{Cig} = \text{Hc } \text{C}_{i0}$$

$$f = \text{fraction of waste in film form} = 1.0$$

$$t = \text{duration of waste on ground (sec)} = 86,400$$

$$A = \text{surface area of landfarm (cm}^2\text{)} = 6.1 \times 10^8$$

$$\text{hp} = \text{soil contamination depth (cm)} = 60.96$$

$$\text{hs} = \text{depth of subsurface injection (cm)} = 0$$

$$\text{Mio} = \text{initial mass of } i \text{ put of ground (g)} = 22,497$$

$$\text{De}_i = \text{effective diffusivity}$$

$$\text{Di} = \text{diffusivity of } i \text{ in air (cm}^2\text{/sec)} = 8.08 \times 10^{-2}$$

$$\text{Cig} = \text{effective wet zone pore space concentration (g/cm}^3\text{)}$$

$$\text{C}_{i0} = \text{initial concentration of } i \text{ in the waste (g/cm}^3\text{)} = .01$$

$$\text{H}_L = \text{Henry's Law Cont in concentration form (cm}^3 \text{ oil/cm}^2 \text{ air)} = 2.4 \times 10^{-5}$$

$$P = \text{soil porosity} = .41$$

$$Q = \text{Emission Rate (Mg/yr)} = 5.54$$

COVERED LANDFILL (Farmer Model)⁷ (Facility #28, methyl ethyl ketone)

$$E = K_D D C_s A \frac{P_a}{P_T^2}^{10/3} \frac{1}{L} \frac{W_i}{W}$$

$$C_s = \frac{P_{vp} M}{RT}$$

$$P_T = 1 - \frac{B}{P}$$

$$P_a = P_i - \theta$$

$$\theta = \frac{W_w}{W} \frac{B}{P_w}$$

E = mass emission rate (g/sec)

K_D = codisposal factor = 1.0

M = molecular wt. of species = 85.0

R = Gas const. = 62,300 mm Hg - cm³/k mole

T = Temp (K) = 298

P_T = soil porosity = .55

L = depth of soil cover = 320 cm

A = surface area of landfill = 1.00 x 10⁸ cm²

$\frac{W_i}{W}$ = weight fraction of species i in waste = 7.243 E-3

B = soil bulk density = 1.56 g/cm³

P = soil particle density = 2.65 g/cm³

P_{vp} = vapor pressure of i (mm Hg) = 438 mm Hg

$\frac{W_w}{W}$ = weight fraction of water in soil cover = .25

P_w = density of water = 1 g/cm³

D = Diffusion coeff. of in i air cm²/sec = .1

$$\theta = .25 \frac{(1.56)}{1.0} = .39$$

$$C_s = \frac{438 (85)}{62,300 (298)} = 2.01 \times 10^{-3} \text{ g/cm}^3$$

$$P_T = 1 - \frac{1.56}{2.65} = .41$$

$$P_a = .41 - .39 = .02$$

$$E = (1)(.1 \text{ cm}^2/\text{sec})(2.01 \times 10^{-3} \text{ g/cm}^3)(1 \times 10^8 \text{ cm}^2) \frac{(.02)^{10/3}}{(.41)^2} \\ \frac{1}{320 \text{ cm}} (7.243 \times 10^{-3})$$

$$E = 5.87 \times 10^{-6} \text{ g/sec}$$

$$= 1.85 \times 10^{-4} \text{ Mg/yr}$$

REFERENCES FOR APPENDIX D

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APPENDIX E

DEVELOPMENT OF UNIT RISK FACTORS

APPENDIX E

DEVELOPMENT OF UNIT RISK FACTORS

INTRODUCTION

Overview

The quantitative expressions of public cancer risks presented in this report are based on (1) a dose-response model that numerically relates the degree of exposure to certain airborne volatile organic compounds (VOC) to the risk of getting cancer, and (2) numerical expressions of public exposure to ambient air concentrations of VOC estimated to be caused by emissions from TSDFs. Each of these factors is discussed briefly below and details are provided in the following sections of this Appendix.

