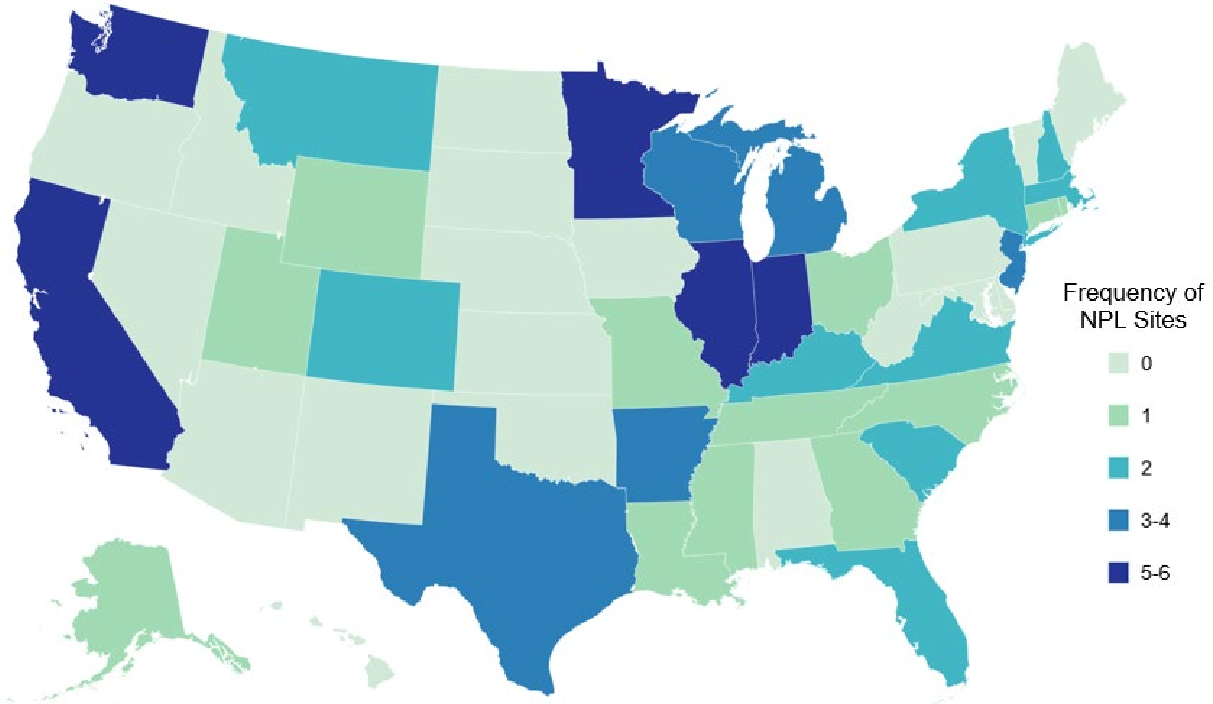
CHAPTER 5. POTENTIAL FOR HUMAN EXPOSURE

5.1 OVERVIEW

CDFs have been identified in at least 76 of the 1,867 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (ATSDR 2019). However, the number of sites in which CDFs have been evaluated is not known. The number of sites in each state is shown in Figure 5-1.

Figure 5-1. Number of NPL Sites with Chlorodibenzofuran (CDF) Contamination



Source: ATSDR 2019

- The most important human exposure route is through the ingestion of foods containing CDFs.
- Inhalation of ambient air, as well as ingestion of drinking water, are minor routes of human exposure to CDFs; exposure can also occur from certain consumer products.
- The lower chlorinated CDFs are semi-volatile; however, the tetra-, penta-, hexa-, and octa-congeners are considered nonvolatile.
- The lower chlorinated CDFs degrade in the atmosphere by reaction with atmospheric oxidants in a matter of days; however, the higher chlorinated congeners are more persistent and subject to long range transport.
- Direct photolysis of CDFs is an important degradation process; however, biodegradation occurs slowly for the higher chlorinated CDFs and they are considered persistent in the environment.

- CDFs have large soil adsorption coefficients and possess low mobility in soil surfaces.
- Higher chlorinated CDFs bioconcentrate in aquatic organisms.

Low levels of CDFs occur as contaminants in certain chemical products and during combustion of certain precursors of CDFs. The processes that are responsible for the production of CDFs in the environment form a mixture of congeners. In addition, many of the combustion processes that produce CDFs also produce structurally similar compounds, such as CDDs and chlorinated dibenzothiophenes (CDTs). Due to the similarity in their physicochemical properties, including low water solubility, high lipid solubility, low vapor pressure, and multiple chlorine substitution, these compounds are generally found together in environmental samples. Therefore, environmental exposures to CDFs occur not only from a mixture of CDFs, but also from CDDs, CDTs, and other structurally similar compounds and other structurally similar compounds present as co-contaminants. To simplify the assessment of human health risk of a mixture of CDDs and CDFs, EPA has recommended the toxic equivalent (TEQ) approach. The TEQ is a weighted quantity of measure based on the toxicity of each member of the dioxin and dioxin-like compounds category relative to the most toxic member of the category, 2,3,7,8-TCDD. TEQs are calculated by multiplying the mass or concentration of each dioxin-like compound by a TEF and summing across all the compounds present.

The sources of CDFs in the environment are combustion processes mainly involving municipal and industrial incineration; combustion of fossil fuels by power plants, home heating, and fireplaces; automobile exhaust; medical waste incineration; yard waste composting; accidental fires or malfunction of PCB-filled transformers and capacitors; improper disposal of chlorinated chemical wastes; use of certain chemical products (e.g., chlorinated phenols); certain high temperature industrial processes, such as copper smelting, electrical arc furnaces in steel mills, and production of metallic magnesium and refined nickel; chlorine bleaching of pulp and paper (this is not a relevant source of CDFs in the United States); and photochemical processes involving certain products, such as chlorinated diphenyl ethers. Some of these sources emit CDFs in the air, while others discharge CDFs as effluents in surface water. The source of these compounds in soil is disposal of chemical wastes containing CDFs as contaminants. The deposition of atmospheric CDFs is also an important source of these compounds in surface water and soil.

In the atmosphere, the higher chlorinated CDFs are present predominantly in the particulate phase, but tetra- and penta-CDFs may be present in the vapor phase as well. Due to higher atmospheric temperatures, the concentrations of CDFs in the vapor phase increase during summer. The most important chemical process in determining the fate of CDFs in air is the reaction with hydroxyl radicals. The lifetime of CDFs due to this process is >10 days, and increases with higher chlorinated CDFs, which allows these compounds to be transported long distances in air. Wet and dry deposition of atmospheric CDFs may also be important for the removal of these compounds from air. CDFs will be present in water mainly in the particulate-sorbed phase. Significant loss of CDFs in water, either due to chemical reactions including photochemical reactions or biodegradation processes, has not been observed. CDFs in water partition into the particulate phase and settle into the sediment. Sediment is the ultimate sink of atmospheric and aquatic CDFs. CDFs bioconcentrate in aquatic organisms. CDFs are very persistent in soils. They also strongly adsorb to soil; consequently, very little vertical movement of these compounds has been observed in soil (e.g., leaching to groundwater).

The concentrations of CDFs in air usually increase in the following order: rural < suburban < urban < industrial/auto tunnel. The concentrations of total tetra-, penta-, hexa-, hepta-, and octaCDF in ambient urban/suburban air were 0.13–7.34, 0.09–5.10, <0.09–12.55, 0.08–12.71, and 0.13–3.78 pg/m^3, respectively. CDFs were detected in 1 of 20 water supplies in New York State. The only congener groups detected in this water were tetra-CDF at a concentration 2.6 ppq (pg/L) and octaCDF at a concentration of 0.8 ppq. The levels of CDFs in contaminated water, such as effluents from a kraft pulp mill, can be 3 orders of magnitude higher than the levels in drinking water. The levels of CDF in various foods consumed in Germany, Japan, Canada, and the United States are also available, and the level in individual food products is on the order of pg/kg.

The general population is exposed to CDFs by inhaling air, ingesting food, soil, and water, and from consumer products (e.g., paper towels, tampons). The estimated total intake of CDDs/CDFs from all of these sources in a Canadian background population is 2.4 pg toxic equivalent to 2,3,7,8-TCDD/kg body weight/day. The intake from food constitutes ≈96% of the total toxic intake. Fish and fish products, milk and milk products, and meat and meat products each constitute ≈30% of CDF food intake in Germany. Because of this CDF body burden in background populations and the tendency of CDFs to bioconcentrate in fat, the levels of CDFs in adipose tissue, human milk, and the lipid portion of blood in both background and exposed populations have been determined.

Workers in sawmills, in the textile industry, in the leather industry, in the pulp and paper industries, in certain chemical manufacturing, and in PCB user industries (repairing transformers or capacitors, using casting waxes containing PCBs) may be exposed to a higher level of CDFs than the background population. Among the general population, groups who consume high amounts of fatty fish, people who are exposed to accidental fires involving PCBs, and nursing babies are potentially exposed to higher levels of CDFs. People living near incinerators or incinerator ash dump sites may be exposed to elevated levels of CDFs. The levels will depend on the nature of the waste being incinerated. People who live adjacent to uncontrolled landfill sites containing high concentration of CDFs or landfill fires may also be exposed to higher concentrations of CDFs. Diverse studies indicate that the levels of CDFs in the adipose tissue of exposed populations are higher than those in unexposed or background populations.

5.2 PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

5.2.1 Production

Table 5-1 lists the facilities in each state that unintentionally produce, store, dispose of, or process dioxin-like substances, including CDFs, and the range of maximum amounts that are stored onsite. This is a special category in the Toxics Release Inventory (TRI) and includes 17 CDFs and chlorinated dioxins. The data from the TRI listed in Table 5-1 should be used with caution, however, since only certain types of facilities were required to report (EPA 2005). This is not an exhaustive list.

Table 5-1. Facilities that Produce, Process, or Use Dioxin and Dioxin-like Compounds

State[a]	Number of facilities	Minimum amount on site in pounds[b]	Maximum amount on site in pounds[b]	Activities and uses[c]
AK	5	0	1	1, 5
AL	45	0	99,999	1, 5, 8, 12, 13, 14
AR	20	0	99,999	1, 5, 12, 13, 14
AZ	13	0	99	1, 5, 6, 13
CA	27	0	99	1, 2, 5, 11, 12, 13, 14
CO	13	0	10	1, 4, 5, 13
CT	1	0	0.10	1, 5
DE	1	0.10	1	1, 13, 14
FL	21	0	10	1, 5, 12, 13, 14
GA	30	0	99,999	1, 2, 5, 12, 13, 14
GU	1	0.10	1	1, 5
HI	4	0	0.10	1, 5
IA	18	0	9,999	1, 5, 13, 14

Table 5-1. Facilities that Produce, Process, or Use Dioxin and Dioxin-like Compounds

State[a]	Number of facilities	Minimum amount on site in pounds[b]	Maximum amount on site in pounds[b]	Activities and uses[c]
ID	3	0	9,999	1, 5, 12, 14
IL	19	0	99	1, 5, 12, 13, 14
IN	28	0	99	1, 5, 12, 13
KS	7	0	1	1, 5, 12
KY	29	0	9,999	1, 5, 13, 14
LA	46	0	99,999	1, 5, 10, 12, 13, 14
MD	5	0	10	1, 5, 14
ME	3	0	1	1, 5, 9
MI	18	0	9,999	1, 2, 5, 12, 13, 14
MN	19	0	999,999	1, 5, 12, 13, 14
MO	25	0	10	1, 2, 5, 12, 13, 14
MS	19	0	99,999	1, 5, 8, 13, 14
MT	5	0	10	1, 5
NC	23	0	99,999	1, 5, 8, 12, 13, 14
ND	12	0	1	1, 5, 12, 13
NE	12	0	99,999	1, 5, 13, 14
NJ	6	0	10	1, 5, 13, 14
NM	3	0	0.10	1, 5, 13
NV	5	0	999,999	1, 5, 13, 14
NY	15	0	9,999	1, 5, 12, 13, 14
OH	31	0	999	1, 3, 5, 13, 14
OK	13	0	99	1, 4, 5, 13, 14
OR	11	0	999,999	1, 5, 14
PA	26	0	10	1, 2, 5, 12, 13, 14
PR	1	0	0.10	1, 5
SC	24	0	10	1, 5, 12, 13, 14
SD	3	0	99	1, 5
TN	24	0	99	1, 5, 8, 12, 13, 14
TX	66	0	9,999	1, 2, 3, 4, 5, 7, 12, 13, 14
UT	17	0	99,999	1, 3, 4, 5, 9, 12, 13, 14
VA	13	0	10	1, 5, 7, 13, 14
VI	2	0	0.10	1, 5
WA	22	0	99,999	1, 2, 5, 6, 13, 14

Table 5-1. Facilities that Produce, Process, or Use Dioxin and Dioxin-like Compounds

State[a]	Number of facilities	Minimum amount on site in pounds[b]	Maximum amount on site in pounds[b]	Activities and uses[c]
WI	26	0	99,999	1, 2, 5, 12, 13, 14
WV	15	0	99	1, 5, 12, 13

[a] Post office state abbreviations used.
[b] Amounts on site reported by facilities in each state.
[c] Activities/uses:

1. Produce
2. Import
3. Used Processing
4. Sale/Distribution
5. Byproduct
6. Reactant
7. Formulation Component
8. Article Component
9. Repackaging
10. Chemical Processing Aid
11. Manufacture Aid
12. Ancillary
13. Manufacture Impurity
14. Process Impurity

Source: TRI21 2022 (Data are from 2021)

CDFs are not manufactured commercially in the United States or any other country except on a laboratory scale for use in chemical laboratories or for toxicological studies. These compounds are produced as undesired by-products during the manufacture of PCBs, polychlorinated phenols, and herbicides. They are also formed during the pyrolysis of PCBs, polychlorinated diphenyl ethers, polychlorinated phenols, polychlorinated benzenes, and phenoxy herbicides. Municipal and industrial incinerators also produce CDFs. These compounds can also be produced from the photolysis of PCBs, polychlorinated diphenyl ethers, and polychlorinated benzenes (van den Berg et al. 1985). Chlorine bleaching at paper and pulp mills can also result in CDF formation (Campin et al. 1991; Näf et al. 1992).

Several methods are available for the synthesis of CDFs; all yield mixtures of isomers (EPA 1985; Gara et al. 1981). Two methods that have been used to synthesize a number of structure-specific CDFs are cyclization of diazotized chlorophenoxy-o-aniline and cyclization of chlorinated diphenylethers, promoted by palladium(I1) acetate (Gara et al. 1981; Gray et al. 1976; Humppi 1986; Kuroki et al. 1984; Norstrom et al. 1979). In the first process, chlorophenates and chloronitrobenzene react to form nitrochlorodiphenyl ethers. The latter compounds are reduced to aminochlorodiphenyl ethers, diazotized, and cyclized with isoamyl nitrite to form the CDFs. In the second method, chlorinated diphenyl ethers are produced by refluxing chlorinated diphenyl iodonium salt with chlorophenolate. The chlorinated diphenyl ethers are cyclized with palladium acetate in the presence of acetic acid and methane sulfonic acid (Kuroki et al. 1984).

Another method that has been used to synthesize 22 high purity CDF isomers is the cyclization of o-hydroxyl PCBs by refluxing with dimethyl sulfoxide and potassium hydroxide (Safe and Safe 1984). The o-hydroxyl PCBs are produced either by a diazo coupling of chlorinated anisidines and symmetrical chlorinated benzenes or by diazo coupling of chlorinated anilines with chlorinated anisoles.

The pyrolysis of PCBs, commercial chlorobenzenes, and chlorinated diphenyl ethers yields CDF mixtures. Although the pyrolysis method produces mixtures of isomeric CDFs, it has been used frequently to prepare qualitative CDF standards, because it is fast and safe (Buser 1979; EPA 1985; Groce et al. 1989). Similarly, qualitative standard mixtures of CDFs have also been produced by the ultraviolet and gamma irradiation of octaCDF (Buser 1976).

5.2.2 Import/Export

Because there is no commercial use of CDFs, there are no import or export volumes of these substances in the United States.

5.2.3 Use

There is no commercial use of CDFs other than small amounts used in toxicology, chemical, and biochemical laboratories.

5.2.4 Disposal

Several methods for disposing CDFs have been proposed; some of these have been put into field use to decontaminate wastes containing CDFs. The most commonly used methods for disposal or decontamination of CDF-containing wastes are photolysis, incineration, chemical destruction, microbial degradation, and landfilling. Each of these methods has limitations, but some may be preferable to others. The common methods for CDF waste disposal/decontamination are discussed below.

