

DRAFT
DO NOT CITE OR QUOTE

EPA/600/P-00/001Cb
December 2003
NAS Review Draft
www.epa.gov/ncea

Exposure and Human Health Reassessment of 2,3,7,8-Tetrachlorodibenzo-*p*-Dioxin (TCDD) and Related Compounds

Part I: Estimating Exposure to Dioxin-Like Compounds

Volume 1: Sources of Dioxin-Like Compounds in the United States

Exposure Assessment and Risk Characterization Group
National Center for Environmental Assessment - Washington Office
Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC

DISCLAIMER

This document is a draft. It has not been formally released by the U.S. Environmental Protection Agency and should not at this stage be construed to represent Agency policy. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

TABLE OF CONTENTS

1.	BACKGROUND AND SUMMARY	1-1
1.1.	BACKGROUND	1-1
1.2.	DEFINITION OF DIOXIN-LIKE COMPOUNDS	1-3
1.3.	TOXIC EQUIVALENCY FACTORS	1-5
1.4.	OVERVIEW OF SOURCES AND EMISSIONS INVENTORY METHODOLOGY	1-10
1.4.1.	Overview and Organization of Source Analysis	1-10
1.4.2.	Quantitative Inventory of Sources	1-12
1.5.	GENERAL FINDINGS OF THE EMISSIONS INVENTORY	1-17
1.6.	GENERAL SOURCE OBSERVATIONS	1-20
1.7.	CONGENER PROFILES OF CDD/CDF SOURCES	1-25
2.	MECHANISMS OF FORMATION OF DIOXIN-LIKE COMPOUNDS DURING COMBUSTION OF ORGANIC MATERIALS	2-1
2.1.	MECHANISM 1: CDD/CDF CONTAMINATION IN FUEL AS A SOURCE OF COMBUSTION STACK EMISSIONS	2-3
2.2.	MECHANISM 2: FORMATION OF CDD/CDFs FROM PRECURSOR COMPOUNDS	2-5
2.3.	MECHANISM 3: THE <i>DE NOVO</i> SYNTHESIS OF CDDs/CDFs DURING COMBUSTION OF ORGANIC MATERIALS	2-12
2.4.	THE ROLE OF CHLORINE IN THE FORMATION OF CDDs AND CDFs IN COMBUSTION SYSTEMS	2-20
2.4.1.	Review of Laboratory-Scale Studies	2-20
2.4.2.	Review of Full Scale Combustion Systems	2-24
2.5.	POTENTIAL PREVENTION OF CDD/CDF FORMATION IN COMBUSTION SYSTEMS	2-27
2.6.	THEORY ON THE EMISSION OF POLYCHLORINATED BIPHENYLS ...	2-28
2.7.	SUMMARY AND CONCLUSIONS	2-30
2.7.1.	Mechanisms of Formation of Dioxin-Like Compounds	2-30
2.7.2.	Role of Chlorine	2-31
2.7.3.	General Conclusion	2-33
3.	COMBUSTION SOURCES OF CDD/CDF: WASTE INCINERATION	3-1
3.1.	MUNICIPAL SOLID WASTE INCINERATION	3-2
3.1.1.	Description of Municipal Solid Waste Incineration Technologies	3-2
3.1.2.	Characterization of MSWI Facilities in Reference Years 1995 and 1987	3-7
3.1.3.	Estimation of CDD/CDF Emissions from MSWIs	3-8
3.1.4.	Summary of CDD/CDF (TEQ) Emissions from MSWIs for 1995 and 1987	3-10
3.1.5.	Congener Profiles of MSWI Facilities	3-11
3.1.6.	Estimated CDD/CDFs in MSWI Ash	3-11
3.1.7.	Recent EPA Regulatory Activities	3-14

TABLE OF CONTENTS (continued)

3.2.	HAZARDOUS WASTE INCINERATION	3-15
3.2.1.	Furnace Designs for Hazardous Waste Incinerators	3-16
3.2.2.	APCDs for Hazardous Waste Incinerators	3-18
3.2.3.	Estimation of CDD/CDF Emission Factors for Hazardous Waste Incinerators	3-20
3.2.4.	Emission Estimates for Hazardous Waste Incinerators	3-22
3.2.5.	Recent EPA Regulatory Activities	3-23
3.2.6.	Industrial Boilers and Furnaces Burning Hazardous Waste . . .	3-24
3.2.7.	Solid Waste from Hazardous Waste Combustion	3-25
3.3.	MEDICAL WASTE INCINERATION	3-25
3.3.1.	Design Types of MWIs Operating in the United States	3-26
3.3.2.	Characterization of MWIs for Reference Years 1995 and 1987	3-27
3.3.3.	Estimation of CDD/CDF Emissions from MWIs	3-29
3.3.4.	EPA/OAQPS Approach for Estimating CDD/CDF Emissions from MWIs	3-30
3.3.4.1.	EPA/OAQPS Approach for Estimating Activity Level	3-30
3.3.4.2.	EPA/OAQPS Approach for Estimating CDD/CDF Emission Factors	3-31
3.3.4.3.	EPA/OAQPS Approach for Estimating Nationwide CDD/CDF TEQ Air Emissions	3-32
3.3.5.	AHA Approach for Estimating CDD/CDF Emissions from MWIs	3-33
3.3.6.	EPA/ORD Approach for Estimating CDD/CDF Emissions from MWIs	3-34
3.3.6.1.	EPA/ORD Approach for Classifying MWIs and Estimating Activity Levels	3-34
3.3.6.2.	EPA/ORD Approach for Estimating CDD/CDF Emission Factors	3-36
3.3.7.	Summary of CDD/CDF Emissions from MWIs	3-37
3.3.8.	Recent EPA Regulatory Activities	3-40
3.4.	CREMATORIA	3-40
3.5.	SEWAGE SLUDGE INCINERATION	3-42
3.5.1.	Emission Estimates from Sewage Sludge Incinerators	3-43
3.5.2.	Solid Waste from Sewage Sludge Incinerators	3-45
3.6.	TIRE COMBUSTION	3-45
3.7.	COMBUSTION OF WASTEWATER SLUDGE AT BLEACHED CHEMICAL PULP MILLS	3-46
3.8.	BIOGAS COMBUSTION	3-47