The Relationship of Exposure to Cancer Risk

The relationship of exposure to the risk of getting lung cancer is derived from epidemiological studies in occupational settings rather than from studies of excess cancer incidence among the public. The epidemiological methods that have successfully revealed associations between occupational exposure and cancer for substances such as asbestos, benzene, vinyl chloride, inorganic arsenic and ionizing radiation, as well as for certain VOC, are not readily applied to the public sector, with its increased number of confounding variables, much more diverse and mobile exposed population, lack of consolidated medical records, and almost total absence of historical exposure data. Given such uncertainties, EPA considers it improbable that any association, short of very large increases in cancer, can be verified in the general population with any reasonable certainty by an epidemiological study. Furthermore, as noted by the National Academy of Sciences (NAS),¹ ". . . when there is exposure to a material, we are not starting at an origin of zero cancers. Nor are we starting at an origin of zero carcinogenic agents in our environment. Thus, it is likely that any carcinogenic agent added to the environment will act by a particular mechanism on a particular cell population

that is already being acted on by the same mechanism to induce cancers." In discussing experimental dose-response curves, the NAS observed that most information on carcinogenesis is derived from studies of ionizing radiation with experimental animals and with humans which indicate a linear no-threshold dose-response relationship at low doses. They added that although some evidence exists for thresholds in some animal tissues, by and large, thresholds have not been established for most tissues. NAS concluded that establishing such low-dose thresholds ". . . would require massive, expensive, and impractical experiments . . ." and recognized that the U.S. population ". . . is a large, diverse, and genetically heterogeneous group exposed to a large variety of toxic agents." This fact, coupled with the known genetic variability to carcinogenesis and the predisposition of some individuals to some form of cancer, makes it extremely difficult, if not impossible, to identify a threshold.

For these reasons, EPA has taken the position, shared by other Federal regulatory agencies, that in the absence of sound scientific evidence to the contrary, carcinogens should be considered to pose some cancer risk at any exposure level. This no-threshold presumption is based on the view that as little as one molecule of a carcinogenic substance may be sufficient to transform a normal cell into a cancer cell. Evidence is available from both the human and animal health literature that cancers may arise from a single transformed cell. Mutation research with ionizing radiation in cell cultures indicates that such a transformation can occur as the result of interaction with as little as a single cluster of ion pairs. In reviewing the available data regarding carcinogenicity, EPA found no compelling scientific reason to abandon the no-threshold presumption for VOC emitted from TSDFs.

In developing the exposure-risk relationship for VOC emitted from TSDFs, EPA has assumed that a linear no-threshold relationship exists at and below the levels of exposure reported in the epidemiological studies of occupational exposure. (It should be noted that no occupational studies have been conducted for hazardous waste treatment, storage, and disposal facilities. The studies referred to here are for other industries emitting TSDF

pollutants.) This means that any exposure to VOC is assumed to pose some risk of lung cancer and that the linear relationship between cancer risks and levels of public exposure is the same as that between cancer risks and levels of occupational exposure.

The numerical constant that defines the exposure-risk relationship used by EPA in its analysis of carcinogens is called the unit risk estimate. The unit risk estimate for an air pollutant is defined as the lifetime cancer risk occurring in a hypothetical population in which all individuals are exposed continuously from birth throughout their lifetimes (about 70 years) to a concentration of $1 \mu\text{g}/\text{m}^3$ of the agent in the air which they breathe. Unit risk estimates are used for two purposes: (1) to compare the carcinogenic potency of several agents with each other, and (2) to give a crude indication of the public health risk which might be associated with estimated air exposure to these agents. The comparative potency of different agents is more reliable when the comparison is based on studies of like populations and on the same route of exposure, preferably inhalation.

Public Exposure

The unit risk estimate is only one of the factors needed to produce quantitative expressions of public health risks. Another factor needed is a numerical expression of public exposure, i.e., of the numbers of people exposed to the various concentrations of pollutants. The difficulty of defining public exposure was noted by the National Task Force on Environmental Cancer and Health and Lung Disease in their 5th Annual Report to Congress, in 1982.² They reported that ". . . a large proportion of the American population works some distance away from their homes and experience types of pollution in their homes, on the way to and from work, and in the workplace. Also, the American population is quite mobile, and many people move every few years." They also noted the necessity and difficulty of dealing with long-term exposures because of ". . . the long latent period required for the development and expression of neoplasia [cancer]. . . ."