In the photolytic process, CDDs/CDFs are destroyed by dechlorination of the compounds by ultraviolet light most efficiently in the presence of hydrogen donors. The most commonly used hydrogen donor is isopropyl alcohol (des Rosiers 1983). TCDD-contaminated soil was decontaminated by ultraviolet treatment of the soil in the presence of olive oil emulsion as a hydrogen donor. A total reduction in excess of 60% was observed after 48 hours of irradiation. The decontamination efficiency of CDFs by ultraviolet radiation was reported to be 90% after 48 hours irradiation of the walls and ceiling of a building contaminated during a PCB fire (Borwitzky and Schramm 1991). When CDFs were extracted from a contaminated soil in hexane and irradiated with ultraviolet light in the presence of a hydrogen donating solvent (propanol), the decontamination efficiency reached 99.9% in 4 hours (Drechsler 1986). The destruction efficiencies of CDFs by liquid phase photolysis are faster than CDDs (Muto and Takizawa 1991). The advantage of photolytic destruction is that it poses only a small risk to workers. The notable disadvantages of the photolysis process are that it is time consuming (when a large area is involved or solvent extraction is performed) and may not be universally applicable to other contaminants (Borwitzky and Schramm 1991).

Incineration is a preferred method for disposing of CDF-containing wastes. In this process, the waste is burned in a stationary or rotary kiln incinerator at temperatures between 900 and 1,000°C and a minimum residence time of 1.8 seconds; however, the destruction of particle bound CDFs may require higher temperatures and longer retention times. Higher temperatures can be attained by adding a secondary combustion chamber to a rotary kiln incinerator. Land-based and at-sea incineration facilities are available. Investigators have postulated the following combustion criteria for land-based incineration of CDF wastes: a 2-second dwell time at 1,200°C or 15-second dwell time at 1,600°C, a combustion efficiency in excess of 99.99%, and a scrubber system to control flue gas emission (Almemark et al. 1991; des Rosiers 1983). EPA considers CDFs as Principal Organic Hazardous Constituents (POHCs) and requires them to be incinerated, in order to achieve a destruction and removal efficiency of 99.99% (EPA 1990a).

Some of the chemical methods available for the destruction of CDFs include alkaline dehydrochlorination; reduction with hydrogen in the presence of a palladium or platinum catalyst at 100°C; catalytic oxidation with ruthenium tetroxide, chlorolysis in the presence of chlorine gas at 600°C and a pressure of 170 atm; or micellar catalysis with either benzalkonium dichloroiodide or cetylpyridinium dichloroiodide. Disadvantages of these methods are generation of unwanted byproducts requiring high temperatures or pressures and, in some cases, cost. The preferable chemical method is dehydrochlorination in a mixture of alkaline polyethylene glycol and inorganic peroxide at a temperature <100°C (des Rosiers 1983; Drechsler 1986; Hagenmaier et al. 1987; Tiernan et al. 1989). A chemical method employing precipitation by the addition of alum or lime at a concentration of 9,000 mg/L removed >98% of CDDs/CDFs from bleach plant filtrates and combined treated mill effluents from pulp and paper industries (Barton et al. 1990). However, the sludge from this process contains the CDDs/CDFs and requires proper disposal. The destruction of CDFs in aqueous solution at a pH of 10 and temperature of 50°C by ozone was reported to be >90% in 4 hours (Palauschek and Scholz 1987).

Decontamination of CDF-containing wastes by a biodegradation method has also been attempted. *Phanerochuete chrysosporium*, a white rot fungus, which degraded TCDD in laboratory experiments (des Rosiers 1986), may be suitable for biodegrading CDFs. However, no successful biotreatment method exists that can satisfactorily decontaminate CDF wastes.

In the past, land disposal of waste materials contaminated with CDDs and CDFs was considered an option under strict technical conditions. Some of these conditions included use of soil with low water permeability, use of synthetic membrane liners to cover the soil, compatibility with the hydrogeology of the site, maintenance of a leachate monitoring program, and acquisition of waivers from the appropriate EPA or state agency (des Rosiers 1983). However, land disposal of certain CDF wastes is presently prohibited. The Toxic Substances Control Act (TSCA) regulates the use, disposal, and distribution in commerce of process waste-water treatment sludges intended for land application that are derived from pulp and paper industries employing chlorination processes (EPA 1991).

5.3 RELEASES TO THE ENVIRONMENT

The Toxics Release Inventory (TRI) data should be used with caution because only certain types of facilities are required to report (EPA 2005). This is not an exhaustive list. Manufacturing and processing facilities are required to report information to the TRI only if they employ ≥10 full-time employees; if their facility is included in Standard Industrial Classification (SIC) Codes 10 (except 1011, 1081, and 1094), 12 (except 1241), 20–39, 4911 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4931 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4939 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4953 (limited to facilities regulated under RCRA Subtitle C, 42 U.S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited to facilities primarily engaged in solvents recovery services on a contract or fee basis); and if their facility produces, imports, or processes ≥25,000 pounds of any TRI chemical or otherwise uses >10,000 pounds of a TRI chemical in a calendar year (EPA 2005).

Table 5-2 contains releases to the environment of the dioxin category of compounds of the TRI.

Table 5-2. Releases to the Environment from Facilities that Produce, Process, or Use Dioxin and Dioxin-like Compounds[a]

		Reported amounts released in grams per year[b]							
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
AL	45	22	110	0	5,186	0	5,280	38	5,319
AK	5	2	0	0	0	0	2	0	2
AZ	13	24	0	0	55	0	24	55	79
AR	20	15	14	0	22	2	47	6	53
CA	27	4	4	0	70	0	26	52	78
CO	13	14	0	0	0	0	14	0	14
CT	1	0	0	0	0	0	0	0	0
DE	1	0	0	0	0	0	0	0	0
FL	21	12	5	0	9	0	24	3	27
GA	30	17	24	0	20	0	61	1	61
HI	4	0	0	0	1	0	0	1	1
ID	3	26	0	0	1,920	0	1,947	0	1,947
IL	19	11	0	0	11	0	11	11	22
IN	28	43	0	0	344	0	124	263	387
IA	18	20	0	0	41	0	20	41	61
KS	7	5	0	0	0	0	5	0	5
KY	29	61	90	0	14,605	3	170	14,589	14,758
LA	46	41	74	0	331	215	256	404	661
ME	3	3	0	0	2	0	3	2	5
MD	5	2	0	0	0	0	2	0	2
MI	16	15	3	0	819	0	730	107	838
MN	19	80	1	0	81	0	81	81	162
MS	19	11	20	0	1,368	0	1,399	0	1,399
MO	25	25	0	0	0	0	25	0	25
MT	5	7	0	0	2	0	7	2	8
NE	12	4	1	0	0	0	5	0	5
NV	5	3	0	0	2	0	3	2	5
NJ	6	1	0	0	25	0	1	25	27
NM	3	3	0	0	0	0	3	0	3
NY	15	8	1	0	3	10	10	12	22
NC	23	85	8	0	8	0	100	0	101
ND	11	14	0	0	0	0	14	0	14
OH	31	26	1	0	755	0	752	31	782
OK	13	6	0	0	50	0	14	42	56
OR	11	2	0	0	7	0	4	5	9

Table 5-2. Releases to the Environment from Facilities that Produce, Process, or Use Dioxin and Dioxin-like Compounds[a]

	Reported amounts released in grams per year[b]								
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
PA	26	12	0	0	0	0	12	0	12
SC	24	12	5	0	0	0	17	0	17
SD	3	11	0	0	0	0	11	0	11
TN	24	27	5	0	1,986	0	1,994	23	2,017
TX	65	281	917	209	36,247	0	8,310	29,345	37,655
UT	17	33	0	0	7,508	0	7,537	4	7,541
VA	13	6	2	0	16	0	10	14	24
WA	22	8	7	0	103	0	15	103	118
WV	15	13	3	0	30	0	16	30	46
WI	25	30	0	0	464	0	30	464	494
WY	9	17	0	0	0	0	17	0	17
GU	1	1	0	0	0	0	1	0	1
PR	1	2	0	0	0	0	2	0	2
VI	2	0	0	0	0	0	0	0	0
Total	799	1,067	1,295	209	72,093	230	29,137	45,758	74,895

[a] The TRI data should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list. Data are rounded to nearest whole number.

[b] Data in TRI are maximum amounts released by each facility; due to TRI reporting guidelines, amounts released for dioxin and dioxin-like compounds are reported in grams.

[c] Post office state abbreviations are used.

[d] Number of reporting facilities.

[e] The sum of fugitive and point source releases are included in releases to air by a given facility.

[f] Surface water discharges, wastewater treatment (metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).

[g] Class I wells, Class II-V wells, and underground injection.

[h] Resource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.

[i] Storage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown.

[j] The sum of all releases of the chemical to air, land, water, and underground injection wells.

[k] Total amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection

Source: TRI21 2022 (Data are from 2021)

CDFs in the environment are primarily of anthropogenic origin (Czuczwa and Hites 1986a, 1986b). Trace amounts of CDFs may come from sources, such as forest fires, which may not be anthropogenic in origin (Bumb et al. 1980). The levels of CDDs and CDFs in archived soil samples collected from the same semi-rural area in southeast England between 1846 and 1986 were found to increase around the turn of the century (A.D. 1900) as anthropogenic sources became more important than natural emissions (Kjeller et al. 1991; Rappe 1991). Higher levels of CDFs are found in human tissue (Ligon et al. 1989; Rappe 1991) and river silt (Schecter 1991) samples collected from industrial countries than those from less industrial countries or from ancient civilization. These results suggest that most CDFs found at present are of anthropogenic origin.

The primary sources of environmental release of CDFs can be divided into the following five categories: thermal reactions, chemical reactions, photochemical reactions, enzymatic reactions, and hazardous waste sites.

Thermal Reactions

Combustion Processes. The combustion processes can be divided into two categories: large systems and small systems. Municipal waste incineration (Bonfanti et al. 1990; Brna and Kilgroe 1990; des Rosiers 1987; Hutzinger and Fiedler 1989; Siebert et al. 1987; Tiernan et al. 1985; Tong and Karasek 1986), incineration of industrial and hazardous wastes (des Rosiers 1987; Muto et al. 1991), and power plants with fossil fuels (des Rosiers 1987; Hutzinger and Fiedler 1989) are examples of large systems. Small combustion systems include home heating and fireplaces (Clement et al. 1985; Safe 1990b), household waste incineration (Harrad et al. 1991a), automobile exhaust (Ballschmiter et al. 1986; Marklund et al. 1987), and medical waste incineration (des Rosiers 1987; Glasser et al. 1991; Lindner et al. 1990). Incineration of industrial and hazardous wastes that produce CDFs include wastes containing PCBs (Choudhry and Hutzinger 1982; Hutzinger and Fiedler 1989; Sedman and Esparza 1991), polychlorinated diphenyl ethers (Choudhry and Hutzinger 1982), 2,4,5-trichlorophenol esters (Choudhry and Hutzinger 1982), chlorinated benzenes (Choudhry and Hutzinger 1982; Öberg and Bergstrom 1987), chlorophenols (Narang et al. 1991; Oberg and Bergstrom 1987), waste oil (Taucher et al. 1992), biosludge from paper and pulp mills (des Rosiers 1987; Mantykoski et al. 1989; Someshwar et al. 1990), polyvinyl chloride (Christmann et al. 1989a), municipal sewage sludge (Clement et al. 1987a; des Rosiers 1987), chlorinated fluorenones, and 9,10-anthraquinones (Boenke and Ballschmiter 1989). The typical concentrations of total tetraCDFs, pentaCDFs, hexaCDFs, heptaCDFs, and octaCDF in municipal waste incineration fly ash are 79.5, 120.3, 116.3, 108.2, and 42.9 ppb, respectively (Safe 1990b). The corresponding CDF concentrations are 28.9, 16.6, 6.2, 1.8, and 0.3 ppb, respectively, in soot from home heating oil and 50.8, 30.0, 11.7, 3.2, and 0.5 ppb, respectively, in soot from coal/wood burning for home heating. The concentrations of 2,3,7,8-tetraCDF congener in municipal fly ash, soot from heating oil, and soot from coal/wood burning are 2.5, 1.1, and 1.9 ppb, respectively. The combined bottom and fly ash from five state-of-the-art mass-burn municipal waste combustors, with a variety of pollution control equipment, were analyzed for CDFs. The concentrations of CDFs (ppt) in ash samples were determined to be: 2,3,7,8-tetraCDF, 176–626; 1,2,3,7,8-pentaCDF, 52–194; 2,3,4,7,8-pentaCDF, 43–171; 1,2,3,4,7,8-hexaCDF, 74–654; 1,2,3,6,7,8-hexaCDF, 131–660; 1,2,3,7,8,9-hexaCDF, 36–479; 2,3,4,6,7,8-hexaCDF, 5–124; 1,2,3,4,6,7,8-heptaCDF, 139–1,842; and 1,2,3,4,7,8,9-heptaCDF, 8–119 (EPA 1990b).

Three mechanisms have been postulated for the formation of CDFs in combustion processes: (1) CDFs are already present in trace amounts within the fuel and are not destroyed during combustion; (2) CDFs are formed during combustion from precursors (e.g., PCBs, polychlorophenols), which are present in the fuel; and (3) *de novo* synthesis from nonchlorinated organic substance and chlorine-containing molecules (Hutzinger and Fiedler 1989). Details about the mechanisms of CDF formation in combustion processes are available (Choudhry and Hutzinger 1982; Hutzinger and Fiedler 1989; Jay and Stieglitz 1991; Stieglitz et al. 1989). Other investigators have studied the control technologies available for the reduction of CDF emissions from municipal waste combustors (Brna and Kilgroe 1990; Jordan 1987; Takeshita and Akimoto 1989). A significant reduction of CDF-concentrations in the flue gas from municipal and industrial waste incinerators and fossil fuel-fired power stations can be achieved by either the addition of a mixture of anhydrous calcium hydrate and coke to the flue gas or by treating the flue gas with titanium dioxide catalyst in the presence of ammonia (Hagenmaier et al. 1991). For three hazardous waste incinerators operating in China, it was determined that concentrations of CDDs and CDFs were highest during the start-up/ignition process, and were up to 5.4 times greater than levels measured during the normal operating period (Cao et al. 2018).

Accidental Fires or Malfunction of PCB-filled Transformers and Capacitors. Some of the major fires/malfunctions involving PCB transformers and capacitors in the United States include a transformer fire inside the state office building in Binghamton, New York, in 1981; a transformer fire inside an office building in Boston, Massachusetts, in 1982; a transformer fire adjacent to a high-rise building in San Francisco, California, in 1983; a transformer fire inside an office building in Chicago, Illinois, in 1983; and a capacitor fire inside an office building in Columbus, Ohio, in 1984 (des Rosiers and Lee 1986; Hryhorczuk et al. 1986; Stephens 1986; Tiernan et al. 1985). CDFs were detected in air, soot, or wipe samples from all of these fire incidents. However, it was determined that in the absence of fire, CDF levels do not appear to increase in PCB fluids in electrical equipment from normal usage (des Rosiers and Lee 1986). The concentrations of total tetraCDFs, pentaCDFs, hexaCDFs, heptaCDFs, and octaCDF in air samples from different locations of a building following a transformer fire in San Francisco ranged from not detected to 53.9, not detected to 11.0, not detected to 1.3, not detected to 3.7, and not detected to 165.0 pg/m^3, respectively (Stephens 1986). A maximum concentration of 2,3,7,8-tetraCDF inside the building air was 18.5 pg/m^3 (Stephens 1986). The concentration range of 2,3,7,8-tetraCDF in soot samples from other transformer/capacitor fires in the United States was 3–1,000 μg/g (des Rosiers and Lee 1986). The mechanism by which many CDFs form in the production of PCBs has been investigated (Erickson 1989; Hutzinger et al. 1985a). A study examining the impact of landfill fires reported elevated levels of total furans in air samples collected while the fire was burning and while it was being extinguished (Weichenthal et al. 2015).

Certain Industrial Processes. Certain high-temperature industrial processes like copper smelting, electrical arc furnaces in steel mills, and production of metallic magnesium and refined nickel emit CDFs into the atmosphere and process wastewaters containing CDFs at concentrations higher than those found in emissions from municipal incineration and automobile exhausts (Oehme et al. 1989; Rappe 1987). It has been theorized that contamination/coating with polyvinyl chloride or polychlorinated paraffins are the precursors for the formation of CDFs in copper smelting and steel production from scrap metals (Rappe 1987). It has been speculated, in the case of magnesium and nickel production, that heavy metals in the presence of chlorine catalyze the formation of CDFs. But the precursors of CDFs have not been identified (Oehme et al. 1989). Solá-Gutiérrez et al. (2019) found that CDFs were formed during the electrochemical oxidation of the antibacterial and antifungal agent triclosan.