TABLE OF CONTENTS (continued)

4. COMBUSTION SOURCES OF CDD/CDF: POWER/ENERGY GENERATION 4-1

4.1. MOTOR VEHICLE FUEL COMBUSTION 4-1

4.1.1. Tailpipe Emission Studies 4-2

4.1.2. Tunnel Emission Studies 4-6

4.1.3. National Emission Estimates 4-9

4.2. WOOD COMBUSTION 4-16

4.2.1. Residential Wood Combustion 4-17

4.2.2. Industrial Wood Combustion 4-20

4.2.3. Solid Waste from Wood Combustion 4-25

4.3. OIL COMBUSTION 4-30

4.3.1. Residential/Commercial Oil Combustion 4-31

4.3.2. Utility Sector and Industrial Oil Combustion 4-31

4.4. COAL COMBUSTION 4-33

4.4.1. Utilities and Industrial Boilers 4-34

4.4.2. Residential/Commercial Coal Combustion 4-36

4.4.3. Solid Wastes from Coal Combustion 4-38

5. COMBUSTION SOURCES OF CDD/CDF: OTHER HIGH TEMPERATURE SOURCES 5-1

5.1. CEMENT KILNS AND LIGHTWEIGHT AGGREGATE KILNS 5-1

5.1.1. Process Description of Portland Cement Kilns 5-1

5.1.2. Cement Kilns That Burn Hazardous Waste 5-3

5.1.3. Air Pollution Control Devices Used on Cement Kilns 5-4

5.1.4. CDD/CDF Emission Factors for Cement Kilns 5-5

5.1.5. National Estimates of CDD/CDF Emissions from Cement Kilns 5-8

5.1.6. Recent EPA Regulatory Activities 5-10

5.1.7. Solid Waste from Cement Manufacturing 5-10

5.2. ASPHALT MIXING PLANTS 5-12

5.3. PETROLEUM REFINING CATALYST REGENERATION 5-14

5.4. CIGARETTE SMOKING 5-19

5.5. PYROLYSIS OF BROMINATED FLAME RETARDANTS 5-22

5.6. CARBON REACTIVATION FURNACES 5-23

5.7. KRAFT BLACK LIQUOR RECOVERY BOILERS 5-26

5.8. OTHER IDENTIFIED SOURCES 5-28

6. COMBUSTION SOURCES OF CDD/CDF: MINIMALLY CONTROLLED AND UNCONTROLLED COMBUSTION SOURCES 6-1

6.1. COMBUSTION OF LANDFILL GAS 6-1

6.2. ACCIDENTAL FIRES 6-2

6.2.1. Soot and Ash Studies 6-3

6.2.2. Fume and Smoke Studies 6-5

6.2.3. Data Evaluation 6-6

TABLE OF CONTENTS (continued)

6.3.	LANDFILL FIRES	6-9
6.4.	FOREST AND BRUSH FIRES	6-11
6.5.	BACKYARD BARREL BURNING	6-15
6.5.1.	Emission Estimates from Backyard Barrel Burning	6-16
6.5.2.	Barrel Burning Ash Composition	6-18
6.6.	UNCONTROLLED COMBUSTION OF POLYCHLORINATED BIPHENYLS (PCBs)	6-18
6.7.	VOLCANOES	6-19
7.	METAL SMELTING AND REFINING SOURCES OF CDD/CDF	7-1
7.1.	PRIMARY NONFERROUS METAL SMELTING/REFINING	7-1
7.1.1.	Primary Copper Smelting and Refining	7-1
7.1.2.	Primary Magnesium Smelting and Refining	7-2
7.1.3.	Primary Nickel Smelting and Refining	7-4
7.1.4.	Primary Aluminum Smelting and Refining	7-5
7.1.5.	Primary Titanium Smelting and Refining	7-6
7.2.	SECONDARY NONFERROUS METAL SMELTING	7-6
7.2.1.	Secondary Aluminum Smelters	7-7
7.2.2.	Secondary Copper Smelters	7-10
7.2.3.	Secondary Lead Smelters	7-16
7.3.	PRIMARY FERROUS METAL SMELTING/REFINING	7-19
7.3.1.	Sinter Production	7-19
7.3.2.	Coke Production	7-22
7.4.	SECONDARY FERROUS METAL SMELTING/REFINING	7-22
7.5.	FERROUS FOUNDRIES	7-24
7.6.	SCRAP ELECTRIC WIRE RECOVERY	7-26
7.7.	DRUM AND BARREL RECLAMATION FURNACES	7-28
7.8.	SOLID WASTE FROM PRIMARY/SECONDARY IRON/STEEL MILLS/FOUNDRIES	7-29
8.	CHEMICAL MANUFACTURING AND PROCESSING SOURCES	8-1
8.1.	BLEACHED CHEMICAL WOOD PULP AND PAPER MILLS	8-1
8.2.	MANUFACTURE OF CHLORINE, CHLORINE DERIVATIVES, AND METAL CHLORIDES	8-5
8.2.1.	Manufacture of Chlorine	8-5
8.2.2.	Manufacture of Chlorine Derivatives and Metal Chlorides	8-6
8.3.	MANUFACTURE OF HALOGENATED ORGANIC CHEMICALS	8-6
8.3.1.	Chlorophenols	8-7
8.3.2.	Chlorobenzenes	8-10
8.3.3.	Chlorobiphenyls	8-12
8.3.4.	Polyvinyl Chloride	8-16
8.3.5.	Other Aliphatic Chlorine Compounds	8-24
8.3.6.	Dyes, Pigments, and Printing Inks	8-25

TABLE OF CONTENTS (continued)