EPA's numerical expression of public exposure is based on two estimates. The first is an estimate of the magnitude and location of long-term average ambient air concentrations of VOC in the vicinity of emitting TSDFs based on dispersion modeling using long-term estimates of TSDF emissions and meteorological conditions. The second is an estimate of the number and distribution of people living in the vicinity of TSDFs based on Bureau of Census data which "locates" people by population centroids in census tract areas. The people and concentrations are combined to produce numerical expressions of public exposure by an approximating technique contained in a computerized model.

Public Cancer Risks

By combining numerical expressions of public exposure with the unit risk estimate, two types of numerical expressions of public cancer risks are produced. The first, called individual risk, relates to the person or persons estimated to live in the area of highest concentration as estimated by the dispersion model. Individual risk is expressed as "maximum lifetime risk." As used here, the word "maximum" does not mean the greatest possible risk of cancer to the public. It is based only on the maximum exposure estimated by the procedure used. The second, called aggregate risk, is a summation of all the risks to people estimated to be living within the vicinity (usually within 50 kilometers) of a source and is customarily summed for all the sources in a particular category. The aggregate risk is expressed as incidences of cancer among all of the exposed population after 70 years of exposure; for statistical convenience, it is often divided by 70 and expressed as cancer incidences per year.

There are also risks of nonfatal cancer and of serious genetic effects, depending on which organs receive the exposure. No numerical expressions of such risks have been developed; however, EPA considers all of these risks when making regulatory decisions on limiting emissions of VOC emitted from TSDFs.

UNIT RISK

Procedures for Determination of Unit Risk for Specific Chemicals

The data used for quantitative estimation are one or both of two types: (1) lifetime animal studies, and (2) human studies where excess cancer risk has been associated with exposure to the agent. In animal studies it is assumed, unless evidence exists to the contrary, that if a carcinogenic response occurs at the dose levels used in the study, then responses will also occur at all lower doses with an incidence determined by the extrapolation model.

There is no solid scientific basis for any mathematical extrapolation model that relates carcinogen exposure to cancer risks at the extremely low concentrations that must be dealt with in evaluating environmental hazards. For practical reasons such low levels of risk cannot be measured directly either by animal experiments or by epidemiologic studies. We must, therefore, depend on our current understanding of the mechanisms of carcinogenesis for guidance as to which risk model to use. At the present time the dominant view of the carcinogenic process involves the concept that most agents that cause cancer also cause irreversible damage to DNA. This position is reflected by the fact that a very large proportion of agents that cause cancer are also mutagenic. There is reason to expect that the quantal type of biological response, which is characteristic of mutagenesis, is associated with a linear non-threshold dose-response relationship. Indeed, there is substantial evidence from mutagenicity studies with both ionizing radiation and wide variety of chemicals that this type of dose-response model is the appropriate one to use. This is particularly true at the lower end of the dose-response curve; at higher doses, there can be an upward curvature, probably reflecting the effects of multistage processes on the mutagenic response. The linear non-threshold dose-response relationship is also consistent with the relatively few epidemiologic studies of cancer responses to specific agents that contain enough information to make the evaluation possible (e.g., radiation-induced leukemia, breast and thyroid cancer, skin cancer induced by

arsenic in drinking water, liver cancer induced by aflatoxins in the diet). There is also some evidence from animal experiments that is consistent with the linear non-threshold model (e.g., liver tumors induced in mice by 2-acetylaminofluorene in the large scale ED₀₁ study at the National Center for Toxicological Research and the initiation stage of the two-stage carcinogenesis model in rat liver and mouse skin).

Because its scientific basis, although limited, is the best of any of the current mathematical extrapolation models, the linear non-threshold model has been adopted as the primary basis for risk extrapolation to low levels of the dose-response relationship.

The mathematical formulation chosen to describe the linear non-threshold dose-response relationship at low doses is the linearized multistage model. This model employs enough arbitrary constants to be able to fit almost any monotonically increasing dose-response data, and it incorporates a procedure for estimating the largest possible linear slope (in the 95% confidence limit) at low extrapolated doses that is consistent with the data at all dose levels of the experiment.