Cigarette Smoke. Both mainstream and side-stream cigarette smoke contain CDFs. The smoke contained 2,3,7,8-substituted congeners of CDFs, and the concentrations of total CDFs in mainstream and side-stream smoke of one common commercial brand of Swedish cigarettes were 720 and 1,670 pg per 20 cigarettes, respectively (Lofroth and Zebuhr 1992).

Chemical Reactions

Certain Chemical Products. CDFs occur as contaminants in a number of chemical products, such as chlorinated phenols, formerly produced PCBs, phenoxy herbicides, chlorodiphenyl ether herbicides, hexachlorobenzene, tetrachlorobenzoquinones, and certain dyes. These chemical products containing CDFs may be released into the environment during their manufacture, use, or disposal.

The level of CDFs in commercial chlorinated phenols from different countries are given in Table 5-3. The difference in the levels of isomeric congeners is due to different degrees of chlorination and different methods of synthesis. The major CDF isomers identified were 1,2,4,6,8-penta-, 1,2,3,4,6,8-hexa-, 1,2,4,6,7,8-hexa-, 1,2,4,6,8,9-hexa-, 1,2,3,4,6,7,8-hepta-, and 1,2,3,4,6,8,9-heptaCDF (Rappe and Buser 1981). Commercial pentachlorophenol and sodium pentachlorophenate, used extensively for the preservation of wood, contain trace amounts of CDFs (Hagenmaier and Brunner 1987). These substances have the potential to migrate away or volatilize from wood surfaces and contaminate indoor air. The concentrations of CDFs in indoor ambient air of a kindergarten building in West Germany using pentachlorophenol (PCP)-treated wood were as follows: non-2,3,7,8-tetraCDF, 0.27 pg/m^3; 1,2,3,7,8-pentaCDF, 0.1 pg/m^3; non-2,3,7,8-pentaCDFs, 3.51 pg/m^3; 1,2,3,4,7,8-hexaCDF, 0.37 pg/m^3; 1,2,3,6,7,8-hexaCDF, 0.60 pg/m^3; 1,2,3,7,8,9-hexaCDF, 0.16 pg/m^3; non-2,3,7,8-hexaCDFs, 12.3 pg/m^3; 1.2,3,4,6,7,8-heptaCDF, 10.7 pg/m^3; 1,2,3,4,7,8,9-heptaCDF, 0.38 pg/m^3; non-2,3,7,8-heptaCDFs, 12.2 pg/m^3; and octaCDF, 6.0 pg/m^3 (Mukerjee et al. 1989). Therefore, use of certain commercial products can be a source of CDFs in air. From the analysis of air particulates and sediment, it was concluded that the likely source of CDFs in a western Lake Ontario site was a pentachlorophenol production facility (Czuczwa and Hites 1986b).

Table 5-3. Levels of Chlorodibenzofurans (CDFs) in Commercial Chlorinated Phenols (µg/g)

	CDFs						
	Tetra	Penta	Hexa	Hepta	Octa	∑CDFs	∑CDDs
2,4,6-Trichlorophenol, Sweden	1.5	17.5	36	4.8	–	60	<3
2,4,6-Trichlorophenol, United States	1.4	2.3	0.7	<0.02	–	4.6	0.3
2,3,4,6-Tetrachlorophenol, Finland	0.5	10	70	70	10	160	12
Pentachlorophenol, United States	0.9	4	32	120	130	280	1,000
Pentachlorophenol, United States	–	–	30	80	80	190	2,6
Pentachlorophenol, United States	≤0.4	40	90	400	260	790	1,900
Pentachlorophenol, Germany	–	–	0.03	0.8	1.3	2.1	6.8

CDDs = chlorinated dibenzo-*p*-dioxins

Source: Rappe and Buser 1981

The manufacture of PCBs stopped in the United States in the late 1970s; however, they are still widespread in the environment and exposure to CDFs continues through past PCB manufacture and use. In Bowes et al. (1975a), commercial Aroclors (i.e., commercial PCB mixtures, Clophen A-60, and Phenoclor DP-6) were analyzed for CDF concentrations (see Table 5-4). In a preceding study, Bowes et al. (1975b) determined the concentrations of 2,3,7,8-tetraCDF and 2,3,4,7,8-pentaCDF in two Aroclors and two Japanese Kanechlors. Concentrations of CDFs in a number of commercial PCB samples are provided in Table 5-4. The CDF isomers identified in commercial PCBs are 2,3,7,8-tetraCDF, 2,3,6,7-tetraCDF, 2,3,6,8-tetraCDF, 2,3,4,7,8-pentaCDF, 1,2,3,7,8-pentaCDF, 1,2,4,7,8-pentaCDF, 1,2,3,4,7,8-hexaCDF, 1,2,4,6,7,8-tetraCDF, 1,2,4,6,8,9-hexaCDF, 1,2,3,4,5,7,8-heptaCDF, and 1,2,3,4,6,8,9-heptaCDF (Rappe and Buser 1981).

Table 5-4. Levels of Chlorodibenzofurans (CDFs) in Commercial Polychlorinated Biphenyls (PCBs) (µg/g)

Sample	Tri	Tetra	Penta	Hexa	Hepta	Total
Aroclor 1248, 1969[a]	–	0.5	1.2	0.3	–	2.0
Aroclor 1254, 1969[a]	–	0.1	0.2	1.4	–	1.7
Aroclor 1254, 1970[a]	–	0.2	0.4	0.9	–	1.5
Aroclor 1254[b]	0.10	0.25	0.7	0.81	–	1/9
Aroclor 1254 (lot KK 602)[b]	–	0.05	0.1	0.02	–	0.2
Aroclor 1260, 1969[a]	–	0.1	0.4	0.5	–	1.0
Aroclor 1260 (lot AK 3)[a]	–	0.2	0.3	0.3	–	0.8
Aroclor 1260[b]	0.06	0.3	1.0	1.1	1.35	3.8
Aroclor 1016, 1972[a]	–	<0.001	<0.001	<0.001		–
Clophen A 60[a]	–	1.4	5.0	2.2	–	8.4
Clophen A 60[a]	0.10	0.3	1.73	2.45	0.82	5.4
Phenoclor DP-6[a]	–	0.7	10.0	2.9	–	13.6

[a]Bowes et al. 1975a.
[b]Rappe and Buser 1981.

Phenoxy herbicides generally contain higher concentrations of CDDs than CDFs. Therefore, more effort has been spent to determine the levels of CDDs rather than CDFs in study samples. According to an EPA (1985) report, two samples of European 2,4,5-trichlorophenoxyacetic acid contained no 2,3,7,8-tetraCDF. Compost from municipal yard waste was also found to contain CDFs, possibly due to the presence of a PCP-based biocide (Harrad et al. 1991b).

CDFs have been detected as contaminants in commercial samples of diphenyl ether herbicides. Concentrations of tetraCDFs, pentaCDFs, and hexaCDFs in these samples were as high as 0.4, 1.0, and 0.2 ppb, respectively (Yamagishi et al. 1981). Three early commercial hexachlorobenzene preparations were analyzed for CDFs. One sample contained a heptaCDF; all three samples contained octaCDF at concentrations ranging from 0.35 to 58.3 ppm (Villanueva et al. 1974).

Samples of eight commercially available tetrachlorobenzoquinones (chloranils) from four different producers were analyzed for CDFs. OctaCDF was found in seven of eight samples at a maximum concentration of 6.02 ppm, while 1,2,3,4,6,7,8-heptaCDF was found in four of eight samples at a maximum concentration of 27 ppb. 1,2,3,4,7,8-HexaCDFs, pentaCDFs, and tetraCDFs were also found in some of the samples (Christmann et al. 1989b).

CDFs are also formed during the bleaching process for the manufacture of pulp and paper (Kitunen and Salkinoja-Salonen 1989; Näf et al. 1992). Low levels (ppt) of 2,3,7,8-substituted congeners of tetra-, penta-, hexa-, and heptaCDF have been identified in the pulp, finished paper boards, effluents, and sludges from paper mills and 2,3,7,8-TCDF has been found in fish downstream of plant effluent.

The chloralkali process utilizing graphite electrodes used for the production of chlorine produces CDFs. Total CDF levels as high as 650 ng/g (ppb) of sludge have been detected in sludge samples from graphite electrodes of a chloralkali plant (Rappe et al. 1991a). The levels of tetra-, penta-, and hexaCDFs in the sludge were found to be approximately the same.

A number of commercial dyes were analyzed for CDFs. These samples contained tetra-, penta-, hexa-, hepta-, and octaCDFs at the ppb level (Heindl and Hutzinger 1989; Remmers et al. 1992; Williams et al. 1992).

Photochemical Reactions

Certain Photochemical Processes Involving Commercial Products. 1,3,7,9-TetraCDF was formed from the photolysis of 2,2',4,4',6,6'-hexachlorobiphenyl in hexane-methanol solution (Safe et al. 1977). The rate of photolysis was markedly higher in oxygen-degassed solutions than in oxygen-saturated solutions, indicating a triplet state as a possible intermediate for the photolysis process (Safe et al. 1977). Photolysis of chlorinated diphenyl ethers at around 300 nm in a degassed methanol solution also produced mono-, di-, tri-, and tetraCDFs (Choudhry et al. 1977). Photodegradation of polychlorobenzenes can also be a source of CDFs (EPA 1985). In addition, dechlorination of higher CDFs can be a source of lower chlorinated CDFs. The relevance of laboratory photolysis to environmental sources of CDFs is unknown.

Enzymatic Reactions. CDFs are formed by enzyme-catalyzed oxidations of 2,4-dichlorophenol, 2,4,5-chlorophenol, 2,3,4,6-tetrachlorophenol, 2,3,5,6-tetrachlorophenol, and PCP (Oberg and Rappe 1992; Svenson et al. 1989a, 1989b). The implication of these investigations is that CDFs may be biogenically formed from wastes containing these chlorophenols, but the significance of the process in contributing to the release of CDFs in the environment has not been assessed.

Hazardous Waste Sites. The improper disposal of CDF-containing wastes in landfill sites will primarily contaminate soils, but the air may also be contaminated by windblown dusts.

5.3.1 Air

Estimated releases of 1,067 g (~2.35 pounds [<1 metric ton]) of dioxin compounds including CDFs to the atmosphere from 799 domestic manufacturing and processing facilities in 2021 accounted for about <1% of the estimated total environmental releases from facilities required to report to the TRI (TRI21 2022). These releases are summarized in Table 5-2.

CDFs are released to air from combustion processes, accidental fires or malfunction of PCB-filled transformers and capacitors, improper disposal of chlorinated chemical wastes, certain chemical products, certain industrial processes, and certain photochemical processes involving commercial products.

5.3.2 Water

Estimated releases of 1,295 g (~2.85 pounds [<1 metric ton]) of dioxin compounds including CDFs to surface water from 799 domestic manufacturing and processing facilities in 2021, accounted for about <1% of the estimated total environmental releases from facilities required to report to the TRI (TRI21 2022). This estimate includes releases to wastewater treatment and publicly owned treatment works (POTWs). These releases are summarized in Table 5-2.

CDFs enter water as a result of deposition after these compounds have been emitted to the atmosphere from combustion sources. The concentrations and congener patterns of CDFs found in the sediment of three lakes and in the atmosphere led the authors to conclude that atmospheric deposition is the primary source of these compounds in lakes (Czuczwa and Hites 1986a).

CDFs will enter surface water as a result of the discharge of CDF contaminated wastewater, which is generated during the manufacture of chemicals containing CDFs contaminants. 2,3,7,8-TetraCDF has been detected at concentrations ≤4.5 ppb in sediment from estuaries adjacent to an industrial site in which chlorinated phenols were produced (Bopp et al. 1991). The typical wastewaters from magnesium and refined nickel production are also examples of such CDF contamination (Oehme et al. 1989). Chemical manufacturing waste contaminated with CDFs that has been improperly disposed of can leach from landfills into groundwater. CDF contaminated soil sites have been found in Butte, Montana, and Kent, Washington (Tiernan et al. 1989). Uncontrolled landfills can be sources of CDFs for adjacent surface waters (Clement et al. 1989a).

Historically, an important source of CDFs in surface water is the discharge of effluents from pulp and paper mills that use the bleached kraft process. The concentrations of 2,3,7,8-tetraCDF in the treated effluents from five bleached kraft pulp and paper mills in the United States ranged from not detected (0.007 ppt) to 2.2 ppt with a mean value of 0.54 ppt, but the wastewater sludges contained 2,3,7,8-tetraCDF at a mean concentration of 0.37 ppb (Amendola et al. 1989). The effluent from a kraft pulp mill from Jackfish Bay, Lake Superior, contained tetraCDFs in concentrations ranging from 0.3 to 1.3 ng/L (9.3–1.3 ppt) (Sherman et al. 1990). Due to guidelines under the Clean Water Act, this is no longer a source of CDF releases in the United States.

Chlorination of water has been shown to be a source of trace amounts (ppq level [i.e., pg/L level]) of CDFs. Apparently, impurities in the water may form CDFs during chlorination.

5.3.3 Soil

Estimated releases of 72,093 g (~159 pounds [<1 metric ton]) of dioxin compounds including CDFs to soil from 799 domestic manufacturing and processing facilities in 2020, accounted for about 96% of the estimated total environmental releases from facilities required to report to the TRI (TRI21 2022). An additional 230 g (~0.46 pounds [<1 metric ton]), accounting for about <1% of the total environmental emissions, were released via underground injection (TRI21 2022). These releases are summarized in Table 5-2.

The main sources of CDFs in soil are atmospheric deposition from combustion and manufacturing processes and disposal of CDF-contaminated wastes. Several instances of CDF environmental contamination from improper disposal of hazardous chemical wastes have been associated with the manufacture or use of certain chlorinated organic compounds and wastes from certain bleaching processes (Someshwar et al. 1990; Tiernan et al. 1989). Soil samples around two wood-preserving facilities in Finland that used chlorophenols contained several congeners of CDFs (Kitunen et al. 1987). The concentrations of octaCDF, 1,2,3,4,6,8,9-heptaCDF, 1,2,3,4,6,7,8-heptaCDF, 1,2,4,6,8,9-hexaCDF, 1,2,4,6,7,8-hexaCDF, and 1,2,3,4,6,8-hexaCDF in the top soil from one of these facilities were 210, 840, 1,400, 440, 340, and 550 µg/kg, respectively. In the other facility, the concentrations of CDFs decreased with soil depth, then increased at a depth of 60–80 cm, and tended to decrease at depths ≥100 cm of soil (Kitunen et al. 1987). Soil contaminated with CDFs from PCP-containing wood preserving waste sites has been found in Butte, Montana, and Kent, Washington, in the United States (Tiernan et al. 1989), and in Finland (Kitunen et al. 1987). Land disposal of treated waste-water sludge from magnesium and nickel production is another source of CDF soil contamination (Oehme et al. 1989). An important source of CDFs in soil is the discharge of waste-water sludge from bleached kraft pulp and paper mills. The sludge from paper mills is known to contain CDFs (Amendola et al. 1989; Sherman et al. 1990; Someshwar et al. 1990). The presence of CDFs in the soil of Superfund sites also indicates that disposal of contaminated waste (e.g., waste from certain combustion processes, chemical wastes) is an important source of CDFs in soil. Biosolids applied to soils may also be a potential source of CDFs (EPA 2007a; Venkatesan and Halden 2014).

5.4 ENVIRONMENTAL FATE

5.4.1 Transport and Partitioning

Air. CDFs are present in the atmosphere both in the vapor and particulate phase (Hites 1990). The ratio of the vapor to particulate-phase CDFs in air increases with increasing temperature. The ratio in Bloomington, Indiana was as high as 2 during the warm summer months and <0.5 in the winter. However, it should be recognized that the distribution of CDFs between the vapor- and particulate-phase will depend on the amount and nature of the particulate matter in the atmosphere, as well as the temperature (Hites 1990). The vapor to particle ratio is also different for the different congeners. Substances with low vapor pressures are more prone to exist in the particulate-phase than the vapor-phase. In the air, a higher proportion of tetraCDF congeners is present in the vapor phase, whereas heptaCDF and octaCDF congeners are found predominantly in the particulate phase (Hites 1990). The transport of atmospheric CDFs to soil and water occurs by dry and wet deposition. Dry deposition refers to the simple gravitational settling of particles and the removal of vapor phase compounds onto surface materials, such as water and vegetation by impaction. Wet deposition refers to the removal of the atmospheric compounds by rain, fog, or snow.