8.3.7.	TSCA Dioxin/Furan Test Rule	8-26
8.3.8.	Halogenated Pesticides and FIFRA Pesticides Data Call-In	8-28
8.4.	OTHER CHEMICAL MANUFACTURING AND PROCESSING SOURCES	8-38
8.4.1.	Municipal Wastewater Treatment Plants	8-38
8.4.2.	Drinking Water Treatment Plants	8-43
8.4.3.	Soaps and Detergents	8-44
8.4.4.	Textile Manufacturing and Dry Cleaning	8-46
9.	BIOLOGICAL SOURCES OF CDD/CDF	9-1
9.1.	BIOTRANSFORMATION OF CHLOROPHENOLS	9-1
9.2.	BIOTRANSFORMATION OF HIGHER CDD/CDFS	9-4
10.	PHOTOCHEMICAL SOURCES OF CDD/CDF	10-1
10.1.	PHOTOTRANSFORMATION OF CHLOROPHENOLS	10-1
10.2.	PHOTOLYSIS OF HIGHER CDD/CDFS	10-3
10.2.1	Photolysis in Water	10-3
10.2.2	Photolysis on Soil	10-4
10.2.3	Photolysis on Vegetation	10-6
10.2.4	Photolysis in Air	10-6
11.	SOURCES OF DIOXIN-LIKE PCBs	11-1
11.1.	GENERAL FINDINGS OF THE EMISSIONS INVENTORY	11-1
11.2	RELEASES OF COMMERCIAL PCBs	11-2
11.2.1.	Approved PCB Disposal/Destruction Methods	11-6
11.2.2.	Accidental Releases of In-Service PCBs	11-9
11.2.3.	Municipal Wastewater Treatment	11-12
11.3.	CHEMICAL MANUFACTURING AND PROCESSING SOURCES	11-13
11.4.	COMBUSTION SOURCES	11-14
11.4.1	Municipal Solid Waste Incineration	11-14
11.4.2.	Industrial Wood Combustion	11-15
11.4.3.	Medical Waste Incineration	11-16
11.4.4.	Tire Combustion	11-16
11.4.5.	Cigarette Smoking	11-17
11.4.6.	Sewage Sludge Incineration	11-18
11.4.7.	Backyard Barrel Burning	11-18
11.4.8.	Petroleum Refining Catalyst Regeneration	11-20
11.5.	NATURAL SOURCES	11-21
11.5.1.	Biotransformation of Other PCBs	11-21
11.5.2.	Photochemical Transformation of Other PCBs	11-24
11.6.	PAST USE OF COMMERCIAL PCBs	11-26

TABLE OF CONTENTS (continued)

12. RESERVOIR SOURCES OF CDD/CDF AND DIOXIN-LIKE PCBs 12-1

 12.1. POTENTIAL RESERVOIRS 12-2

 12.2. CHARACTERIZATION OF RESERVOIR SOURCES 12-3

 12.2.1. Soil 12-3

 12.2.2. Water 12-13

 12.2.3. Sediment 12-16

 12.2.4. Biota 12-19

 12.3. SUMMARY AND CONCLUSIONS 12-23

 12.3.1. Reservoir Sources 12-23

 12.3.2. Implications for Human Exposure 12-25

13. BALL CLAY 13-1

 13.1 INTRODUCTION 13-1

 13.2 CHARACTERISTICS OF MISSISSIPPI EMBAYMENT BALL CLAYS 13-1

 13.3 LEVELS OF DIOXIN-LIKE COMPOUNDS IN BALL CLAY 13-2

 13.4 EVIDENCE FOR BALL CLAY AS A NATURAL SOURCE 13-3

 13.5 ENVIRONMENTAL RELEASES OF DIOXIN-LIKE COMPOUNDS FROM
 THE MINING AND PROCESSING OF BALL CLAY 13-5

REFERENCES R-1

LIST OF TABLES

Table 1-1.	The TEF Scheme for I-TEQ _{DF}	1-28
Table 1-2.	The TEF Scheme for Dioxin-Like PCBs, as Determined by the World Health Organization in 1994	1-29
Table 1-3.	The TEF Scheme for TEQ _{DFP} -WHO ₉₈	1-30
Table 1-4.	Nomenclature for Dioxin-Like Compounds	1-31
Table 1-5.	List of Known and Suspected CDD/CDF Sources	1-32
Table 1-6.	Confidence Rating Scheme for U.S. Emission Estimates	1-35
Table 1-7.	Inventory of Environmental Releases (grams/year) of I-TEQ _{DF} from Known Sources in the United States for 1995 and 1987	1-36
Table 1-8.	Inventory of Environmental Releases (grams/year) of TEQ _{DF} -WHO ₉₈ from Known Sources in the United States for 1995 and 1987	1-38
Table 1-9.	I-TEQ _{DF} Emission Factors Used to Develop National Emission Inventory Estimates of Releases to Air	1-40
Table 1-10.	TEQ _{DF} -WHO ₉₈ Emission Factors Used to Develop National Emission Inventory Estimates of Releases to Air	1-41
Table 1-11.	Identification of Products Containing CDD/CDF in 1995 and 1987 . . .	1-42
Table 1-12.	Identification of Products Containing CDD/CDF in 1995 and 1987 . . .	1-42
Table 2-1.	Concentration of CDD/CDFs on Municipal Incinerator Fly Ash at Varying Temperatures	2-34
Table 2-2.	CDD/CDFs Formed from the Thermolytic Reaction of 690 mg Benzene + FeCl ₃ Silica Complex	2-35
Table 2-3.	<i>De Novo</i> Formation of CDDs/CDFs after Heating Mg-Al Silicate, 4% Charcoal, 7% Cl, 1% CuCl ₂ ·2H ₂ O at 300°C	2-36
Table 3-1.	Inventory of MSWIs in 1995 by Technology, APCD, and Annual Activity Level	3-49
Table 3-2.	Inventory of MSWIs in 1987 by Technology, APCD, and Annual Activity Level	3-51
Table 3-3.	CDD/CDF TEQ Emission Factors (ng TEQ per kg waste) for Municipal Solid Waste Incineration	3-53
Table 3-4a.	Annual I-TEQ _{DF} Emissions (g/yr) from MSWIs Operating in 1995	3-55
Table 3-4b.	Annual TEQ _{DF} -WHO ₉₈ Emissions (g/yr) from MSWIs Operating in 1995	3-56
Table 3-5a.	Annual I-TEQ _{DF} Emissions to the Air From MSWIs Operating in 1987	3-57
Table 3-5b.	Annual TEQ _{DF} -WHO ₉₈ Emissions to the Air From MSWIs Operating in 1987	3-58
Table 3-6.	Fly Ash from a Municipal Incinerator	3-59
Table 3-7.	Comparison of the Amount of TEQs Generated Annually in MSWI Ash	3-60
Table 3-8.	CDD/CDF Emission Factors for Hazardous Waste Incinerators and Boilers	3-61