Animals--

Description of the low-dose animal extrapolation model. Let $P(d)$ represent the lifetime risk (probability) of cancer at dose d . The multistage model has the form

$$P(d) = 1 - \exp [-(q_0 + q_1d + q_2d^2 + \dots + q_kd^k)]$$

where

$$q_i \geq 0, \quad i = 0, 1, 2, \dots, k$$

Equivalently,

$$P_t(d) = 1 - \exp [-(q_1 d + q_2 d^2 + \dots + q_k d^k)]$$

where

$$P_t(d) = \frac{P(d) - P(0)}{1 - P(0)}$$

is the extra risk over background rate at dose d or the effect of treatment.

The point estimate of the coefficients q_i , $i = 0, 1, 2, \dots, k$, and consequently the extra risk function $P_t(d)$ at any given dose d , is calculated by maximizing the likelihood function of the data.

The point estimate and the 95% upper confidence limit of the extra risk, $P_t(d)$, are calculated by using the computer program GLOBAL79, developed by Crump and Watson (1979). At low doses, upper 95% confidence limits on the extra risk and lower 95% confidence limits on the dose producing a given risk are determined from a 95% upper confidence limit, q_1^* , on parameter q_1 . Whenever $q_1 > 0$, at low doses the extra risk $P_t(d)$ has approximately the form $P_t(d) = q_1 \times d$. Therefore, $q_1^* \times d$ is a 95% upper confidence limit on the extra risk and R/q_1^* is a 95% lower confidence limit on the dose producing an extra risk of R . Let L_0 be the maximum value of the log-likelihood function. The upper limit, q_1^* , is calculated by increasing q_1 to a value q_1^* such that when the log-likelihood is remaximized subject to this fixed value, q_1^* , for the linear coefficient, the resulting maximum value of the log-likelihood L_1 satisfies the equation

$$2 (L_0 - L_1) = 2.70554$$

where 2.70554 is the cumulative 90% point of the chi-square distribution with one degree of freedom, which corresponds to a 95% upper-limit (one-sided). This approach of computing the upper confidence limit for the extra risk $P_t(d)$

is an improvement on the Crump et al. (1977) model. The upper confidence limit for the extra risk calculated at low doses is always linear. This is conceptually consistent with the linear non-threshold concept discussed earlier. The slope, q_1^* , is taken as an upper-bound of the potency of the chemical in inducing cancer at low doses. (In the section calculating the risk estimates, $P_t(d)$ will be abbreviated as P.)

In fitting the dose-response model, the number of terms in the polynomial is chosen equal to $(h-1)$, where h is the number of dose groups in the experiment including the control group.

Whenever the multistage model does not fit the data sufficiently well, data at the highest dose is deleted, and the model is refit to the rest of the data. This is continued until an acceptable fit to the data is obtained. To determine whether or not a fit is acceptable, the chi-square statistic

$$X^2 = \sum_{i=1}^h \frac{(X_i - N_i P_i)^2}{N_i P_i (1 - P_i)}$$

is calculated where N_i is the number of animals in the i^{th} dose group, X_i is the number of animals in the i^{th} dose group with a tumor response, P_i is the probability of a response in the i^{th} dose group estimated by fitting the multistage model to the data, and h is the number of remaining groups. The fit is determined to be unacceptable whenever X^2 is larger than the cumulative 99% point of the chi-square distribution with f degrees of freedom, where f equals the number of dose groups minus the number of non-zero multistage coefficients.

Selection of data. For some chemicals, several studies in different animals species, strains, and sexes, each run at several doses and different routes of exposure, are available. A choice must be made as to which of the data sets from several studies to use in the model. It may also be appropriate to correct for metabolism differences between species and absorption factors via

different routes of administration. The procedures used in evaluating these data are consistent with the approach of making a maximum-likely risk estimate. They are listed as follows.

1. The tumor incidence data are separated according to organ sites or tumor types. The set of data (i.e., dose and tumor incidence) used in the model is the set where the incidence is statistically significantly higher than the control for at least one test dose level and/or where the tumor incidence rate shows a statistically significant trend with respect to dose level. The data set that gives the highest estimate of the lifetime carcinogenic risk, $q_1 0^*$, is selected in most cases. However, efforts are made to exclude data sets that produce spuriously high risk estimates because of a small number of animals. That is, if two sets of data show a similar dose-response relationship, and one has a very small sample size, the set of data that has the larger sample size is selected for calculating the carcinogenic potency.