The overall determined average dry to wet deposition ratio for atmospheric CDFs was 5:1 (Hites 1990). Therefore, dry deposition is more important than wet deposition for removal of atmospheric CDFs. Both particulate- and vapor-phase compounds can be removed from the atmosphere by wet deposition. Particle-scavenging is the process by which rainfall removes particles from the atmosphere. About 40% of tetraCDF and pentaCDF homologues and 80% of the hexaCDF through octaCDF homologues in Bloomington, Indiana air were removed by particle scavenging. Therefore, particle scavenging during wet deposition is generally a more important process than gas scavenging (Eitzer and Hites 1989a; Hites 1990). Wet deposition of vapor-phase CDFs is a relatively minor loss process (Atkinson 1991).

In addition to the intermedia transport of CDFs from air to water and soil, intramedia transport of CDFs is also significant. The long atmospheric lifetimes of tetra- and higher chlorinated congeners and the presence of these CDFs in remote areas far removed from an emission source indicates that these substances are susceptible to long-range atmospheric transport (Atkinson 1991; Czuczwa et al. 1985; Oehme 1991; Rappe et al. 1989).

Water. The two significant processes in the transport of a chemical from water are volatilization and adsorption to sediment. The first process transfers the chemical from water to air and the second process transfers the chemical from water phase to sediment. The volatilization of CDFs from water, as with other chemicals, depends on their Henry's law constants. Since the values of the Henry's law constants for tetra- and higher CDFs are $<1.48 \times 10^{-5}$ atm-m^3/mol (see Table 4-2), the rate of volatilization of these CDFs is slow and is controlled by slow diffusion through air (Thomas 1982). The volatilization rates are further decreased because the CDFs are present in water predominantly in the adsorbed states. The adsorption of CDFs to suspended solids and sediment in water depends on their K_{oc} values. The estimated log K_{oc} values for 2,3,7,8-TCDD and octaCDF are 5.61 and 8.57, respectively (see Table 4-2). Therefore, these compounds strongly adsorb to suspended solids and sediment in water. As a result, almost all of the literature provides concentrations of CDFs in sediment, and not in water; concentration in water is so low that it is rarely measured. Therefore, sediments are the ultimate environmental sinks for CDFs (Czuczwa and Hites 1986b).

The estimated high log K_{ow} values for 2,3,7,8-tetraCDF and octaCDF (see Table 4-2) suggest that the bioconcentration of CDFs in aquatic organisms is high. The experimental bioconcentration factor (BCF) for octaCDF in the guppy (*Poecilia reticulata*) was 589 on wet weight basis and 7,760 on lipid weight basis (Frank and Schrap 1990). Similarly, steady-state concentrations of slightly >0.001 μg/g (wet weight) in tissues were found in guppies after feeding the fish 10.6–40.6 μg/g octaCDF in food (Clark and Mackay 1991). In a static laboratory test, the determined bioconcentration factors for 1,2,3,7,8-pentaCDF and 2,3,4,7,8-pentaCDF in guppies were 2,400 and 5,000, respectively (Opperhuizen and Sijm 1990). In another laboratory experiment, the determination of bioconcentration of 2,3,7,8-tetraCDF in goldfish (*Carassius auratus*) was attempted by exposing the fish to fly ash (containing <1,400 ppt 2,3,7,8-tetraCDF) and contaminated sediment (containing <68 ppt 2,3,7,8-tetraCDF) in aquaria for 10 weeks (O'Keefe et al. 1986). Fish in both tests contained only 0.7 ppt 2,3,7,8-tetraCDF. The BCF could not be determined because the concentration of 2,3,7,8-tetraCDF in water was too low. Laboratory experiments in fish exposed to contaminated sediments and in Wisconsin River fish showed that residues of 2,3,7,8-substituted congeners of CDFs are selectively enriched in carp (*Cyprinus carpio*) (Kuehl et al. 1987). Since the concentrations of CDF isomers were too low for determination, the authors reported the following bioavailability indices (ratio of concentration of a compound in fish lipid to concentration in sediment based on carbon content): 0.06 for 2,3,7,8-tetraCDF, 0.21 for 2,3,4,7,8-pentaCDF, 0.033 for 1,2,3,6,7,8-hexaCDF, and 0.0033 for 1,2,3,4,6,7,8-heptaCDF (Kuehl et al. 1987). In another study, highest bioavailable indices were achieved for organisms filtering or ingesting organic particles (mussels, chironomids) and those consuming benthic organisms (crayfish suckers) (Muir et al. 1992).

It is clear from the above experiments that the BCFs for CDFs in aquatic organisms are lower than other polychlorinated aromatic compounds such as octachlorobiphenyl (Clark and Mackay 1991). Several explanations have been proposed to explain the lower-than-expected bioconcentration of CDFs in fish. One possible explanation is the rapid depuration (elimination) of the chemicals from fish, probably via biotransformation through a cytochrome P450 system mediated mixed function oxidase with the formation and elimination of polar metabolites, such as hydroxylated compounds (Frank and Schrap 1990; Opperhuizen and Sijm 1990). Another explanation for the lower-than-expected BCF is a low rate of membrane permeation of these highly hydrophobic compounds (Opperhuizen and Sijm 1990). The theory of low permeation is disputed by other investigators (Frank and Schrap 1990). In addition, CDF congeners are present in the water mostly in the adsorbed state and the inability to distinguish between the adsorbed and free CDFs (bioavailability will be lower in the adsorbed state) may have largely overestimated the dissolved CDFs in water. As a result, the BCF derived from the overestimated water concentration may be responsible for underestimating the true bioconcentration potential. Khairy et al. (2019) investigated the uptake and bioaccumulation potential of chlorinated pesticides, perfluoroalkyl acids, CDDs, and CDFs in aquatic organisms in the Passaic River, New Jersey, and determined that uptake occurred more through sediment and pore-water for CDFs rather than the river water itself. Estimated BCFs and bioaccumulation factors (BAFs) were calculated using the EPA Estimation Programs Interface Suite (EPI Suite^{TM}) software using the quantitative structure-activity relationships (QSARs) described in Arnot et al. (2009). (See Appendix E for definitions of bioaccumulation and bioconcentration). The results are shown in Table 5-5. These estimated values suggest that bioaccumulation in aquatic organisms is very high for most congeners.

Table 5-5. Estimated BCFs and BAFs for Chlorodibenzofurans (CDFs) in Aquatic Organisms

Congener	Estimated BCF	Estimated BAF
1,3,7,8-TetraCDF	12,800	11,384
2,3,6,8-TetraCDF	12,800	11,384
2,3,7,8-TetraCDF	9,451	2,573
1,2,3,4,8-PentaCDF	14,000	14,993
1,2,3,7,8-PentaCDF	4,732	22,533
2,3,4,7,8-PentaCDF	4,732	54,231
1,2,3,4,7,8-HexaCDF	14,000	239,208
1,2,3,6,7,8-HexaCDF	14,000	239,208
1,2,3,7,8,9-HexaCDF	4,712	12,280
1,2,4,6,7,9-HexaCDF	4,732	45,385
2,3,4,6,7,8-HexaCDF	6,902	64,676
1,2,3,4,6,7,8-HeptaCDF	6,902	64,676
1,2,3,4,6,7,9-HeptaCDF	3,336	93,467
1,2,3,4,7,8,9-HeptaCDF	3,336	93,467
OctaCDF	4,712	12,280

BAF = bioaccumulation factor; BCF = bioconcentration factor

Source: EPA 2012

Compared to other aquatic organism such as fish, crabs lack the ability to metabolize most of the CDF isomers and uptake more of these substances than fish via sediment and tend to have high concentrations of CDFs (Khairy et al. 2019; Oehme et al. 1990). The concentrations of 2,3,7,8-tetra-, 2,3,4,7,8-penta-, and 1,2,3,6,7,8-hexaCDFs in the hepatopancreas of crabs collected from a contaminated river were 2.3, 1.6, and 4.6 ppb. These values are ≈3 orders of magnitude higher than those found in fish (Kuehl et al. 1987). Therefore, bioconcentration of CDFs in crabs will be much higher than in fish that are known to metabolize CDFs, but no values for bioconcentration of CDFs in crabs were provided (Oehme et al. 1990). This is apparently due to a lack of data concerning the concentrations of CDFs in water.

The biomagnification of CDFs in a littoral food chain consisting of phytoplankton → blue mussel (*Mytilus edulis*) → juvenile eider duck (*Somateria mollissima*) and a pelagic food chain consisting of phytoplankton → zooplankton → herring (*Clupea harengus*) → cod (*Gadus morrhua*) was studied (Broman et al. 1992). It was concluded that the total concentrations of 2,3,7,8-substituted CDFs decreased with increasing trophic level, whereas the toxic content of the 2,3,7,8-substituted CDFs increased with increasing trophic level. The result implied a selective enrichment of 2,3,7,8-substituted isomers with high toxic equivalency factors.

Amutova et al. (2021) reviewed 28 published articles regarding the bioconcentration potential and the transfer rates of CDD/CDFs to milk and eggs. Of the 10 CDF congeners studied, they determined that the highest transfer rate to milk occurred for 2,3,4,7,8-pentaCDF (35.6±14.8%). Transfer to hen eggs was considered high for several CDF congeners, including 2,3,7,8-tetraCDF, 2,3,4,7,8-pentaCDF, 1,2,3,7,8-pentaCDF, 1,2,3,4,7,8-hexaCDF, 1,2,3,6,7,8-hexaCDF, and 1,2,3,7,8,9-hexaCDF.

Sediment and Soil. The transport of CDFs from soil to air is possible via volatilization and by windblown dusts. The very low vapor pressures and high soil sorption coefficients of those CDFs for which data are available (see Table 4-2) indicate that volatilization of these compounds from soil is insignificant (Hutzinger et al. 1985b). The observation that essentially no loss of 2,3,7,8-TCDD, a structurally similar compound, from the contaminated soil at Times Beach, Missouri, occurred in 4 years (Yanders et al. 1989), strongly suggests that volatilization is insignificant for CDFs as well. No evidence of appreciable loss of CDFs due to volatilization was found in contaminated soils during a period of 8 years (Hagenmaier et al. 1992). CDFs may be transported from soil to water via leaching and runoff. Soil leaching experiments indicate that CDFs remain strongly adsorbed even in sandy soil and leaching of these compounds from soil by rainwater is not significant (Carsch et al. 1986). The vertical movement of CDFs was found to be very slow and >90% of CDFs were found in the top 10 cm after 3 years (Hagenmaier et al. 1992). Therefore, transport of CDF from landfill soil to adjacent land or surface water by runoff water is more likely than leaching. Leaching or vertical movement of CDFs in soil can occur under special conditions, such as saturation of the sorption sites of the soil matrix, presence of organic solvents in the soil facilitating co-solvent action, cracks in the soil, or burrowing activity of animals (Hagenmaier et al. 1992; Hutzinger et al. 1985b). The bioavailability of CDDs and CDFs was studied in soil samples obtained from a former creosote producing hazardous waste site (Roberts et al. 2019). The bioaccessibility percentage of CDFs calculated using the levels in the soil pre- and post-extraction using a physiologically-based extraction fluid ranged from 34.3% (2,3,7,8-tetraCDF) to 60.6% (1,2,3,4,7,8,9-heptaCDF).

Data regarding the translocation of CDFs from the roots to the above-ground parts of plants were not located. Because there is little bioaccumulation of CDDs in plants from soil (EPA 1985), bioaccumulation of CDFs in plants is also probably insignificant. As in the case with CDDs (EPA 1985), due to absorption by underground roots of some plants such as carrots, the roots can accumulate more CDFs, compared to aerial parts. In most plants (plants with higher aerial surface area and leaf surfaces with compounds that enhance adsorption), higher concentrations of CDFs are likely to be found on aerial portions of plants due to deposition of airborne particles and vapor. The estimated accumulation potential of CDFs on pine needles (ratio of CDF concentration in a gram of pine needles or concentration in a gram of air) due to deposition of airborne particles for 10 months was 104 to 105 (Reischl et al. 1989).

Other Media. The biotransfer of CDFs from contaminated soil to grazing animals was studied with chickens as a model (Petreas et al. 1991). Compared to controls, the concentration of CDFs in eggs of exposed chickens increased 10-fold at low exposure levels (total CDF concentration in soil was 555 ppt) and 100-fold at high exposure levels (total CDF concentration was 11,841 ppt). The bio-transfer factors (ratio of concentration in egg fat over concentration in soil) for different congeners of CDFs were <1. However, statistically significant ($p<0.05$) concentration dependence of bio-transfer factors, as a result of high and low exposure, were found for only 2,3,7,8-tetraCDF and 1,2,3,4,7,8,9-heptaCDF. Warenik-Bany et al. (2019) observed that, in general, BAFs decreased with increasing number of chlorine atoms in terrestrial game animals such as deer and wild boar.

5.4.2 Transformation and Degradation

Air. The loss of vapor-phase CDFs by reactions with hydroxyl radicals, nitrate radicals, and ozone has been estimated to occur slowly for the highly chlorinated congeners (Atkinson 1991). The estimated rate constants for the reactions of vapor phase CDFs with OH radicals are as follows (-10^{-12} cm^3/molecule-second): tetraCDFs, 1.4–8.3; pentaCDFs, 1.0–4.3; hexaCDFs, 0.74–2.6; heptaCDFs, 0.53–0.92; and octaCDFs, 0.39. Using a 12-hour average daytime hydroxyl radical concentration of $1.5x10^6/cm^3$, the estimated tropospheric lifetimes of tetra-, penta-, hexa-, hepta-, and octaCDF are 1.9–11, 3.6–15, 5.9–22, 17–31, and 39 days, respectively. The vapor-phase reaction of CDFs with hydroxyl radicals is the dominant loss process and this loss process is more important for the lower, than the higher, chlorinated congeners, because the lifetimes due to this reaction are shorter for lower chlorinated congeners and the vapor-phase concentrations of lower chlorinated congeners are higher. Based on the available information, the reactions of hydroxyl radicals with particulate-phase CDFs are insignificant and the principal air removal mechanism for particulate-phase CDFs is wet and dry deposition.

Photodegradation of CDFs bound to atmospheric particles is not an important process in removing these compounds from air (Koester and Hites 1992). No data regarding vapor-phase photolysis of CDFs were located. In the absence of data, the half-lives of these compounds in the vapor phase have been estimated from aqueous phase photolysis data and it was concluded that photolysis is relatively unimportant, even when compared to reaction with hydroxyl radicals (with the possible exception of 1,3,6,8-tetraCDF) (Atkinson 1991).

Water. The loss of CDFs in water by abiotic processes such as hydrolysis and oxidation is not likely to be significant (EPA 1985). The photolysis of CDFs in solution indicates that significant photolysis occurs in hydrogen donating solvents. Photolysis was faster in methanol than in hexane. Photolysis in these solvents proceeds with rapid dechlorination and eventual formation of unidentified resinous polymeric products (Hutzinger et al. 1973), and may proceed at a much faster rate at shorter wavelengths (254 nm) than are available from sunlight (>290 nm). In addition, the rate of photolysis in hexane is faster for CDFs than CDDs and the higher chlorinated congeners photodegrade faster than lower chlorinated congeners (Muto and Takizawa 1991). The rates of photolysis of 2,3,7,8-substituted congeners in solution are faster than the rates of non-2,3,7,8-substituted congeners (Tysklind and Rappe 1991). During the photolysis of octaCDF in dioxane under xenon lamp, hexa- and pentaCDFs were the major products, with small amounts of hepta- and tetraCDFs (Koshioka et al. 2014).

The estimated photolysis lifetimes of CDDs by sunlight in surface waters at 40° latitude range from 0.4 to 225 days, depending upon the specific congener and the season of the year (shorter lifetimes in summer than in winter) (Atkinson 1991). If the photolysis rates of CDFs are assumed to be faster than CDDs (Muto and Takizawa 1991), the photolysis lifetimes of CDFs are expected to be shorter than those for CDDs. However, the persistence of CDFs in natural water (based on a half-life of 1 year for CDDs in a model aquatic ecosystem) (EPA 1985), contradicts the estimated photolytic lifetimes in natural water. This discrepancy is possibly due to the fact that CDDs/CDFs in natural water are present predominantly in a particulate-sorbed phase. The rate of photolysis is much slower in the sorbed phase compared to solution phase photolysis (the estimated lifetimes data of Atkinson [1991] is based on solution phase photolysis) (Tysklind and Rappe 1991).

No data in the literature indicate that biodegradation of CDFs in water is significant. Biodegradation studies in sediments of lake water indicate that 2,3,7,8-TCDD resists biodegradation (EPA 1985). Therefore, biodegradation of CDFs in water may also be insignificant.