LIST OF TABLES (continued)

Table 3-9.	Summary of Annual Operating Hours for Each MWI Type	3-62
Table 3-10.	OAQPS Approach: PM Emission Limits for MWIs and Corresponding Residence Times in the Secondary (2 ^o) Combustion Chamber	3-63
Table 3-11.	OAQPS Approach: Estimated Nationwide I-TEQ _{DF} Emissions (g/yr) for 1995	3-64
Table 3-12.	AHA Approach: I-TEQ _{DF} Emission Factors Calculated for Air Pollution Control	3-65
Table 3-13.	AHA Assumptions of the Percent Distribution of Air Pollution Control on MWIs Based on PM Emission Limits	3-66
Table 3-14.	AHA Approach: Estimated Annual Nationwide I-TEQ _{DF} Emissions	3-67
Table 3-15.	Comparison Between Predicted Residence Times and Residence Times Confirmed by State Agencies in EPA/ORD Telephone Survey	3-68
Table 3-16.	EPA/ORD Approach: TEQ Emissions from Medical Waste Incineration for Reference Year 1995	3-69
Table 3-17.	Summary of Annual TEQ Emissions from Medical Waste Incineration (MWI) for Reference Year 1987	3-70
Table 3-18.	Comparison of Basic Assumptions Used in the EPA/ORD, the EPA/OAQPS, and the AHA Approaches to Estimating Nationwide CDD/CDF TEQ Emissions from MWIs in 1995	3-71
Table 3-19.	CDD/CDF Air Emission Factors for a Crematorium	3-72
Table 3-20.	CDD/CDF Emission Factors for Sewage Sludge Incinerators	3-73
Table 3-21.	CDD/CDF Air Emission Factors for Tire Combustion	3-74
Table 3-22.	CDD/CDF Emission Factors for Combustion of Bleached-Kraft Mill Sludge in Wood Residue Boilers	3-75
Table 4-1.	Descriptions and Results of Vehicle Emission Testing Studies for CDDs and CDFs	4-40
Table 4-2.	Diesel-Fueled Automobile CDD/CDF Congener Emission Factors	4-41
Table 4-3.	Diesel-Fueled Truck CDD/CDF Congener Emission Factors	4-42
Table 4-4.	Leaded Gasoline-Fueled Automobile CDD/CDF Congener Emission Factors	4-43
Table 4-5.	Unleaded Gasoline-Fueled (Without Catalytic Converters) Automobile CDD/CDF Congener Emission Factors	4-44
Table 4-6.	Unleaded Gasoline-Fueled (With Catalytic Converters) Automobile CDD/CDF Congener Emission Factors	4-45
Table 4-7.	European Tunnel Study Test Results	4-46
Table 4-8.	Baltimore Harbor Tunnel Study: Estimated Emission Factors for Heavy-Duty (HD) Diesel Vehicles	4-47
Table 4-9.	CDD/CDF Emission Factors for Industrial Wood Combustors	4-48
Table 4-10.	CDD/CDF Concentrations in Residential Chimney Soot from Wood Stoves and Fireplaces	4-49
Table 4-11.	CDD/CDF Concentrations in Residential Bottom Ash from Wood Stoves and a Fireplace	4-50
Table 4-12.	CDD/CDF Concentrations in Chimney Soot (Bavaria, Germany)	4-51
Table 4-13.	Fly Ash from Wood Working Industry	4-52

LIST OF TABLES (continued)

Table 4-14.	Electrostatic Precipitator Waste Ash from Wood-Fired Industrial Boiler	4-53
Table 4-15.	Estimated CDD/CDF Emission Factors for Oil-Fired Residential Furnaces	4-54
Table 4-16.	CDD/CDF Emission Factors for Oil-Fired Utility/Industrial Boilers	4-55
Table 4-17.	CDD/CDF Concentrations in Stack Emissions from U.S. Coal-Fired Power Plants	4-56
Table 4-18.	Characteristics of U.S. Coal-Fired Power Plants Tested by DOE	4-57
Table 4-19.	CDD/CDF Emission Factors for Coal-Fired Utility/Industrial Power Plants	4-58
Table 4-20.	CDD/CDF Emission Factors from Residential Coal Combustors	4-59
Table 4-21.	Coal-Fired Utility Solid Wastes	4-60
Table 5-1.	CDD/CDF Emission Factors for Cement Kilns	5-30
Table 5-2.	CDD/CDF Emission Factors for Petroleum Catalytic Reforming Units	5-31
Table 5-3.	CDD Concentrations in Japanese Cigarettes, Smoke, and Ash	5-32
Table 5-4.	CDD/CDF Emissions in Cigarette Smoke	5-33
Table 5-5.	CDD/CDF Concentrations in Cigarette Tobacco	5-34
Table 5-6.	CDD/CDF Emission Factors for Black Liquor Recovery Boilers	5-35
Table 5-7.	Concentrations of CDD/CDF in Candle Materials and Emissions	5-36
Table 5-8.	CDD/CDF Concentrations in Ash Samples from Cement Kiln Electric Static Precipitator and LWA Kiln Fabric Filter	5-37
Table 6-1.	CDD/CDF Emission Factors for a Landfill Flare	6-21
Table 6-2.	CDD/CDF Air Emission Factors from Barrel Burning of Household Waste	6-22
Table 6-3.	PCDD/PCDF Analysis for Composite Ash Samples from Barrel Burning	6-23
Table 6-4.	PCB Analysis for Composite Ash Samples from Barrel Burning	6-24
Table 6-5.	CDD/CDF in Dust Fall and Ashes from Volcanoes	6-25
Table 7-1.	CDD/CDF Emission Factors for Secondary Aluminum Smelters	7-31
Table 7-2.	CDD/CDF Emission Factors for Secondary Copper Smelter	7-32
Table 7-3.	CDD/CDF Emission Factors for Secondary Lead Smelters	7-33
Table 7-4.	CDD/CDF Emission Factors for Sinter Plants	7-34
Table 7-5.	Operating Parameters for U.S. Iron Ore Sinter Plants	7-35
Table 7-6.	CDD/CDF Emission Factors for a Ferrous Foundry	7-36
Table 7-7.	CDD/CDF Emission Factors for a Scrap Wire Incinerator	7-37
Table 7-8.	Geometric Mean CDD/CDF Concentrations in Fly Ash and Ash/Soil at Metal Recovery Sites	7-38
Table 7-9.	CDD/CDF Emission Factors for a Drum and Barrel Reclamation Furnace	7-39
Table 8-1.	CDD/CDF Concentrations in Pulp and Paper Mill Bleached Pulp, Wastewater Sludge, and Effluent (circa 1988)	8-49
Table 8-2.	CDD/CDF Concentrations in Pulp and Paper Mill Bleached Pulp, Wastewater Sludge, and Effluent (circa 1996)	8-50
Table 8-3.	Summary of Bleached Chemical Pulp and Paper Mill Discharges of 2,3,7,8-TCDD and 2,3,7,8-TCDF	8-51