2. If there are two or more data sets of comparable size that are identical with respect to species, strain, sex, and tumor sites, the geometric mean of q_1^* , estimated from each of these data sets, is used for risk assessment. The geometric mean of numbers A_1, A_2, \dots, A_m is defined as

$$(A_1 \times A_2 \times \dots \times A_m)^{1/m}$$

3. If two or more significant tumor sites are observed in the same study, and if the data are available, the number of animals with at least one of the specific tumor sites under consideration is used as incidence data in the model.

Calculation of human equivalent dosages from animal data. Following the suggestion of Mantel and Schneiderman (1975), we assume that mg/surface area/day is an equivalent dose between species. Since, to a close approximation, the surface area is proportional to the 2/3rd power of the weight as would be the case for a perfect sphere, the exposure in mg/day per

2/3rds power of the weight is also considered to be equivalent exposure. In an animal experiment this equivalent dose is computed in the following manner.

Let

L_e = duration of experiment

l_e = duration of exposure

m = average dose per day in mg during administration of the agent
(i.e., during l_e), and

W = average weight of the experimental animal

Then, the lifetime average exposure is

$$d = \frac{l_e \times m}{L_e \times W^{2/3}}$$

Oral. Often, exposures are not given in units of mg/day and it becomes necessary to convert the given exposures into mg/day. For example, in most feeding studies exposure is in terms of ppm in the diet. Similarly in drinking water studies exposure is in ppm in the water. In these cases the exposure in mg/day is

$$m = \text{ppm} \times F \times r$$

where ppm is parts per million of the carcinogenic agent in the diet or water, F is the weight of the food or water consumed per day in kg, and r is the absorption fraction. In the absence of any data to the contrary, r is assumed to be equal to one. For a uniform diet, the weight of the food consumed is proportional to the calories required, which in turn is proportional to the surface area or 2/3rds power of the weight. Water demands are also assumed proportional to the surface area, so that

$$m = \text{ppm} \times W^{2/3} \times r$$

or

$$\frac{m}{rW^{2/3}} = \text{ppm}$$

As a result, ppm in the diet or in water is often assumed to be an equivalent exposure between species. However, we feel that this is not justified since the calories/kg of food are very different in the diet of man compared to laboratory animals primarily due to moisture content differences. Consequently, the amount of drinking water required by each species differs also because of the amount of moisture in the food. Therefore, we use an empirically-derived factor, $f = F/W$, which is the fraction of a species body weight that is consumed per day as food or water. We use the following rates:

Species	W	Fraction of Body Weight Consumed as	
		f_{food}	f_{water}
Man	70	0.028	0.029
Rats	0.035	0.05	0.078
Mice	0.03	0.13	0.17

Thus, when the exposure is given as a certain dietary or water concentration in ppm, the exposure in $\text{mg}/W^{2/3}$ is

$$\frac{m}{rW^{2/3}} = \frac{\text{ppm} \times F}{W^{2/3}} = \frac{\text{ppm} \times f \times W}{W^{2/3}} = \text{ppm} \times f \times W^{1/3}$$

When exposure is given in terms of $\text{mg}/\text{kg}/\text{day} = m/Wr = s$, the conversion is simply

$$\frac{m}{rW^{2/3}} = s \times W^{1/3}$$

Calculation of the unit risk from animal studies. The 95% upper-limit risk associated with $d \text{ mg/kg}^{2/3}/\text{day}$ is obtained from GLOBAL79 and, for most cases of interest to risk assessment, can be adequately approximated by $P(d) = 1 - \exp(-q_1^* d)$. A "unit risk" in units X is simply the risk corresponding to an exposure of $X = 1$. To estimate this value we simply find the number of $\text{mg/kg}^{2/3}/\text{day}$ corresponding to one unit of X and substitute this value into the above relationship. Thus, for example, if X is in units of $\mu\text{g}/\text{m}^3$ in the air, we have that for case 1, $d = 0.29 \times 70^{1/3} \times 10^{-3} \text{ mg/kg}^{2/3}/\text{day}$, and for case 2, $d = 1$, when $\mu\text{g}/\text{m}^3$ is the unit used to compute parameters in animal experiments.