Sediment and Soil. The photodegradation of thin film CDIs of fly ash bound CDFs under sunlight was much slower than solution phase photolysis (Hutzinger et al. 1973; Tysklind and Rappe 1991).

Direct evidence of sunlight-initiated photolysis of CDFs in soil was not located. Given the fact that sunlight cannot penetrate beyond the surface layer of soil and the lack of photolysis of CDFs adsorbed to fly ash (Koester and Hites 1992; Tysklind and Rappe 1991), the photolysis of CDFs in soil and sediment may not be significant. It may be significant for airborne particles.

No significant changes in the concentration patterns of homologous or isomeric CDFs could be detected in contaminated soil samples taken in 1981, 1987, and 1989 at the same sites and from the same depth (Hagenmaier et al. 1992). This underlines the persistence of CDFs in soil. No direct evidence was located in the literature suggesting that biodegradation of CDFs in soil and sediments is significant. The lack of biodegradation of CDDs in soil and sediments (although a few microbes degraded 2,3,7,8-TCDD at a slow rate) (EPA 1985) and the lack of evidence for any degradation of CDFs in dated lake sediments (Czuczwa and Hites 1986b; Czuczwa et al. 1985) indirectly suggest that biodegradation of CDFs in soil or sediments is not significant.

5.5 LEVELS IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to CDFs depends, in part, on the reliability of supporting analytical data from environmental samples and biological specimens. Concentrations of CDFs in unpolluted atmospheres and in pristine surface waters are often so low as to be near the limits of current analytical methods. In reviewing data on CDFs levels monitored or estimated in the environment, it should also be noted that the amount of chemical identified analytically is not necessarily equivalent to the amount that is bioavailable.

Table 5-6 shows the lowest limit of detections that are achieved by analytical analysis in environmental media. An overview summary of the range of concentrations detected in environmental media is presented in Table 5-7.

Table 5-6. Lowest Limit of Detection Based on Standards[a]

Media	Detection limit	Reference
Air	~1 fg/m^{3b}	EPA 2013
Drinking water	10–50 pg/L (ppq)	EPA 1994 (Method 1613)
Surface water and groundwater	0.025–1 ng/L (ppt)	Tondeur et al. 1989 (EPA Method 8290)
Soil	0.4–0.8 ng/g (ppb)	Draper et al. 1991

Table 5-6. Lowest Limit of Detection Based on Standards[a]

Media	Detection limit	Reference
Sediment	~1 ng/g (ppb)	EPA 2007b (Method 8280B)
Whole blood	5 pg/kg (ppq)	Patterson et al. 1987, 1989

[a] Detection limits based on using appropriate preparation and analytics. These limits may not be possible in all situations.
[b] Detection limits in air are dependent upon the sampling time/sampling volume. Typical detection limits are in the pg/m^3 range; however, this study had extended sampling times and large volume collections (>150 m^3) ensuring very low detection limits.

Table 5-7. Summary of Environmental Levels of Chlorodibenzofurans (CDFs)

Media	Low	High	For more information
Outdoor air (ppbv)	<LOD	5.2×10^{-4}	Section 5.5.1
Indoor air (ppbv)	<LOD	0.00023	Section 5.5.1
Surface water (ppb)	<LOD	1.5	Section 5.5.2
Groundwater (ppb)	<LOD	445	Section 5.5.2
Drinking water (ppb)	<LOD	0.23	Section 5.5.2
Food (ppb)	<LOD	0.005	Section 5.5.4
Soil (ppb)	<LOD	21,000	Section 5.5.3

LOD = limit of detection

Detections of CDFs in air, water, and soil at NPL sites are summarized in Table 5-8.

Table 5-8. Chlorodibenzofuran (CDF) Levels in Water, Soil, and Air of National Priorities List (NPL) Sites

Medium	Median[a]	Geometric mean[a]	Geometric standard deviation[a]	Number of quantitative measurements	NPL sites
Tetrachlorodibenzofuran					
Water (ppb)	0.000295	0.00029	1.31	2	2
Soil (ppb)	0.2	0.634	59.9	11	8
Air (ppbv)			No data		
2,3,7,8-Tetrachlorodibenzofuran					
Water (ppb)			No data		
Soil (ppb)	0.32	0.514	22.2	17	12
Air (ppbv)			No data		

Table 5-8. Chlorodibenzofuran (CDF) Levels in Water, Soil, and Air of National Priorities List (NPL) Sites

Medium	Median[a]	Geometric mean[a]	Geometric standard deviation[a]	Number of quantitative measurements	NPL sites
Pentachlorodibenzofuran					
Water (ppb)			No data		
Soil (ppb)	4.05	3.83	13.7	14	7
Air (ppbv)			No data		
1,2,3,7,8-Pentachlorodibenzofuran					
Water (ppb)			No data		
Soil (ppb)	0.387	0.207	26.8	6	6
Air (ppbv)			No data		
2,3,4,7,8-Pentachlorodibenzofuran					
Water (ppb)			No data		
Soil (ppb)	1.3	0.553	43.5	5	4
Air (ppbv)			No data		
Hexachlorodibenzofuran					
Water (ppb)			No data		
Soil (ppb)	33	22.2	19.0	18	11
Air (ppbv)			No data		
1,2,3,4,7,8-Hexachlorodibenzofuran					
Water (ppb)			No data		
Soil (ppb)	7.8	3.06	77.2	7	6
Air (ppbv)			No data		
1,2,3,6,7,8-Hexachlorodibenzofuran					
Water (ppb)			No data		
Soil (ppb)	5.1	1.32	65.2	8	7
Air (ppbv)			No data		
1,2,3,7,8,9-Hexachlorodibenzofuran					
Water (ppb)			No data		
Soil (ppb)	12.7	6.26	455	6	5
Air (ppbv)			No data		
2,3,4,6,7,8-Hexachlorodibenzofuran					
Water (ppb)			No data		
Soil (ppb)	15	2.12	117	5	4
Air (ppbv)			No data		
Heptachlorodibenzofuran					
Water (ppb)	161	1.11	7,940	3	3
Soil (ppb)	38.9	26.4	27.7	28	16
Air (ppbv)			No data		

Table 5-8. Chlorodibenzofuran (CDF) Levels in Water, Soil, and Air of National Priorities List (NPL) Sites

Medium	Median[a]	Geometric mean[a]	Geometric standard deviation[a]	Number of quantitative measurements	NPL sites
1,2,3,4,6,7,8-Heptachlorodibenzofuran					
Water (ppb)	0.0000655	0.0000274	8.56	2	2
Soil (ppb)	114	22.4	58.9	10	8
Air (ppbv)			No data		
1,2,3,4,7,8,9-Heptachlorodibenzofuran					
Water (ppb)			No data		
Soil (ppb)	30	12.0	352	5	4
Air (ppbv)			No data		
1,2,3,4,6,7,8,9-Octachlorodibenzofuran					
Water (ppb)	0.83	0.489	2,600	7	5
Soil (ppb)	65.4	22.0	37.5	31	19
Air (ppbv)			No data		
Dibenzofurans, chlorinated					
Water (ppb)			No data		
Soil (ppb)	39.4	39.4	1	2	1
Air (ppbv)			No data		

[a] Concentrations found in ATSDR site documents from 1981 to 2019 for 1,867 NPL sites (ATSDR 2019). Maximum concentrations were abstracted for types of environmental media for which exposure is likely. Pathways do not necessarily involve exposure or levels of concern.

5.5.1 Air

The National Dioxin Air Monitoring Network (NDAMN) was established by the EPA in 1998 to determine background air concentrations of CDDs, CDFs, and dioxin-like PCBs in the United States (EPA 2013). Congener-specific data from June 1998 through November 2004 at 34 NDAMN stations (urban 4 stations, rural 23 stations, and remote 7 stations) throughout the United States are shown in Table 5-9. Large sampling times and large volumes of collected air guaranteed low detection limits and a high detection frequency. The maximum concentration of 4,498 fg/m^{3}was observed for 1,2,3,4,6,7,8-heptaCDF.

Table 5-9. Congener-specific Monitoring Data from the NDAMN 1998–2004

Congener	Detection frequency (%)	Mean (fg/m^3)	SD (fg/m^3)
2,3,7,8-TetraCDF	96	2.1	9.6
1,2,3,7,8-PentaCDF	94	2.4	14.1
2,3,4,7,8-PentaCDF	96	4.3	28.8
1,2,3,4,7,8-HexaCDF	98	5.6	41.4
2,3,4,6,7,8-HexaCDF	99	6.4	41.3
1,2,3,7,8,9-HexaCDF	74	1.5	22.3
1,2,3,4,6,7,8-HeptaCDF	100	27.3	178.1
1,2,3,4,7,8,9-HeptaCDF	91	3.5	25.2
OctaCDF	99	21.9	142.8

NDAMN = National Dioxin Air Monitoring Network; SD = standard deviation

Source: EPA 2013

High levels of CDFs and dioxin like substances were observed following the terrorist attacks at the World Trade Center (WTC) complex in New York City on September 11, 2001 (Rayne et al. 2005). Predicted gas-phase concentrations in Manhattan 6 weeks after the attack were estimated to be as high as 9,600 fg/m^3 (9.6 pg/m^3) for 2,3,7,8-tetraCDF.

Lin et al. (2010) studied atmospheric levels of CDDs and CDFs in the air of Taiwan in the vicinity of water treatment facilities. Average atmospheric levels in pg/m^3 were as follows: 2,3,7,8-tetraCDF, 0.082; 1,2,3,7,8-pentaCDF, 0.108; 2,3,4, 7,8-pentaCDF, 0.197; 1,2,3,4,7,8-hexaCDF, 0.230; 1,2,3,6,7,8-hexaCDF, 0.209; 1,2,3,7,8,9-hexaCDF, 0.0.013; 2,3,4, 6,7,8-hexaCDF, 0.241; 1,2,3,4,6,7,8-heptaCDF, 0.729; 1,2,3,4,7,8,9-heptaCDF 0.125; and octaCDF 0.727. Levels were consistently higher in the spring as compared to summer, fall, and winter months.

As part of the Stockholm Convention on Persistent Organic Pollutants (POPs) Global Monitoring Plan (GMP), a study was conducted between 2017 and 2019 to monitor dioxin-like POPs in developing countries (Abad et al. 2022). The results were expressed as TEQs. The findings indicated that there a noticeable downward trend for PCDD/PCDF TEQs only in Latin American nations and that the highest levels were determined to be in African nations. Results from a GMP study conducted in Brazil showed that mass concentrations of PCDD/PCDFs in Sao Paulo declined from 0.0265 to 0.0133 pg/m^3 from 2010 to 2015 (Hu et al. 2019). Similar monitoring studies were conducted in a rural area of Mexico (Sinaloa) from 2016 to 2018 as part of the GMP (Valenzuela et al. 2022). Ten CDFs and seven CDD congeners were monitored in ambient air. The range of values for the sum of these 17 CDDs/CDFs was 0.015–

0.028 pg/m^3. The predominant CDFs detected were 1,2,3,4,6,7,8-heptaCDF (0.022–0.027 pg/m^3) and 2,3,4,7,8-pentaCDF (0.015–0.022 pg/m^3).

Levels of CDFs determined in ambient air in North America are presented in Table 5-10. As expected, the concentrations of CDFs in air show geographical variability based on the sources of emissions. Generally, the levels show the following trend: tunnel > urban > suburban > rural (Eitzer and Hites 1989a). Even in a particular area, the level shows daily and seasonal variability. For example, the concentrations of CDFs are generally higher on rainy days with high humidity and on less windy days (Nakano et al. 1990). The levels are also higher in winter than in summer, due to increases in the contribution from combustion sources (heating) (CARB 1990). Table 5-10 indicates that the concentrations of total tetra-, penta-, hexa-, hepta-, and octaCDFs in ambient urban/suburban air can vary within the ranges of 0.13–7.34, 0.09–5.10, <0.09–12.55, 0.08–12.71, and 0.13–3.78 pg/m^3, respectively. In rural areas, the concentrations of total tetra-, penta-, hexa-, hepta-, and octaCDFs are below their detection limits. It has also been determined that the vapor/particulate phase ratio of the CDFs in ambient air depends on the season of the year and the number of chlorine substituents. Generally, the tetra- and pentaCDFs are present at higher ratios in the vapor phase, while hepta- and octaCDF are present predominantly in the particulate phase in the atmosphere. This ratio of vapor/particulate phase increases during summer, compared to winter (CARB 1990; Eitzer and Hites 1989a; Nakano et al, 1990). The congener profile in the atmosphere follows the congener profile of their sources; that is, if the major source of CDFs in the atmosphere is a municipal incinerator, the congener pattern in the air follows the congener pattern in flue gas from that municipal incinerator (Edgerton et al. 1989; Eitzer and Hites 1989a).

Table 5-10. Concentrations of Chlorodibenzofurans (CDFs) in Ambient Indoor and Outdoor Air in North America and Oceans

Site	Sampling year	CDF	Concentration (pg/m^3)	Reference
Bridgeport, Connecticut (outdoor)	1987–1988	2,3,7,8-TetraCDF	0.078	Hunt and Maisel 1990
		Total tetraCDF	0.856	
		1,2,3,7,8-PentaCDF	0.031	
		2,3,4,7,8-PentaCDF	0.047	
		Total pentaCDF	0.547	
		1,2,3,4,7,8-HexaCDF	0.106	
		1,2,3,6,7,8-HexaCDF	0.039	
		2,3,4,6,7,8-HexaCDF	0.087	
		1,2,3,7,8,9-HexaCDF	0.007	
		Total hexaCDF	0.580	
		1,2,3,4,6,7,8-HeptaCDF	0.212	
		1,2,3,4,7,8,9-HeptaCDF	0.033	
		Total heptaCDF	0.369	
		OctaCDF	0.211	
Toronto Island, Canada (outdoor)	1988–1989	Total tetraCDF	0.404	Steer et al. 1990
		Total pentaCDF	0.118	
		Total hexaCDF	0.204	
		Total heptaCDF	0.240	
		OctaCDF	0.142	
Dorset, Canada (outdoor)	1988–1989	Total tetraCDF	0.064	Steer et al. 1990
		Total pentaCDF	0.200	
		Total hexaCDF	0.074	
		Total heptaCDF	0.52	
		OctaCDF	0.194	
Windsor, Canada (outdoor)	1988–1989	Total tetraCDF	0.733	Steer et al. 1990
		Total pentaCDF	0.383	
		Total hexaCDF	0.333	
		Total heptaCDF	0.550	
		OctaCDF	0.182	
Boston, Massachusetts (indoor)	No data	2,3,7,8-TetraCDF	(0.37)[a]–1.4	Kominsky and Kwoka 1989
		Total tetraCDF	(0.64)[a]–6.2	
		Total pentaCDF	(0.12)[a]–1.9	
		Total hexaCDF	(0.39–(1.5)a	
		OctaCDF	(0.54)–(1.8)[a]	
Albany, New York (outdoor)	1987–1988	Total tetraCDF	3.86	Smith et al. 1990a
		2,3,7,8-tetraCDF/unknown isomer	0.89	
		Total pentaCDF	2.00	
		Total hexaCDF	0.28	
		Total heptaCDF	<0.34	
		OctaCDF	<0.50	
Binghamton, New York (outdoor)	1988	Total tetraCDF	0.94	Smith et al. 1990a
		2,3,7,8-tetraCDF/unknown isomer	0.18	
		Total pentaCDF	0.25	
		Total hexaCDF	<0.09	
		Total heptaCDF	<0.14	
		OctaCDF	<0.30	

Table 5-10. Concentrations of Chlorodibenzofurans (CDFs) in Ambient Indoor and Outdoor Air in North America and Oceans