LIST OF TABLES (continued)

Table 8-4.	CDD/CDF Concentrations in Graphite Electrode Sludge from Chlorine Production	8-52
Table 8-5.	CDD/CDF Concentrations in Metal Chlorides	8-53
Table 8-6.	CDD/CDF Concentrations in Mono- through Tetra-Chlorophenols	8-54
Table 8-7.	CDD/CDF Concentrations in Historical and Current Technical Pentachlorophenol Products	8-55
Table 8-8.	Historical CDD/CDF Concentrations in Pentachlorophenol-Na	8-57
Table 8-9.	Summary of Specific Dioxin-Containing Wastes That Must Comply with Land Disposal Restrictions	8-58
Table 8-10.	CDD/CDF Concentrations in Chlorobenzenes	8-60
Table 8-11.	Concentrations of CDD/CDF Congener Groups in Unused Commercial PCB Mixtures	8-61
Table 8-12.	2,3,7,8-Substituted Congener Concentrations in Unused PCB Mixtures	8-62
Table 8-13.	Reported CDD/CDF Concentrations in Wastes from PVC Manufacture	8-63
Table 8-14.	CDD/CDF Measurements in Treated Wastewater and Wastewater Solids from U.S. EDC/VCM/PVC Manufacturers	8-64
Table 8-15.	CDD/CDF Measurements in Products from U.S. EDC/VCM/PVC Manufacturers	8-65
Table 8-16.	CDD/CDF Concentrations in Dioxazine Dyes and Pigments (Canada)	8-66
Table 8-17.	CDD/CDF Concentrations in Printing Inks (Germany)	8-67
Table 8-18.	Chemicals Requiring TSCA Section 4 Testing under the Dioxin/Furan Rule	8-68
Table 8-19.	Congeners and Limits of Quantitation (LOQ) for Which Quantitation is Required under the Dioxin/Furan Test Rule and Pesticide Data Call-In	8-69
Table 8-20.	Precursor Chemicals Subject to Reporting Requirements under TSCA Section 8(a)	8-70
Table 8-21.	Results of Analytical Testing for Dioxins and Furans in the Chemicals Tested to Date under Section 4 of the Dioxin/Furan Test Rule	8-71
Table 8-22.	CDDs and CDFs in Chloranil and Carbazole Violet Samples Analyzed Pursuant to the EPA Dioxin/Furan Test Rule	8-72
Table 8-23.	Status of First Pesticide Data Call-In: Pesticides Suspected of Having the Potential to Become Contaminated with Dioxins if Synthesized under Conditions Favoring Dioxin Formation	8-73
Table 8-24.	Status of Second Pesticide Data Call-In: Pesticides Suspected of Being Contaminated with Dioxins	8-77
Table 8-25.	Summary of Results for CDDs and CDFs in Technical 2,4-D and 2,4-D Ester Herbicides	8-80
Table 8-26.	Summary of Analytical Data Submitted to EPA in Response to Pesticide Data Call-Ins	8-81
Table 8-27.	CDD/CDF Concentrations in Samples of 2,4-D and Pesticide Formulations Containing 2,4-D	8-82
Table 8-28.	Mean CDD/CDF Measurements in Effluents from Nine U.S. POTWs	8-83

LIST OF TABLES (continued)

Table 8-29.	CDD/CDF Concentrations Measured in EPA's National Sewage Sludge Survey	8-84
Table 8-30.	CDD/CDF Concentrations Measured in 99 Sludges Collected from U.S. POTWs During 1994	8-85
Table 8-31.	Quantity of Sewage Sludge Disposed of Annually by Primary, Secondary, or Advanced Treatment POTWs and Potential Dioxin TEQ Releases . . .	8-86
Table 8-32.	CDD/CDF Concentrations in Swedish Liquid Soap, Tall Oil, and Tall Resin	8-87
Table 11-1.	List of Known and Suspected Source Categories for Dioxin-like PCBs	11-28
Table 11-2.	Quantitative Inventory of Dioxin-Like PCB TEQ _p -WHO ₉₈ Releases in the United States	11-29
Table 11-3.	Weight Percent Concentrations of Dioxin-like PCBs in Aroclors, Clophens, and Kanechlors	11-31
Table 11-4.	Disposal Requirements for PCBs and PCB Items	11-33
Table 11-5.	Off-site Transfers of PCBs Reported in TRI (1988-1996)	11-34
Table 11-6.	Releases of PCBs Reported in TRI (1988-1996)	11-35
Table 11-7.	Aroclor Concentrations Measured in EPA's National Sewage Sludge Survey	11-36
Table 11-8.	Dioxin-Like PCB Concentrations Measured in Sludges Collected from 74 U.S. POTWs During 1994	11-37
Table 11-9.	Dioxin-Like PCB Concentrations in Sludges Collected from a U.S. POTW During 1999	11-38
Table 11-10.	Quantity of Sewage Sludge Disposed of Annually by Primary, Secondary, or Advanced Treatment POTWs and Potential Dioxin-Like PCB TEQ Releases	11-39
Table 11-11.	PCB Congener Group Emission Factors for Industrial Wood Combustors	11-40
Table 11-12.	PCB Congener Group Emission Factors for Medical Waste Incinerators (MWIs)	11-41
Table 11-13.	PCB Congener Group Emission Factors for a Tire Combustor	11-42
Table 11-14.	Dioxin-Like PCB Concentrations in Cigarette Tobacco	11-43
Table 11-15.	Dioxin-Like PCB Concentrations in Stack Gas Collected from a U.S. Sewage Sludge Incinerator	11-44
Table 11-16.	Dioxin-Like PCB Emission Factors from Backyard Barrel Burning	11-45
Table 11-17.	PCB Congener Group Emission Factors for a Petroleum Catalytic Reforming Unit	11-46
Table 11-18.	Estimated Tropospheric Half-Lives of Dioxin-Like PCBs with Respect to Gas-Phase Reaction with the OH Radical	11-47
Table 11-19.	Estimated PCB Loads in the Global Environment as of 1985	11-48
Table 11-20.	Domestic Sales of Aroclors (1957-1974)	11-49
Table 11-21.	Estimated U.S. Usage of PCBs by Use Category (1930-1975)	11-50
Table 11-22.	Estimated Direct Releases of Aroclors to the U.S. Environment (1930-1974)	11-51