If exposures are given in terms of ppm in air, we may simply use the fact that

$$1 \text{ ppm} = 1.2 \times \frac{\text{molecular weight (gas) mg/m}^3}{\text{molecular weight (air)}}$$

Note, an equivalent method of calculating unit risk would be to use mg/kg/day for the animal exposures and then increase the j^{th} polynomial coefficient by an amount

$$(W_h/W_a)^{j/3} \quad j = 1, 2, \dots, k$$

and use mg/kg equivalents for the unit risk values.

Adjustment for less than lifespan duration of experiment. If the duration of experiment, L_e , is less than the natural lifespan of the test animal, L , the slope, q_1^* , or more generally the exponent, $g(d)$, is increased by multiplying a factor $(L/L_e)^3$. We assume that if the average dose, d , is continued, the age-specific rate of cancer will continue to increase as a constant function of the background rate. The age-specific rates for humans increase at least by the 2nd power of the age and often by a considerably higher power as demonstrated by Doll (1971). Thus, we would expect the cumulative tumor rate to increase by at least the 3rd power of age. Using this fact, we assume that

the slope, q_1^* , or more generally the exponent, $g(d)$, would also increase by at least the 3rd power of age. As a result, if the slope q_1^* [or $g(d)$] is calculated at age L_e , we would expect that if the experiment had been continued for the full lifespan, L , at the given average exposure, the slope q_1^* [or $g(d)$] would have been increased at least $(L/L_e)^3$.

This adjustment is conceptually consistent with the proportional hazard model proposed by Cox (1972) and the time-to-tumor model considered by Crump (1979) where the probability of cancer by age t and at dose d is given by

$$P(d,t) = 1 - \exp [-f(t) \times g(d)]$$

Interpretation of quantitative estimates. For several reasons, the unit risk estimate based on animal bioassays is only an approximate indication of the absolute risk in populations exposed to known carcinogen concentrations. First, there are important species differences in uptake, metabolism, and organ distribution of carcinogens, as well as species differences in target site susceptibility, immunological responses, hormone function, dietary factors, and disease. Second, the concept of equivalent doses for humans compared to animals on a mg/surface area basis is virtually without experimental verification regarding carcinogenic response. Finally, human populations are variable with respect to genetic constitution and diet, living environment, activity patterns, and other cultural factors.

The unit risk estimate can give a rough indication of the relative potency of a given agent compared with other carcinogens. The comparative potency of different agents is more reliable when the comparison is based on studies in the same test species, strain, and sex, and by the same route of exposure, preferably by inhalation.

The quantitative aspect of the carcinogen risk assessment is included here because it may be of use in the regulatory decision-making process, e.g., setting regulatory priorities, evaluating the adequacy of technology-based controls, etc. However, it should be recognized that the estimation of cancer

risks to humans at low levels of exposure is uncertain. At best, the linear extrapolation model used here provides a rough but plausible estimate of the upper-limit risk; i.e., it is not likely that the true risk would be much more than the estimated risk, but it could very well be considerably lower. The risk estimates presented in subsequent sections should not be regarded as an accurate representation of the true cancer risks even when the exposures are accurately defined; however, the estimates presented may be factored into regulatory decisions to the extent that the concept of upper risk limits is found to be useful.

Alternative methodological approaches. The methods used by the Carcinogen Assessment Group (CAG) for quantitative assessment are consistently conservative, i.e., tending toward high estimates of risk. The most important part of the methodology contributing to this conservatism is the linear non-threshold extrapolation model. There are a variety of other extrapolation models that could be used, all of which would give lower risk estimates. These alternative models have not been used by the CAG. The CAG feels that with the limited data available from these animal bioassays, especially at the high-dose levels required for testing, almost nothing is known about the true shape of the dose-response curve at low environmental levels. The position is taken by the CAG that the risk estimates obtained by use of the linear non-threshold model are plausible upper limits, and that the true risk could be lower.

In terms of the choice of animal bioassay as the basis for extrapolation, the general approach is to use the most sensitive responder on the assumption that humans are as sensitive as the most sensitive animal species tested. The average response of all of the adequately tested bioassay animals was used; this is because three well-conducted valid drinking water studies using different strains of rats showed similar target organs and about the same level of response.

Extrapolations from animals to humans could also be done on the basis of relative weights rather than relative surface areas. The latter approach,

used here, has more basis in human pharmacological responses; it is not clear which of the two approaches is more appropriate for carcinogens. In the absence of information on this point, it seems appropriate to use the most generally employed method, which also is more conservative. In the case of the TCI study, the use of extrapolation based on surface area rather than weight increases the unit risk estimates by a factor of 12 to 13.