Site	Sampling year	CDF	Concentration (pg/m^3)	Reference
Utica, New York (outdoor)	1988	Total tetraCDF	7.34	Smith et al. 1990a
		2,3,7,8-tetraCDF/unknown isomer	1.15	
		Total pentaCDF	3.16	
		Total hexaCDF	<0.36	
		Total heptaCDF	<0.24	
		OctaCDF	<0.61	
Niagara Falls, New York (outdoor)	1987–1988	Total tetraCDF	1.53	Smith et al. 1990a
		2,3,7,8-tetraCDF/unknown isomer	<0.11	
		Total pentaCDF	0.98	
		Total hexaCDF	1.45	
		Total heptaCDF	1.37	
		OctaCDF	0.51	
United States and Canada ambient air (outdoor)	No data	Total tetraCDF	1.09	Waddell et al. 1990
		Total pentaCDF	0.63	
		Total hexa CDP	0.72	
		Total heptaCDF	1.14	
		OctaCDF	0.62	
Bloomington, Indiana	1986	2,3,7,8-/2,3,4,8-/2,3,4,6-TetraCDF	0.048	Eitzer and Hites 1989b
		Total tetraCDF	0.263	
		1,2,3,7,8-/1,2,3,4,8-pentaCDF	0.017	
		2,3,4,7,8-/1,2,3,6,9-pentaCDF Total	0.017	
		pentaCDF	0.20	
		1,2,3,4,7,8-/1,2,3,4,6,7-HexaCDF	0.023	
		1,2,3,6,7,8-/1,2,3,4,7,9-HexaCDF	0.016	
		2,3,4,6,7,8-HexaCDF	0.015	
		1,2,3,7,8,9-HexaCDF	0.0007	
		Total hexaCDF	0.113	
		1,2,3,4,6,7,8-HeptaCDF	0.039	
		1,2,3,4,7,8,9-HeptaCDF	0.005	
		Total heptaCDF	0.071	
		OctaCDF	0.28	
Southern California (outdoor)	1987–1989	2,3,7,8-TetraCDF	<0.007–0.482	CARB 1990
		1,2,3, 7,8-PentaCDF	<0.010–1.9	
		2,3,4,7,8-PentaCDF	<0.009–0.110	
		1,2,3,4,7,8-HexaCDF	<0.001–0.27	
		1,2,3,6,7,8-HexaCDF	<0.001–0.800	
		2,3,4,6,7,8-HexaCDF	<0.001–0.280	
		1,2,3,4,6,7,8-HeptaCDF	<0.002–1.58	
		1,2,3,4,7,8,9-HeptaCDF	<0.002–0.092	

Table 5-10. Concentrations of Chlorodibenzofurans (CDFs) in Ambient Indoor and Outdoor Air in North America and Oceans

Site	Sampling year	CDF	Concentration (pg/m^3)	Reference
Los Angeles, California (outdoor)	1987	2,3,7,8-TetraCDF	0.021	Maisel and Hunt 1990
		Other tetraCDF	0.30	
		1,2,3,7,8-PentaCDF	0.077	
		2,3,4,7,8-PentaCDF	0.077	
		Other pentaCDF	0.41	
		1,2,3,4,7,8-HexaCDF	0.151	
		1,2,3,6,7,8-HexaCDF	0.25	
		2,3,4,6,7,8-HexaCDF	<0.069	
		1,2,3,7,8,9-HexaCDF	<0.083	
		Other hexaCDF	<0.080	
		1,2,3,4,6,7,8-HeptaCDF	<0.190	
		1,2,3,4,7,8,9-HeptaCDF	<0.018	
		Other heptaCDF	0.26	
		OctaCDF	0.056	
Dayton, Ohio (outdoor, suburban/ roadside)	1988	Total tetraCDF	0.13	Tiernan et al. 1989
		Total pentaCDF	0.24	
		Total hexaCDF	0.14	
		Total heptaCDF	0.11	
		OctaCDF	<0.07	
Dayton, Ohio (outdoor, municipal solid waste incinerator)	1988	Total tetraCDF	1.23	Tiernan et al. 1989
		2,3,7,8-tetraCDF	0.11	
		Total pentaCDF	5.10	
		1,2,3,7,8-pentaCDF/unknown isomer	0.46	
		2,3,4,7,8-pentaCDF	0.53	
		Total hexaCDF	12.55	
		1,2,3,4,7,8-hexaCDF/unknown isomer	1.18	
		1,2,3,6,7,8-hexaCDF	2.27	
		1,2,3,7,8,9-hexaCDF	<0.06	
		2,3,4,6,7,8-hexaCDF	<0.41	
		Total heptaCDF	12.71	
		1,2,3,4,6,7,8-heptaCDF	8.22	
		1,2,3,4,7,8,9-heptaCDF	0.56	
		OctaCDF	3.78	
Dayton, Ohio (outdoor, rural area)	1988	Total tetraCDF	<0.02	Tiernan et al. 1989
		Total pentaCDF	<0.02	
		Total hexaCDF	<0.05	
		Total heptaCDF	<0.07	
		OctaCDF	<0.17	
Windsor, Canada (outdoor)	1987–1988	Total tetraCDF	0.21	Bobet et al. 1990
		Total pentaCDF	0.09	
		Total hexaCDF	0.10	
		Total heptaCDF	0.08	
		OctaCDF	0.13	
Walpole Island, Canada (outdoor)	1987–1988	Total tetraCDF	<0.05	Bobet et al. 1990
		Total pentaCDF	<0.07	
		Total hexaCDF	<0.10	
		Total heptaCDF	<0.07	
		OctaCDF	<0.14	

Table 5-10. Concentrations of Chlorodibenzofurans (CDFs) in Ambient Indoor and Outdoor Air in North America and Oceans

Site	Sampling year	CDF	Concentration (pg/m^3)	Reference
Lake Trout, Wisconsin (outdoor)	1987	Total tetraCDF	0.083	Edgerton et al. 1989
		Total pentaCDF	0.067	
		Total hexaCDF	0.031	
		Total heptaCDF	0.012	
		OctaCDF	0.006	
Akron, Ohio (outdoor)	1987	2,3,7,8-TetraCDF	0.200	Edgerton et al. 1989
		Total tetraCDF	1.23	
		1,2,3,7,8-PentaCDF	0.029	
		2,3,4,7,8-PentaCDF	0.036	
		Total pentaCDF	0.590	
		1,2,3,4,7,8-HexaCDF	0.083	
		1,2,3,6,7,8-HexaCDF	0.065	
		2,3,4,6,7,8-HexaCDF	<0.021	
		1,2,3,7,8,9-HexaCDF	0.032	
		Total hexaCDF	0.620	
		1,2,3,4,6,7,8-HeptaCDF	0.237	
		1,2,3,4,7,8,9-HeptaCDF	<0.029	
		Total heptaCDF	0.383	
		OctaCDF	0.180	
Columbus, Ohio (outdoor)	1987	2,3,7,8-TetraCDF	0.405	Edgerton et al. 1989
		Total tetraCDF	2.85	
		1,2,3,7,8-PentaCDF	0.045	
		2,3,4,7,8-PentaCDF	<0.056	
		Total pentaCDF	0.995	
		1,2,3,4,7,8-HexaCDF	0.165	
		1,2,3,6,7,8-HexaCDF	0.141	
		2,3,4,6,7,8-HexaCDF	<0.02	
		1,2,3,7,8,9-HexaCDF	0.079	
		Total hexaCDF	0.785	
		1,2,3,4,6,7,8-HeptaCDF	0.335	
		1,2,3,4,7,8,9-HeptaCDF	<0.021	
		Total heptaCDF	0.450	
		OctaCDF	<0.260	
Waldo, Ohio (outdoor)	1987	2,3,7,8-TetraCDF	0.130	Edgerton et al. 1989
		Total tetraCDF	0.890	
		1,2,3,7,8-PentaCDF	0.021	
		2,3,4,7,8-PentaCDF	<0.033	
		Total pentaCDF	0.500	
		1,2,3,4,7,8-HexaCDF	0.098	
		1,2,3,6,7,8-HexaCDF	0.014	
		2,3,4,6,7,8-HexaCDF	<0.008	
		1,2,3,7,8,9-HexaCDF	0.097	
		Total hexaCDF	0.510	
		1,2,3,4,6,7,8-HeptaCDF	0.220	
		1,2,3,4,7,8,9-HeptaCDF	0.019	
		Total heptaCDF	0.290	
		OctaCDF	0.077	

Table 5-10. Concentrations of Chlorodibenzofurans (CDFs) in Ambient Indoor and Outdoor Air in North America and Oceans

Site	Sampling year	CDF	Concentration (pg/m^3)	Reference
Chicago, Illinois (outdoor)	2004–2007	ΣCDDs/CDFs	1.3±0.10	Venier et al. 2009
Eagle Harbour, Michigan (outdoor)	2004–2007	ΣCDDs/CDFs	0.12±0.013	Venier et al. 2009
Sturgeon Point, New York	2004–2007	ΣCDDs/CDFs	0.74±0.083	Venier et al. 2009
Sleeping Bear Dunes, (outdoor) Michigan	2004–2007	ΣCDDs/CDFs	0.40±0.093	Venier et al. 2009
Calcasieu Parish, Louisiana (outdoor)	2001–2002	ΣCDDs/CDFs	0.0027–0.0924	Gibbs et al. 2003
North Atlantic	2010–2011	ΣCDFs	0.008 (gas) 0.0094 (aerosol)	Morales et al. 2014
South Atlantic	2010–2011	ΣCDFs	0.006 (gas) 0.014 (aerosol)	Morales et al. 2014
Indian Ocean	2010–2011	ΣCDFs	0.0061 (gas) 0.0093 (aerosol)	Morales et al. 2014
South Pacific	2010–2011	ΣCDFs	0.0045 (gas) 0.0066 (aerosol)	Morales et al. 2014
North Pacific	2010–2011	ΣCDFs	0.0069 (gas) 0.0094 (aerosol)	Morales et al. 2014
Global	2010–2011	ΣCDFs	0.0067 (gas) 0.0100 (aerosol)	Morales et al. 2014

[a]Detection limit.

The majority of CDFs found in the air are non-2,3,7,8-substituted congeners, which are much less toxic than 2,3,7,8-substituted congeners. Among the 2,3,7,8-substituted isomers in the air, the 1,2,3,4,6,7,8-heptaCDF congener dominates, followed by 2,3,7,8-tetraCDF. It has been shown that 2,3,7,8-tetraCDF constitutes ≈9% of total tetraCDFs; 1,2,3,7,8-penta- and 2,3,4,7,8-pentaCDF constitute ≈9 and 10.4%, respectively, of total pentaCDFs; 1,2,3,4,7,8-hexa-, and 1,2,3,6,7,8-hexaCDF constitute ≈9.4 and 18.1%, respectively, of the total hexaCDFs; and 1,2,3,4,6,7,8-heptaCDF and

1,2,3,4,7,8,9-heptaCDF constitute ≈64.7 and 4.4%, respectively, of the total heptaCDFs present in the air near a municipal solid waste incinerator in Dayton, Ohio (Tiernan et al. 1989).

Considerably higher concentrations of CDFs have been detected in the indoor air and wipe samples of buildings after accidental fires involving PCB capacitors/transformers. For example, the concentrations of total CDFs and 2,3,7,8-tetraCDF (plus co-eluting isomers) in wipe samples from the transformer vault after the 1983 transformer fire in Chicago were 12,210 and 410 ng/100 cm^2 (41,000 ng/m^2), respectively (Hryhorczuk et al. 1986). The concentrations of total tetraCDFs in air and wipe samples inside the vault 4 months after the 1983 San Francisco transformer fire were 1,000–3,000 pg/m^3 and 1,000–23,000 ng/100 cm^2 (100,000–2,300,000 ng/m^2), respectively (Stephens 1986). Seven months following the fire, the maximum concentration of 2,3,7,8-substituted CDFs in air of the building that contained the transformer vault was 19.5 pg/m^3. The concentrations of total tetraCDFs, 2,3,7,8-tetraCDF (plus co-eluting isomers) and total pentaCDFs of indoor air in a Binghamton, New York, office building 1.5–2 years after cleanup following a 1981 electric fire were ≤23, 195, and 60 pg/m^3, respectively (Smith et al. 1986). The mean indoor air levels of combined 2,3,7,8-TCDD and 2,3,7,8-tetraCDF was 24.5 pg/m^3 in the melting shop area of an electric arc furnace steelmaking plant (Aries et al. 2008). Concentrations of tetraCDF, pentaCDF, hexaCDF, heptaCDF and octaCDF were ≤0.4, 0.6, 2.2, 4.4, and 4.8 ng/100 cm^2, respectively, present in the wipe samples of a building used for the improper incineration of PCBs (Thompson et al. 1986). Following the attacks on the World Trade Center, CDD/CDF levels of window films within 1 km of the World Trade Center site in lower Manhattan were as large as 630,000 pg/m^2 (630 ng/m^2) (Rayne et al. 2005). Dust samples obtained from 21 homes in Albany, New York had CDF levels ranging from 13 to 5,600 pg/g (Tue et al. 2013).

5.5.2 Water

The concentrations of CDFs in most waters are so low that it is difficult to determine the levels in drinking water and surface water, unless the surface water is sampled close to points of effluent discharge containing CDFs. Because of their low water solubilities and high K_{oc} values, the CDFs partition from the water to sediment in environmental water or in sludge during the treatment of wastewaters. Therefore, more monitoring data are available for CDFs levels in the latter two media.

A drinking water sample in Sweden contained 2,3,4,7,8-pentaCDF at a concentration of 0.002 ppq (Rappe 1991). The levels of CDFs in drinking water from 20 communities in New York state were measured (Meyer et al. 1989). Total tetraCDFs at a concentration of 2.6 ppq (pg/L) and octaCDF at a concentration

0.8 ppq were the only two congener groups detected in 1 of 20 water supplies (Lockport, New York). The concentration of 2,3,7,8-tetraCDF in water from Lockport was 1.2 ppq. The raw water that served as the source of this drinking water contained several CDFs at the following concentrations (ppq): total tetraCDF, 18.0; 2,3,7,8-tetraCDF, not detected (detection limit 0.7); 1,2,3,7,8-pentaCDF, 2.0; total pentaCDF, 27.0; 1,2,3,4,7,8-hexaCDF, 39.0; 1,2,3,6,7,8-hexaCDF, 9.2; total hexaCDF, 85.0; 1,2,3,4,6,7,8-heptaCDF, 210; total heptaCDF, 210; and octaCDF, 230. Since the finished drinking water contained 2,3,7,8-tetraCDF, and the raw water did not contain any detectable level of this compound, the source of 2,3,7,8-tetraCDF in the drinking water must be the chlorination process. Considerably higher concentrations of CDFs were detected in the sediment of the raw water. This provides more indirect evidence that chlorination may be partially responsible for the in-situ production of CDFs.

Lin et al. (2010) studied concentrations of CDFs in drinking water in Taiwan to better understand how atmospheric deposition of CDFs influence these concentrations. Tap water levels in pg/L were as follows: 2,3,7,8-tetraCDF, 0.021; 1,2,3,7,8-pentaCDF, 0.0023; 2,3,4, 7,8-pentaCDF, 0.0026; 1,2,3,6,7,8-hexaCDF, 0.0019; 1,2,3,7,8,9-hexaCDF, 0.0005; 2,3,4, 6,7,8-hexaCDF, 0.0021; 1,2,3,4,6,7,8-heptaCDF, 0.0071; 1,2,3,4,7,8,9-heptaCDF 0.0017; octaCDF 0.0256. The authors found tap water levels for total CDDs/CDFs to be approximately 55% less than that in source water and that atmospheric deposition to uncovered water treatment facilities likely increased the levels in finished water.

Because of CDFs high soil adsorption, leaching to groundwater is unlikely with an exception for buried wastes or highly contaminated sites. CDFs have been detected in groundwater at several NPL sites with octaCDF being detected at a concentration of 445 ppb (μg/L) at a former wood production facility (ATSDR 2017).

Effluents from bleached kraft and sulfite mill pulp in the United States, Canada, and Europe contained total tetraCDFs in the concentration range of <0.01–4,100 ppt, whereas the concentrations of 2,3,7,8-tetraCDF varied from <0.002 to 8.4 ppt. The octaCDF levels in these effluents ranged from <0.05 to 0.5 ppt. The sludge from the treated effluents from paper mills contained much higher concentrations of CDFs. In one case, the sludge from a chloralkali process contained ≤52,000 ppt of 2,3,7,8-tetraCDF and 81,000 ppt of octaCDF (Clement et al. 1989b, 1989c; Rappe et al. 1990a; Waddell et al. 1990; Whittemore et al. 1990).

Surface water adjacent to a landfill near Tonawanda, New York, contained the following concentrations of CDFs (ppt): total tetraCDFs, 0.2–77; total pentaCDFs, 0.3–130; total hexaCDFs, 0.8–200; total heptaCDFs, 1.0–980; and octaCDF, 1.2–1,500 (Clement et al. 1989a). Leachates from bottom and fly ash disposal facilities of five state-of-the-art mass burn municipal waste combustors, with a variety of pollution control equipment, were analyzed for CDFs. With the exception of the leachate from one facility, leachates from the other four facilities contained CDFs below the detection level (0.01–0.06 ppb). HeptaCDF at a concentration of 0.076 ppb was detected in the remaining leachate sample (EPA 1990b).