LIST OF TABLES (continued)

Table 11-23. Estimated Releases of Dioxin-Like PCB TEQs to the U.S. Environment
During 1930-1977 11-52

Table 12-1. Historical Production, Sales, and Usage Quantities for 2,4-D 12-27

Table 12-2. Historical Production, Sales, and Usage Quantities 2,4,5-T 12-29

Table 12-3. CDD/CDF Concentrations in Recent Sample of 2,4,5-T 12-31

Table 12-4. PCB 138 Fluxes Predicted by Harner et al. (1995) 12-32

Table 12-5. Summary of Flux Calculations for Total PCBs in Green Bay, 1989 . . . 12-33

Table 12-6. Comparison of Estimated PCB Concentrations with Observed Values . 12-34

Table 13-1. Concentrations of CDDs Determined in Eight (8) Ball Clay Samples in
the U.S. 13-7

Table 13-2. Comparison of the Mean CDD/CDF Congener Group Distribution in
Ball Clay to the Mean Congener Group Distributions in Urban and
Rural Soils in North America 13-8

LIST OF FIGURES

Figure 1-1.	Chemical Structure of 2,3,7,8-TCDD and Related Compounds	1-43
Figure 1-2.	Estimated CDD/CDF I-TEQ Emissions to Air from Combustion Sources in the United States (Reference Time Period: 1995)	1-44
Figure 1-3.	Estimated CDD/CDF I-TEQ Emissions to Air from Combustion Sources in the United States (Reference Time Period: 1987)	1-45
Figure 1-4.	Comparison of Estimates of Annual I-TEQ Emissions to Air (grams I-TEQ/year) for Reference Years 1987 and 1995	1-46
Figure 1-5.	Estimated CDD/CDF WHO-TEQ Emissions to Air from Combustion Sources in the United States (Reference Time Period: 1995)	1-47
Figure 1-6.	Estimated CDD/CDF WHO-TEQ Emissions to Air From Combustion Sources in the United States (Reference Time Period: 1987)	1-48
Figure 1-7.	Comparison of Estimates of Annual WHO-TEQ Emissions to Air (grams WHO-TEQ/year) for Reference Years 1987 and 1995	1-49
Figure 1-8.	The Congener Profiles (as fractional distributions to total CDD/CDF) of Anthropogenic Sources of Chlorinated Dibenzo-p-Dioxins and Chlorinated Dibenzofurans in the United States	1-50
Figure 2-1.	The <i>de novo</i> Synthesis of CDD/CDFs from Heating Carbon Particulate at 300°C at Varying Retention Times	2-37
Figure 2-2.	Temperature Dependence on CDD/CDF Formation	2-38
Figure 2-3.	The Association Between Vapor Phase Cl ₂ and the Formation of CDDs/CDFs	2-39
Figure 3-1.	Typical Mass Burn Waterwall Municipal Solid Waste Incinerator	3-76
Figure 3-2.	Typical Mass Burn Rotary Kiln Combustor	3-77
Figure 3-3.	Typical Modular Excess-Air Combustor	3-78
Figure 3-4.	Typical Modular Starved-Air Combustor with Transfer Rams	3-79
Figure 3-5.	Typical Dedicated RDF-Fired Spreader Stoker Boiler	3-80
Figure 3-6.	Fluidized-Bed RDF Incinerator	3-81
Figure 3-7.	MSWI Design Classes for 1987	3-82
Figure 3-8.	MSWI Design Classes for 1995	3-83
Figure 3-9.	Congener and Congener Group Profiles for Air Emissions from a Mass-Burn Waterwall MSWI, Equipped with a Dry Scrubber and Fabric Filter	3-84
Figure 3-10.	Congener Profile for Air Emissions from Hazardous Waste Incinerators	3-85
Figure 3-11.	Congener and Congener Group Profiles for Air Emissions from Boilers and Industrial Furnaces Burning Hazardous Waste	3-86
Figure 3-12.	Congener and Congener Group Profiles for Air Emissions from Medical Waste Incinerators without APCD	3-87
Figure 3-13.	Congener and Congener Group Profiles for Air Emissions from Medical Waste Incinerators Equipped with a Wet Scrubber, Baghouse, and Fabric Filter	3-88
Figure 3-14.	Congener and Congener Group Profiles for Air Emissions from a Crematorium	3-89
Figure 3-15.	Congener and Congener Group Profiles for Air Emissions from Sewage Sludge Incinerators	3-90

LIST OF FIGURES (continued)