Humans--Model for Estimation of Unit Risk Based on Human Data--

If human epidemiologic studies and sufficiently valid exposure information are available for the compound, they are always used in some way. If they show a carcinogenic effect, the data are analyzed to give an estimate of the linear dependence of cancer rates on lifetime average dose, which is equivalent to the factor B_H . If they show no carcinogenic effect when positive animal evidence is available, then it is assumed that a risk does exist, but it is smaller than could have been observed in the epidemiologic study, and an upper limit to the cancer incidence is calculated assuming hypothetically that the true incidence is below the level of detection in the cohort studied, which is determined largely by the cohort size. Whenever possible, human data are used in preference to animal bioassay data.

Very little information exists that can be utilized to extrapolate from high exposure occupational studies to low environmental levels. However, if a number of simplifying assumptions are made, it is possible to construct a crude dose-response model whose parameters can be estimated using vital statistics, epidemiologic studies, and estimates of worker exposures.

In human studies, the response is measured in terms of the relative risk of the exposed cohort of individuals compared to the control group. The mathematical model employed assumes that for low exposures the lifetime probability of death from lung cancer (or any cancer), P_0 , may be represented by the linear equation

$$P_0 = A + B_H x$$

where A is the lifetime probability in the absence of the agent, and x is the average lifetime exposure to environmental levels in some units, say ppm. The factor, B_H , is the increased probability of cancer associated with each unit increase of the agent in air.

If we make the assumption that R, the relative risk of lung cancer for exposed workers compared to the general population, is independent of the length or age of exposure but depends only upon the average lifetime exposure, it follows that

$$R = \frac{P}{P_0} = \frac{A + B_H (x_1 + x_2)}{A + B_H x_1}$$

or

$$RP_0 = A + B_H (x_1 + x_2)$$

where x_1 = lifetime average daily exposure to the agent for the general population, x_2 = lifetime average daily exposure to the agent in the occupational setting, and P_0 = lifetime probability of dying of cancer with no or negligible TCI exposure.

Substituting $P_0 = A + B_H x_1$, and rearranging gives

$$B_H = \frac{P_0 (R - 1)}{x_2}$$

To use this model, estimates of R and x_2 must be obtained from the epidemiologic studies. The value P_0 is derived from the age-cause-specific death rates for combined males found in the 1976 U.S. Vital Statistics tables using the life table methodology. For lung cancer the estimate of P_0 is 0.036. This methodology is used in the section on unit risk based on human studies.

References for Appendix E

1. National Academy of Sciences, "Arsenic", Committee on Medical and Biological Effects of Environmental Pollutants, Washington, D.C., 1977. Docket Number (OAQPS 79-8) II-A-3.
2. U.S. EPA, et. al., "Environmental Cancer and Heart and Lung Disease," Fifth Annual Report to Congress by the Task Force on Environmental Cancer and Health and Lung Disease, August, 1982.

APPENDIX F

NATIONWIDE EXTRAPOLATION BASED ON MASS BALANCE

Table 1: National estimates of the total air emissions and annual incidence as calculated from data presented in the draft final report, mass balance of throughput volumes, and the GCA Preliminary National Air Emissions report.

	Total Air Emissions (Gg/yr)				Total Annual Incidence		
	I	II	III	IV	I	II	III
Storage Tank	14	14*	14*	17	<1 - 7	<1 - 7*	<1 - 7*
Open Treatment Tanks and Surface Impoundments	810	2292	1220	2580	<1 - 44	2 - 230	2 - 200
Landtreatment	97	82	5	70	<1 - 13	<1 - 6	<1
Landfill	24	343	29	906 ^a 31	<1	<1 - 1	<1 - 1
Totals	945	2731	1268	3573 ^a 2698	<1 - 64	<1 - 240	<1 - 210

I - Draft Final Report (risk assessment)

II - Mass balance of waste throughput based on GCA estimation of organics in site visit reports

III - Mass balance of waste throughput based on 0.36% volatile organics

IV - GCA National Air Emissions report

* - not analyzed by mass balance

a - It is not anticipated these projections are valid; see text of GCA National Air Emissions report
(The 31 Gg/yr represents emissions based on temporary covers)