The level of CDFs has also been measured in rainwater. The concentrations of total tetraCDFs, total pentaCDFs, total hexaCDFs, total heptaCDFs and octaCDF in rainwater from Bloomington, Indiana; Dorset, Canada; and Toronto, Canada, were <0.6–5.7, 0.2–6.0, 0.7–6.0, <0.8–2.4, and <0.8–0.8 ppq, respectively (Eitzer and Hites 1989b; Reid et al. 1990). As expected, the concentrations of CDFs were lower in rainwater from the rural site (Dorset) than from the urban site (Toronto) (Reid et al. 1990). The levels of CDFs in fog have also been measured, and the congener profile was similar to rainwater; however, the concentrations of CDFs were higher in fog than in rainwater, due to enhanced particle scavenging by fog (Czuczwa et al. 1989).

Khairy and Lohmann (2020) measured levels of CDFs in porewater at four locations in the lower Passaic River, New Jersey. Due to industrial activities, this area is historically known for its contamination with PCBs and PCDDs/PCDFs. The data from this study are summarized in Table 5-11. Porewater concentrations of CDFs (pg/L) at four locations of the lower Passaic River were obtained during four sampling periods.

Table 5-11. Porewater Concentrations of Chlorodibenzofurans (CDFs) (pg/L) at Four Locations of the Lower Passaic River Obtained During Four Sampling Periods

Congener	06/2015–08/2015	08/2015–10/2015	10/2015–12/2015	12/2015–02/2016
River Bank Park, Lower Passaic River				
2-MonoCDF	14.69	12.98	11.04	8.86
2,8-DiCDF	4.33	5.25	5.68	5.85
2,3,8-TriCDF	2.11	2.56	2.34	2.54
2,3,7,8-TetraCDF	0.21	0.25	0.23	0.20
1,2,3,4,7-PentaCDF	0.03	0.02	0.03	0.03
2,3,4,7,8-PentaCDF	0.044	0.03	0.03	0.02
1,2,3,4,7,8-HexaCDF	0.02	0.02	0.02	0.03

Table 5-11. Porewater Concentrations of Chlorodibenzofurans (CDFs) (pg/L) at Four Locations of the Lower Passaic River Obtained During Four Sampling Periods

Congener	06/2015–08/2015	08/2015–10/2015	10/2015–12/2015	12/2015–02/2016
1,2,3,6,7,8-HexaCDF	<LOD	<LOD	<LOD	<LOD
1,2,3,7,8,9-HexaCDF	<LOD	<LOD	<LOD	<LOD
2,3,4,6,7,8-HexaCDF	<LOD	<LOD	<LOD	<LOD
1,2,3,4,6,7,8- HeptaCDF	0.03	0.03	0.03	0.02
1,2,3,4,7,8,9-HeptaCDF	<LOD	<LOD	<LOD	<LOD
1,2,3,4,6,7,8,9-OctaCDF	0.02	0.02	0.02	0.01
Bridge Street, Passaic River				
2-MonoCDF	13.408	8.120	NA	NA
2,8-DiCDF	6.824	9.481	NA	NA
2,3,8-TriCDF	4.835	4.011	NA	NA
2,3,7,8-TetraCDF	0.213	0.294	NA	NA
1,2,3,4,7-PentaCDF	0.092	0.075	NA	NA
2,3,4,7,8-PentaCDF	<LOD	<LOD	NA	NA
1,2,3,4,7,8-HexaCDF	<LOD	<LOD	NA	NA
1,2,3,6,7,8-HexaCDF	<LOD	<LOD	NA	NA
1,2,3,7,8,9-HexaCDF	<LOD	<LOD	NA	NA
2,3,4,6,7,8-HexaCDF	<LOD	<LOD	NA	NA
1,2,3,4,6,7,8- HeptaCDF	<LOD	<LOD	NA	NA
1,2,3,4,7,8,9-HeptaCDF	<LOD	<LOD	NA	NA
1,2,3,4,6,7,8,9-OctaCDF	<LOD	<LOD	NA	NA
Doremus Street, Passaic River				
2-MonoCDF	11.98	11.91	12.02	12.90
2,8-DiCDF	10.21	10.53	11.86	13.13
2,3,8-TriCDF	11.23	11.62	10.37	10.54
2,3,7,8-TetraCDF	0.255	0.336	0.313	0.277
1,2,3,4,7-PentaCDF	0.027	0.023	0.026	0.030
2,3,4,7,8-PentaCDF	0.019	0.017	0.013	0.013
1,2,3,4,7,8-HexaCDF	0.009	0.011	0.014	0.012
1,2,3,6,7,8-HexaCDF	<LOD	<LOD	<LOD	<LOD
1,2,3,7,8,9-HexaCDF	<LOD	<LOD	<LOD	<LOD
2,3,4,6,7,8-HexaCDF	<LOD	<LOD	<LOD	<LOD
1,2,3,4,6,7,8- HeptaCDF	0.012	0.013	0.017	0.013
1,2,3,4,7,8,9-HeptaCDF	<LOD	<LOD	<LOD	<LOD
1,2,3,4,6,7,8,9-OctaCDF	<LOD	<LOD	<LOD	<LOD

Table 5-11. Porewater Concentrations of Chlorodibenzofurans (CDFs) (pg/L) at Four Locations of the Lower Passaic River Obtained During Four Sampling Periods

Congener	06/2015–08/2015	08/2015–10/2015	10/2015–12/2015	12/2015–02/2016
Passaic Ave, Passaic River				
2-MonoCDF	12.47	15.49	13.87	11.89
2,8-DiCDF	5.93	7.21	7.91	7.35
2,3,8-TriCDF	4.66	4.04	3.84	3.27
2,3,7,8-TetraCDF	0.26	0.31	0.31	0.26
1,2,3,4,7-PentaCDF	0.03	0.03	0.02	0.02
2,3,4,7,8-PentaCDF	<LOD	<LOD	<LOD	<LOD
1,2,3,4,7,8-HexaCDF	<LOD	<LOD	<LOD	<LOD
1,2,3,6,7,8-HexaCDF	<LOD	<LOD	<LOD	<LOD
1,2,3,7,8,9-HexaCDF	<LOD	<LOD	<LOD	<LOD
2,3,4,6,7,8-HexaCDF	<LOD	<LOD	<LOD	<LOD
1,2,3,4,6,7,8- HeptaCDF	<LOD	<LOD	<LOD	<LOD
1,2,3,4,7,8,9-HeptaCDF	<LOD	<LOD	<LOD	<LOD
1,2,3,4,6,7,8,9-OctaCDF	<LOD	<LOD	<LOD	<LOD

LOD = limit of detection; NA = not applicable

Source: Khairy and Lohmann (2020)

5.5.3 Sediment and Soil

Levels of CDF congeners were monitored in sediment at four locations in the lower Passaic River, New Jersey (Khairy and Lohmann 2020). Ranges of values in ppt (pg/g) were as reported as 2-monoCDF 2.7–14.1; 2,8-diCDF 48.0–152.9; 2,3,8-triCDF 25.5–194.9; 2,3,7,8-tetraCDF 19.1–91.5; 1,2,3,4,7-pentaCDF 1.7–18.2; 2,3,4,7,8-pentaCDF 6.1–30.3; 1,2,3,4,7,8-hexaCDF 28.5–135.6; 1,2,3,7,8,9-hexaCDF 3.0–12.3; 2,3,4,6,7,8-hexaCDF 4.1–12.1; 1,2,3,4,6,7,8-heptaCDF 90.0–314.6; 1,2,3,4,7,8,9-heptaCDF 3.9–12.4; and octaCDF 147.0–479.6. The maximum 2,3,7,8-tetraCDF and 2,3,7,8-substituted CDF concentrations of 0.3 ppt (ng/kg) and 11.0 ppt, respectively, were determined for sediments from an uncontaminated river (Elk River) in Minnesota (Reed et al. 1990). The maximum concentrations of total pentaCDFs, hexaCDFs, heptaCDFs, and octaCDF in sediment samples from the same river were 25.0, 12.0, 30.0, and 23.0 ppt, respectively. In all cases, the analyte was not detected in some samples. The concentrations of 2,3,7,8-tetraCDF in sediment from the lower Hudson River (New York), Cuyahoga River (Ohio), Menominee River (Wisconsin), Fox River (Wisconsin), Raisin River

(Michigan), and Saginaw River (Wisconsin) ranged from 5 to 97 ppt (O'Keefe et al. 1984; Smith et al. 1990b). The concentration of 2,3,7,8-tetraCDF in sediment from an uncontaminated lake (Lake Pepin) in Wisconsin was <l ppt, while its concentration in sediment from Lake Michigan in Green Bay (Wisconsin) was 24 ppt (Smith et al. 1990b). The concentrations of 2,3,7,8-tetraCDF in estuarine sediment varied from 15.0 ppt for an uncontaminated sediment in Long Island Sound (New York) to 4,500 ppt in sediment from an estuary adjacent to a 2,4,5-trichlorophenoxyacetic acid production facility in Newark, New Jersey (Bopp et al. 1991; Norwood et al. 1989). A concentration ≤1,400 ppt was also detected in sediment from New Bedford Harbor (Massachusetts) near a Superfund site (Norwood et al. 1989). The concentrations of 2,3,7,8-tetraCDF and other 2,3,7,8-substituted congeners of pentaCDF were higher in contaminated sediments than uncontaminated sediments (Norwood et al. 1989). In a survey of harbor sediment near a wood treatment facility at Thunder Bay (Ontario), the concentration of tetraCDFs and pentaCDFs were below the detection limit, while the levels of the higher congeners increased with the degree of chlorination (maximum of 6.5 ng/g [6,500 ppt] for hexaCDF to 400 ng/g for octaCDF) (McKee et al. 1990). Iyer et al. (2016) compiled data on levels of CDDs and CDFs in the San Jacinto River and Houston Ship Channel. The maximum concentration for CDFs occurred for octaCDF, 12 ng/g (12,000 ppt) in the Buffalo Bayou in August 2005.

The concentrations (ppt) of CDFs in uncontaminated soils from the vicinity of Elk River, Minnesota were as follows: 2,3,7,8-tetraCDF, not detected; total tetraCDF, not detected to 1.2; total hexaCDFs, 6.7–150; 1,2,3,4,6,7,8-heptaCDF, 26–72; total heptaCDFs, 30–260; and octaCDF, not detected to 270 (Reed et al. 1990). The concentrations (ppt) of CDFs in soils adjacent to a refuse incineration facility in Hamilton, Ontario, were as follows: total tetraCDFs, not detected to 71; total pentaCDFs, not detected to 6.0; total hexaCDFs, not detected; total heptaCDFs, not detected to 180; and octaCDF, not detected to 811 (McLaughlin et al. 1989). These levels were not elevated compared to urban control samples. High levels of CDFs may be detected at hazardous waste sites. For example, 1,2,3,7,8,9-hexaCDF was detected at a concentration of 21 ppm (soil depth unspecified) at a hazardous waste site in Illinois (ATSDR 2017).

Biosolids obtained from wastewater or sewage treatment facilities are applied to agricultural lands in order to add nutrients to the soils used for commercial farming applications. CDFs were detected in biosolids collected in 32 U.S. states and the District of Columbia from 94 wastewater treatment plants by the EPA in its 2001 national sewage sludge survey (EPA 2007a). Minimum levels of CDFs ranged from about 0.1 (2,3,7,8-tetraCDF) to1 ng/kg (octaCDF).

5.5.4 Other Media

The Food and Drug Administration (FDA) conducts Total Diet Studies (TDS) and Market Basket Surveys (MBS) to determine if certain toxic substances are in the U.S. commercial food supply. The TDS is FDA's ongoing market basket survey of approximately 280 food staples in the food supply of America. It can be used to estimate exposures of substances in representative diets of specific age-gender groups in the nation. Typically, four market baskets are collected each year, once in each of four geographic regions of the nation. For each market basket, food samples are collected from commercial grocery stores and fast-food restaurants in three cities within the region, and also prepared table-ready foods (i.e., as they would be consumed). In 2000, the FDA began monitoring for dioxin-like substances including CDFs. Data from the 2004 TDS indicated that CDFs were detected in food items at or above the detection limits in 269 out of 3,944 food items tested (FDA 2007). The highest concentration of CDFs occurred in liver (beef/calf), pan-cooked with oil, which had a concentration of 2.8 pg/g for octaCDF. 2,3,7,8-TCDF was detected in 28 items tested with a maximum concentration of 0.13 pg/g in baked salmon steaks/fillets.

The concentrations of CDFs in meat, fish, and dairy products purchased from a supermarket in upstate New York were 0.14–7.0, 0.07–1.14, and 0.3–5 ppt (pg/g) (wet weight), respectively (Schecter et al. 1993). The concentrations of 2,3,7,8-TCDF in these meat, fish, and dairy products were 0.01–0.1, 0.02–0.73, and 0.02–0.15 ppt (wet weight), respectively (Schecter et al. 1993). Levels of CDF congeners in herring and cod liver were 0.01–1.89 and 0.03–11.16 pg/g, respectively, with the largest values occurring for 2,3,7,8-tetraCDF (Kang et al. 2017). Gonzalez and Domingo (2021) summarized the results of published studies (2010–2021) that reported levels of PCDDs and PCDFs in foods from different originating nations and where available dietary intakes were reported. The study authors noted that there were no recent studies during this reporting period from Canada or the United States. Total CDF levels (sum of all congeners) ranged from 32.7 to 1201.8 pg/kg for plant food samples from five surveyed regions in mainland China (Sun et al. 2021). The highest levels were observed in cereals and beans, while vegetables, edible fungi, and vegetable oils tended to have lower levels. Chen et al. (2021) provided estimated dietary intakes (EDIs) by way of global pork consumption. They reported that total PCDD/PCDF levels in pork products in the United States are 5 times greater than those from Canada and as a result, Canadians consuming pork received 51.9% of the PCDD/PCDFs via the consumption of imported pork from the United States.

A large number of data concerning the levels of CDFs in fish collected from different waters are available (De Vault et al. 1989; Gardner and White 1990; Mikolajczyk et al. 2021, 2022; O'Keefe et al. 1984;

Pagano et al. 2018; Petty et al. 1983; Smith et al. 1990b; Zacharewski et al. 1989) and representative data on the concentrations of CDFs are presented in Table 5-12. It is evident from the table that 2,3,7,8-tetraCDF is the prevalent CDF congener present in fish, followed by 2,3,4,7,8-pentaCDF. The concentrations of CDFs are significantly higher in the hepatopancreas than in the meat of crabs and lobster. The levels of CDFs in fish obtained from the Great Lakes have been dropping over the past decades. Pagano et al. (2018) analyzed the trend in 2,3,7,8-tetraCDF concentrations in fish caught in the Great Lakes from 2004 to 2014 and noted a 51.8% decrease in concentrations found in walleye and lake trout over this time frame. A retrospective analysis using data collected over the period of 1977−2014 showed a decrease of 94% for 2,3,7,8-tetraCDF levels in lake trout from Lake Ontario. Levels of 2,3,7,8-tetraCDFs in eggs from mature Chinook and Coho salmon decreased 61.4% between 2004 and 2014 from the Salmon River fish hatchery in Altmar, New York (Garner and Pagano 2019). Levels of 2,3,7,8-tetraCDF decreased from 285±136 pg/g (1989) to 1.31±0.67 pg/g (2012) in white sucker collected from Jackfish Bay and Mountain Bay, Lake Superior following engineering controls applied to a pulp mill, which discharged to these areas (Dahmer et al. 2015). The mean level of total 2,3,7,8-substituted CDFs in gutted whole fish from the St. Maurice River, Quebec, caught immediately downstream of a kraft mill was 260 pg/g (ppt), but the level declined to 112 ppt at 95 km downstream (Hodson et al. 1992). Data on 2,3,7,8-substituted CDF congeners in aquatic fauna were analyzed by principal component analysis. In this method, the congener profile in aquatic fauna can be used to predict the principal source of contamination such as pulp mill effluent, deposition from combustion source, and effluent from magnesium production (Zitko 1992).