Figure 3-16.	Congener and Congener Group Profiles for Air Emissions from a Tire Combustor	3-91
Figure 4-1.	Congener and Congener Group Profiles for Air Emissions from Diesel-fueled Vehicles	4-61
Figure 4-2.	Congener and Congener Group Profiles for Air Emissions from Leaded Gas-fueled Vehicles	4-62
Figure 4-3.	Congener and Congener Group Profiles for Air Emissions from Unleaded Gas-fueled Vehicles	4-63
Figure 4-4.	Tunnel Air Concentrations	4-64
Figure 4-5a.	Congener and Congener Group Profiles for Air Emissions from Industrial Wood Combustors	4-65
Figure 4-5b	Congener and Congener Group Profiles for Air Emissions from Bleached Kraft Mill Bark Combustors	4-66
Figure 4-6.	Congener Group Profile for Air Emissions from Residential Oil-fueled Furnaces	4-67
Figure 4-7.	Congener and Congener Group Profiles for Air Emissions from Industrial Oil-fueled Boilers	4-68
Figure 4-8.	Congener and Congener Group Profiles for Air Emissions from Industrial/Utility Coal-fueled Combustors	4-69
Figure 4-9.	Congener Group Profile for Air Emissions from Residential Coal-fueled Combustors	4-70
Figure 5-1.	Congener Profile for Air Emissions from Cement Kilns Burning Hazardous Waste	5-38
Figure 5-2.	Congener and Congener Group Profiles for Air Emissions from Cement Kilns Not Burning Hazardous Waste	5-39
Figure 5-3.	Congener and Congener Group Profiles for Air Emissions from Petroleum Catalytic Reforming Units	5-40
Figure 5-4.	CDD Profiles for Japanese Cigarettes, Smoke, and Ash	5-41
Figure 5-5.	Congener Group Profiles for Mainstream and Sidestream Cigarette Smoke	5-42
Figure 5-6.	Congener Group Profiles for Cigarette Tobacco from Various Countries	5-43
Figure 5-7.	Congener and Congener Group Profiles for Air Emissions from Kraft Black Liquor Recovery Boilers	5-44
Figure 6-1.	Congener Profile for Landfill Flare Air Emissions	6-26
Figure 7-1.	Congener and Congener Group Profiles for Air Emissions from Secondary Aluminum Smelters	7-40
Figure 7-2a.	Congener Group Profile for Air Emissions from a Secondary Copper Smelter	7-41
Figure 7-2b.	Congener and Congener Group Profiles for a Closed Secondary Copper Smelter	7-42
Figure 7-3.	Congener and Congener Group Profiles for Air Emissions from Secondary Lead Smelters	7-43
Figure 7-4.	Congener Profiles for Air Emissions from U.S. Iron Ore Sinter Plants . .	7-44

LIST OF FIGURES (continued)

Figure 7-5. Congener Group Profile for Air Emissions from a Scrap Wire Incinerator 7-45

Figure 7-6. Congener Group Profile for Air Emissions from a Drum Incinerator 7-46

Figure 8-1. 104 Mill Study Full Congener Analysis Results for Pulp 8-88

Figure 8-2. 104 Mill Study Full Congener Analysis Results for Sludge 8-89

Figure 8-3. 104 Mill Study Full Congener Analysis Results for Effluent 8-90

Figure 8-4. Congener and Congener Group Profiles for Technical PCP 8-91

Figure 8-5. Congener Profile for 2,4-D (salts and esters) 8-92

Figure 8-6. Congener Profiles for Sewage Sludge 8-93

Figure 12-1. Fluxes Among Reservoirs 12-35

LIST OF ACRONYMS

AHA	American Hospital Association
AISI	American Iron and Steel Institute
AlCl ₃	Aluminum Chloride
AMSA	Association of Metropolitan Sewerage Agencies
APC	Air Pollution Control
APCD	Air Pollution Control Device
atm	Atmosphere
ATSDR	Agency for Toxic Substances and Disease Registry
BAAQMD	Bay Area Air Quality Management District
BCF	Bioconcentration Factor
BDDs	Polybrominated Dibenzo-p-dioxins or PBDDS
BDFs	Polybrominated Dibenzofurans or PBDFs
BHF	Bag House Filter
Btu	British Thermal Unit
CAA	Clean Air Act
CaCl ₂	Calcium Chloride
CARB	California Air Resources Board
CBI	Confidential Business Information
°C	Degree Celsius
CD	Compact Disk
CDDs	Polychlorinated Dibenzo-p-dioxins or PCDDs
CDFs	Polychlorinated Dibenzofurans or PCDFs
CEQ	Council on Environmental Quality
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act (also know as Superfund)
C-ESP	Cold-side Electrostatic Precipitator
CETRED	Combustion Emissions Technical Resource Document
CFR	Code of Federal Regulations
CSF	Confidential Statement of Formula
CKD	Cement Kiln Dust
Cl ⁻	Chloride
Cl ₂	Dichloride
cm	Centimeters
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CRWQCB	California Regional Water Quality Control Board
CR	Confidence Rating
CuCl	Copper (Cupric) Chloride
CuCl ₂	Copper (Cupric) Dichloride
D	Symbol for Congener Class: Dibenzo-p-dioxin
D	Symbol for di (i.e., Two Halogen Substitution)
DBF	Dibenzofuran
DCBz	Dichlorobenzene
DCI	Data Call-In

LIST OF ACRONYMS (continued)

DCP	Dichlorophenols
DHHS	U.S. Department of Health and Human Services
DL	Detection Limit
DOC	U.S. Department of Commerce
DOE	U.S. Department of Energy
d_p	Physical Diameter
dscm	Dry Standard Cubic Meter
DSI	Dry Sorbent Injection
EAF	Electric Arc Furnaces
EDC	Ethylene Dichloride
EEL	Edison Electric Institute
EF	Emission Factor
e.g.	For example
EGB	Electro Granular Bed
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	Electrostatic Precipitator
F	Symbol for Congener Class: Dibenzofuran
FF	Fabric Filter
°F	Degree Fahrenheit
FB-RDF	Fluidized Bed Refuse-Derived Fuel
FCEM	Field Chemical Emissions Measurement
$FeCl_2$	Ferric (Iron) Dichloride
$FeCl_3$	Ferric (Iron) Trichloride
FGD	Flue Gas Desulfurization
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
ft	Feet
ft^3	Cubic Feet
g	Gram
GAC	Granular Activated Carbon
GC-ECD	Gas Chromatography/Electron Capture Detector
GC-MS	Gas Chromatography/Mass Spectrometry
gplg	Grams Per Leaded Gallon
gpg	Gram Per Gallon
gr/dscf	Grains Per Dry Standard Cubic Foot
HAPs	Hazardous Air Pollutants
HCl	Hydrogen Chloride
HCBz	Hexachlorobenzene
HD	Heavy Duty
HDD	Polyhalogenated Dibenzo-p-Dioxins
HDF	Pollyhalogenated Dibenzofurans
H-ESP	Hot-side Electrostatic Precipitator
Hp	Symbol for Hepta (i.e., Seven Halogen Substitution)

LIST OF ACRONYMS (continued)

hr	Hour
HWI	Hazardous Waste Incineration
Hx	Symbol for Hexa (i.e., Six Halogen Substitution)
HxCB	Hexachlorobiphenyl
i.e.	That Is
ITC	U.S. International Trade Commission
IUPAC	International Union of Pure and Applied Chemistry
J	Joules
KCl	Potassium Chloride
kg	Kilogram
km	Kilometer
kW	Kilowatt
L	Liter
lb	Pound
LII	Liquid Injection Incinerator
LOQ	Limits of Quantitation
M	Symbol for Mono (i.e., One Halogen Substitution)
MACT	Maximum Achievable Control Technologies
MB	Mass Burn
MB-RC	Mass Burn Rotary Kiln
MB-REF	Mass Burn Refractory-Walled
MB-WW	Mass Burn Waterwall
MCBz	Monochlorobenzene
MCP	Monochlorophenol
MgCl ₂	Magnesium Chloride
MgO	Magnesium Oxide
μg	Microgram
mg	Milligram
mm	Millimeter
mol	Mole (Unit of Substance)
MOD/EA	Modular Excess Air
MOD/SA	Modular Starved Air
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incinerator
MWI	Medical Waste Incineration
m ²	Square Meter
m ³	Cubic Meter
Na	Sodium
NA	Not Applicable
NaCl	Sodium Chloride
NaOCl	Sodium Hypochlorite
NATO	North Atlantic Treaty Organization
ng	Nanogram
NCASI	National Council of the Paper Industry for Air and Stream Improvement

LIST OF ACRONYMS (continued)

ND	Not Detected
NCEA	National Center for Environmental Assessment
NEG	Expected To Be Negligible or Non-existent
NESHAP	National Emission Standards for Hazardous Air Pollutants
NiCl ₂	Nickel Chloride
NiO	Nickel Oxide
Nm ³	Standard Cubic Meter
NMOC	Nonmethane Organic Compounds
NR	Not Reported
NYSDEC	New York State Department of Environmental Conservation
NYSDOH	New York State Department of Health
O	Symbol for Octa (i.e., Eight Halogen Substitution)
OAQPS	Office of Air Quality Planning and Standards
O ₂	Molecular Oxygen
OH	Hydroxide ion
OMS	Office of Mobile Sources
OPP	Office of Pesticide Programs
OPPT	Office of Pollution Prevention and Toxics
ORD	Office of Research and Development
OSW	Office of Solid Waste
Pa	Pascals (i.e., Unit of Pressure)
PAH	Polycyclic Aromatic Hydrocarbons
Pb	Lead
PBDDs	Polybrominated Dibenzo-p-dioxins or BDDs
PBDFs	Polybrominated Dibenzofurans or BDFs
PBS	Packed Bed Scrubber
PCA	Portland Cement Association
PCBs	Polychlorinated Biphenyls
PCDDs	Polychlorinated Dibenzo-p-dioxins or CDDs
PCDFs	Polychlorinated Dibenzofurans or CDFs
PCP	Pentachlorophenol
PCP-Na	Pentachlorophenate
PCT	Polychlorinated Terphenyl
Pe	Symbol for Penta (i.e., Five Halogen Substitution)
PeCB	Pentachlorobiphenyl
PeCBz	Pentachlorobenzene
pg	Picogram
PL	Public Law
PM	Particulate Matter
POM	Polycyclic Organic Matter
POTW	Publicly Owned Treatment Works
ppb	Parts Per Billion
ppm	Parts Per Million
ppmv	Parts Per Million (Volume Basis)

LIST OF ACRONYMS (continued)

ppq	Parts Per Quadrillion
ppt	Parts Per Trillion
ppt/v	Parts Per Trillion (Volume Basis)
PUF	Polyurethane Foam Plug
PVC	Polyvinyl Chloride
QA/QC	Quality Assurance/Quality Control
QWASI	Quantitative Water Sediment Interaction
RCRA	Resource Conservation and Recovery Act
RDF	Refuse-Derived Fuel
RT	Residence Time
SAB	Science Advisory Board
sec	Second
SIC	Standard Industrial Code
SiCl ₄	Silium Tetrachloride
SIPs	State Implementation Plans
SNUR	Significant New Use Rule
SO ₂	Sulfur Dioxide
sq	Square
T	Symbol for Tetra (i.e., Four Halogen Substitution)
TCBz	Trichlorobenzene
TCDD	2,3,7,8-tetrachlorobidbenzo-p-dioxin
TCDF	2,3,7,8-tetrachlorobidbenzofuran
TCLP	Toxicity Characteristic Leachate Procedure
TeCB	Tetrachlorobiphenyls
TeCP	Tetrachlorophenols
TEF	Toxicity Equivalency Factor
TEQ	Toxicity Equivalent
TEQ/yr	Toxicity Equivalent Per Year
TiCl ₄	Titanium Tetrachloride
Tr	Symbol for Tri (i.e., Three Halogen Substitution)
TrCBs	Trichlorobiphenyls
TrCP	Trichlorophenols
TRI	Toxics Release Inventory
TSCA	Toxics Substances Control Act
2,4-D	2,4-Dichlorophenoxyacetic Acid
2,4-DB	4-(2,4-Dichlorophenoxy) Butyric Acid
2,4-DCP	2,4-Dichlorophenol
2,4-DP	2-(2,4-Dichlorophenoxy) Propionic Acid
2,4,5-T	2,4,5-Trichlorophenoxy (Phenoxy Herbicides)
2378	Halogen Substitutions in the 2,3,7,8 Positions
μg	Microgram
UK	United Kingdom
UNC	Uncontrolled
USDA	U.S. Department of Agriculture

LIST OF ACRONYMS (continued)

USITC	U.S. International Trade Commission
USWAG	Utility Solid Wastes Activity Group
UV	Ultraviolet
VCM	Vinyl Chloride Monomer
v/v	Volume per Volume
WHO	World Health Organization
wk ⁻¹	Per Week
WS	Wet Scrubber
yr	Year

SYMBOLS:

@	At
/	Per
μ	Micro
%	Percent
<	Less than
>	Greater than
\leq	Less than or equal to
\geq	Greater than or equal to
\sim	Difference