Table 5-12. Levels of Chlorodibenzofurans (CDFs) in Fish and Other Aquatic Organisms

Species	Sampling area	CDF	Concentration (ppt [wet weight])	Reference
Striped bass (*Morone saxatilis*), meat	Newark Bay and New York Bight	2,3,7,8-TetraCDF	68.7	Rappe et al. 1991b
		Total tetraCDF	92.5	
		1,2,3,7,8-/1,2,3,4,8-PentaCDF	7.1	
		2,3,4,7,8-PentaCDF	30.3	
		Total pentaCDF	58.5	
		1,2,3,4,7,8-/1,2,3,4,7,9-HexaCDF	1.1	
		1,2,3,6,7,8-HexaCDF	0.4	
		1,2,3,7,8,9-HexaCDF	<0.1	
		2,3,4,6,7,8-HexaCDF	<2.6	
		Total hexaCDF	3.2	
		1,2,3,4,6,7,8-HeptaCDF	1.6	
		1,2,3,4,7,8,9-HeptaCDF	<0.4	
		OctaCDF	<3.0	

Table 5-12. Levels of Chlorodibenzofurans (CDFs) in Fish and Other Aquatic Organisms

Species	Sampling area	CDF	Concentration (ppt [wet weight])	Reference
Blue crab (*Callinectes sapidus*), meat	Newark Bay and New York Bight	2,3,7,8-TetraCDF	13.3	Rappe et al. 1991b
		Total tetraCDF	148.7	
		1,2,3,7,8-/1,2,3,4,8-PentaCDF	5.5	
		2,3,4,7,8-PentaCDF	7.3	
		Total pentaCDF	91.9	
		1,2,3,4,7,8-/1,2,3,4,7,9-HexaCDF	2.6	
		1,2,3,6,7,8-HexaCDF	0.6	
		1,2,3,7,8,9-HexaCDF	<0.2	
		2,3,4,6,7,8-HexaCDF	<2.3	
		Total hexaCDF	9.4	
		1,2,3,4,6,7,8-HeptaCDF	3.2	
		1,2,3,4,7,8,9-HeptaCDF	<0.9	
		Total Hepta CDF	3.2	
		OctaCDF	<7.1	
Blue crab (*C. sapidus*), hepatopancreas	Newark Bay and New York Bight	2,3,7,8-TetraCDF	628.3	Rappe et al. 1991b
		Total tetraCDF	7,049.3	
		1,2,3,7,8-/1,2,3,4,8-PentaCDF	185.7	
		2,3,4,7,8-PentaCDF	391.4	
		Total pentaCDF	4,219.1	
		1,2,3,4,7,8-/1,2,3,4,7,9-HexaCDF	261.0	
		1,2,3,6,7,8-HexaCDF	43.3	
		1,2,3,7,8,9-HexaCDF	<5.0	
		2,3,4,6,7,8-HexaCDF	9.8	
		Total hexaCDF	803.3	
		1,2,3,4,6,7,8-HeptaCDF	184.6	
		1,2,3,4,7,8,9-HeptaCDF	7.1	
		OctaCDF	<51	
Lobster (*Homarus americanus*), meat	Newark Bay and New York Bight	2,3,7,8-TetraCDF	<0.3	Rappe et al. 1991b
		Total tetraCDF	27.1	
		1,2,3,7,8-/1,2,3,4,8-PentaCDF	2.4	
		2,3,4,7,8-PentaCDF	1.8	
		Total pentaCDF	33.6	
		1,2,3,4,7,8-/1,2,3,4,7,9-HexaCDF	0.4	
		1,2,3,6,7,8-HexaCDF	<0.2	
		1,2,3,7,8,9-HexaCDF	<0.2	
		2,3,4,6,7,8-HexaCDF	<2.0	
		Total hexaCDF	7.8	
		1,2,3,4,6,7,8-HeptaCDF	<0.9	
		1,2,3,4,7,8,9-HeptaCDF	<0.9	
		OctaCDF	<7.7	

Table 5-12. Levels of Chlorodibenzofurans (CDFs) in Fish and Other Aquatic Organisms

Species	Sampling area	CDF	Concentration (ppt [wet weight])	Reference
Lobster (*H. americanus*), hepatopancreas	Newark Bay and New York Bight	2,3,7,8-TetraCDF	365.7	Rappe et al. 1991b
		Total tetraCDF	1,568.6	
		1,2,3,7,8-/1,2,3,4,8-PentaCDF	79.5	
		2,3,4,7,8-PentaCDF	179.2	
		Total pentaCDF	1,008.4	
		1,2,3,4,7,8-/1,2,3,4,7,9-HexaCDF	10.7	
		1,2,3,6,7,8-HexaCDF	<6.0	
		1,2,3,7,8,9-HexaCDF	<3.0	
		2,3,4,6,7,8-HexaCDF	7.0	
		Total hexaCDF	172.1	
		1,2,3,4,6,7,8-HeptaCDF	<3.8	
		1,2,3,4,7,8,9-HeptaCDF	<3.8	
		OctaCDF	<29.2	
Lobster (*H. americanus*), digestive gland	Mipamichi Bay and Limestone Point, New Brunswick; Sydney Harbor and Port Morien, Nova Scotia	Total tetraCDF	189.8	Clement et al. 1987b
		Total pentaCDF	52.2	
		Total hexaCDF	37.9	
		Total heptaCDF	<9.1	
		OctaCDF	(2–10)[a]	
Carp (*Cyprinus carpio*); Coho salmon (*Oncorhynchus kitutch*); lake trout (*Salvelimus namayeush*); bloater (*Copegonus hoyi*); brown trout (*Salmo trutta*); walleye trout (*Stizostedion vitreum vitreum*), composite	Lake Ontario	Total pentaCDFs	1,015	Stalling et al. 1985
		Total tetraCDFs	327	

Table 5-12. Levels of Chlorodibenzofurans (CDFs) in Fish and Other Aquatic Organisms

Species	Sampling area	CDF	Concentration (ppt [wet weight])	Reference
Lake trout (*S. namaycush*); walleye trout (*S. vitreum vitreum*), composite	Lake St. Clair	2,3,7,8-TetraCDF	24.8	Zacharewski et al. 1989
		1,2,3,7,8-PentaCDF	3.7	
		2,3,4,7,8-PentaCDF	5.4	
		1,2,3,4,7,8-HexaCDF	0.5	
		1,2,3,6,7,8-HexaCDF	0.5	
		1,2,3,7,8,9-HexaCDF	<0.05	
		2,3,4,6,7,8-HexaCDF	0.9	
		1,2,3,4,6,7,8-HeptaCDF	0.5	
		1,2,3,4,7,8,9-HeptaCDF	<0.2	
		OctaCDF	0.8	
Lake trout (*S. namaycush*); walleye trout (*S. vitreum vitreum*), composite	Lake Michigan	2,3,7,8-TetraCDF	34.8	Zacharewski et al. 1989
		1,2,3,7,8-PentaCDF	4.9	
		2,3,4,7,8-PentaCDF	10.2	
		1,2,3,4,7,8-HexaCDF	1.4	
		1,2,3,6,7,8-HexaCDF	1.1	
		1,2,3,7,8,9-HexaCDF	<0.05	
		2,3,4,6,7,8-HexaCDF	1.3	
		1,2,3,4,6,7,8-HeptaCDF	0.9	
		1,2,3,4,7,8,9-HeptaCDF	<0.2	
		OctaCDF	<0.2	
Lake trout (*S. namaycush*); walleye trout (*S. vitreum vitreum*), composite	Lake Ontario	2,3,7,8-TetraCDF	20.6	Zacharewski et al. 1989
		1,2,3,7,8-PentaCDF	4.7	
		2,3,4,7,8-PentaCDF	20.2	
		1,2,3,4,7,8-HexaCDF	12.7	
		1,2,3,6,7,8-HexaCDF	1.9	
		1,2,3,7,8,9-HexaCDF	<0.1	
		2,3,4,6,7,8-HexaCDF	1.2	
		1,2,3,4,6,7,8-HeptaCDF	0.9	
		1,2,3,4,7,8,9-HeptaCDF	<0.1	
		OctaCDF	<0.9	
Lake trout (*S. namaycush*); walleye trout (*S. vitreum vitreum*), composite	Lake Huron	2,3,7,8-TetraCDF	22.8	Zacharewski et al. 1989
		1,2,3,7,8-PentaCDF	6.2	
		2,3,4,7,8-PentaCDF	12.8	
		1,2,3,4,7,8-HexaCDF	1.6	
		1,2,3,6,7,8-HexaCDF	1.2	
		1,2,3,7,8,9-HexaCDF	<0.07	
		2,3,4,6,7,8-HexaCDF	1.4	
		1,2,3,4,6,7,8-HeptaCDF	0.5	
		1,2,3,4,7,8,9-HeptaCDF	<0.1	
		OctaCDF	<0.3	

Table 5-12. Levels of Chlorodibenzofurans (CDFs) in Fish and Other Aquatic Organisms

Species	Sampling area	CDF	Concentration (ppt [wet weight])	Reference
Lake trout (*S. namaycush*); walleye trout (*S. vitreum vitreum*), composite	Lake Erie	2,3,7,8-TetraCDF 1,2,3,7,8-PentaCDF 2,3,4,7,8-PentaCDF 1,2,3,4,7,8-HexaCDF 1,2,3,6,7,8-HexaCDF 1,2,3,7,8,9-HexaCDF 2,3,4,6,7,8-HexaCDF 1,2,3,4,6,7,8-HeptaCDF 1,2,3,4,7,8,9-HeptaCDF OctaCDF	11.3 1.4 2.7 0.2 0.3 <0.1 0.5 0.6 <0.2 <1.1	Zacharewski et al. 1989
Lake trout (*S. namaycush*); walleye trout (*S. vitreum vitreum*), composite	Lake Superior	2,3,7,8-TetraCDF 1,2,3,7,8-PentaCDF 2,3,4,7,8-PentaCDF 1,2,3,4,7,8-HexaCDF 1,2,3,6,7,8-HexaCDF 1,2,3,7,8,9-HexaCDF 2,3,4,6,7,8-HexaCDF 1,2,3,4,6,7,8-HeptaCDF 1,2,3,4,7,8,9-HeptaCDF OctaCDF	15.7 1.7 2.8 0.5 0.3 <0.06 0.4 0.4 <0.2 <0.8	Zacharewski et al. 1989
Sperm whales	Mediterranean Ocean	ΣCDFs	23.9–35.9	Bartalini et al. 2019
Walleye	Lake Erie	2,3,7,8-TetraCDF	9.52 (average)	Pagano et al. 2018
Walleye	Lake Erie	2,3,7,8-TetraCDF	3.24 (average)	Pagano et al. 2018
Lake trout	Lake Erie	2,3,7,8-TetraCDF	10.0 (average)	Pagano et al. 2018
Lake trout	Lake Huron	2,3,7,8-TetraCDF	26.86 (average)	Pagano et al. 2018
Lake trout	Lake Michigan	2,3,7,8-TetraCDF	16.10 (average)	Pagano et al. 2018
Lake trout	Lake Ontario	2,3,7,8-TetraCDF	17.84 (average)	Pagano et al. 2018
Lake trout	Lake Superior	2,3,7,8-TetraCDF	12.58 (average)	Pagano et al. 2018
Lake trout	Lake Superior	2,3,7,8-TetraCDF	7.46 (average)	Pagano et al. 2018
Roach	Rybnicki, Poland	2,3,7,8-teraCDF 1,2,3,7,8-PentaCDF 2,3,4,7,8-PentaCDF 1,2,3,4,7,8-HexaCDF 1,2,3,6,7,8-HexaCDF 1,2,3,7,8,9 -HexaCDF 2,3,4,6,7,8-HexaCDF 1,2,3,4,6,7,8-HeptaCDF 1,2,3,4,7,8,9-HeptaCDF OctaCDF	0.204–0.734 0.048–0.249 0.020–0.250 <0.021–0.026 <0.006–0.019 <0.004 <0.002–0.024 <0.017 <0.006–0.012 <0.05	Mikolajczyk et al. 2022

Table 5-12. Levels of Chlorodibenzofurans (CDFs) in Fish and Other Aquatic Organisms

Species	Sampling area	CDF	Concentration (ppt [wet weight])	Reference
Bream	Rybnicki, Poland	2,3,7,8-TCDF	0.526–5.099	Mikolajczyk et al. 2022
		1,2,3,7,8-PentaCDF	0.091–0.890	
		2,3,4,7,8-PentaCDF	0.180–2.030	
		1,2,3,4,7,8-HexaCDF	0.047–0.424	
		1,2,3,6,7,8-HexaCDF	0.031–0.318	
		1,2,3,7,8,9 -HexaCDF	<0.004	
		2,3,4,6,7,8-HexaCDF	0.026–0.248	
		1,2,3,4,6,7,8-HeptaCDF	0.019–0.116	
		1,2,3,4,7,8,9-HeptaCDF	0.007–0.017	
		OctaCDF	<0.05	
Roach	Maróz Poland	2,3,7,8-teraCDF	0.083–0.184	Mikolajczyk et al. 2022
		1,2,3,7,8-PentaCDF	<0.011–0.013	
		2,3,4,7,8-PentaCDF	0.024–0.050	
		1,2,3,4,7,8-HexaCDF	<0.021	
		1,2,3,6,7,8-HexaCDF	<0.006	
		1,2,3,7,8,9 -HexaCDF	<0.004	
		2,3,4,6,7,8-HexaCDF	<0.002–0.007	
		1,2,3,4,6,7,8-HeptaCDF	<0.017–0.021	
		1,2,3,4,7,8,9-HeptaCDF	<0.006–0.007	
		OctaCDF	<0.05	
Bream	Maróz Poland	2,3,7,8-teraCDF	0.138–0.331	Mikolajczyk et al. 2022
		1,2,3,7,8-PentaCDF	0.017–0.069	
		2,3,4,7,8-PentaCDF	0.046–0.159	
		1,2,3,4,7,8-HexaCDF	0.026–0.044	
		1,2,3,6,7,8-HexaCDF	0.008–0.025	
		1,2,3,7,8,9 -HexaCDF	<0.004	
		2,3,4,6,7,8-HexaCDF	0.004–0.021	
		1,2,3,4,6,7,8-HeptaCDF	<0.017–0.022	
		1,2,3,4,7,8,9-HeptaCDF	<0.006–0.010	
		OctaCDF	<0.05	
Pike	Maróz Poland	2,3,7,8-teraCDF	0.032–0.163	Mikolajczyk et al. 2022
		1,2,3,7,8-PentaCDF	0.019–0.024	
		2,3,4,7,8-PentaCDF	0.007–0.061	
		1,2,3,4,7,8-HexaCDF	<0.021–0.088	
		1,2,3,6,7,8-HexaCDF	0.006–0.009	
		1,2,3,7,8,9 -HexaCDF	<0.004	
		2,3,4,6,7,8-HexaCDF	0.003–0.010	
		1,2,3,4,6,7,8-HeptaCDF	<0.017	
		1,2,3,4,7,8,9-HeptaCDF	<0.006–0.009	
		OctaCDF	<0.05	

Table 5-12. Levels of Chlorodibenzofurans (CDFs) in Fish and Other Aquatic Organisms

Species	Sampling area	CDF	Concentration (ppt [wet weight])	Reference
Pike	Lipczyno Wielkie Poland	2,3,7,8-teraCDF 1,2,3,7,8-PentaCDF 2,3,4,7,8-PentaCDF 1,2,3,4,7,8-HexaCDF 1,2,3,6,7,8-HexaCDF 1,2,3,7,8,9 -HexaCDF 2,3,4,6,7,8-HexaCDF 1,2,3,4,6,7,8-HeptaCDF 1,2,3,4,7,8,9-HeptaCDF OctaCDF	0.072–0.709 <0.011–0.165 0.016–0.416 <0.021–0.028 <0.006–018 <0.004 <0.002–015 <0.017–0.022 <0.006–0.011 <0.05	Mikolajczyk et al. 2022
Bream	Łańskie, Poland	2,3,7,8-teraCDF 1,2,3,7,8-PentaCDF 2,3,4,7,8-PentaCDF 1,2,3,4,7,8-HexaCDF 1,2,3,6,7,8-HexaCDF 1,2,3,7,8,9 -HexaCDF 2,3,4,6,7,8-HexaCDF 1,2,3,4,6,7,8-HeptaCDF 1,2,3,4,7,8,9-HeptaCDF OctaCDF	0.147–1.160 0.013–0.165 0.053–0.407 0.066–0.090 0.039–0.049 <0.004 0.003–030 0.023–0.028 <0.006 <0.05	Mikolajczyk et al. 2022
Salmon	Baltic Sea	2,3,7,8-teraCDF 2,3,4,7,8-PentaCDF	~6 ~3	Mikolajczyk et al. 2021
Trout	Baltic Sea	2,3,7,8-teraCDF 2,3,4,7,8-PentaCDF	~4 ~2	Mikolajczyk et al. 2021
Herring	Baltic Sea	2,3,7,8-teraCDF 2,3,4,7,8-PentaCDF	~2 ~0.9	Mikolajczyk et al. 2021
Cod	Baltic Sea	2,3,7,8-teraCDF 2,3,4,7,8-PentaCDF	~0.10 ~0.06	Mikolajczyk et al. 2021
Flounder	Baltic Sea	2,3,7,8-teraCDF 2,3,4,7,8-PentaCDF	~2 ~1	Mikolajczyk et al. 2021
Sprat	Baltic Sea	2,3,7,8-teraCDF 2,3,4,7,8-PentaCDF	~2–3 ~2–4	Mikolajczyk et al. 2021
Lake trout	Lake Champlain	2,3,7,8-teraCDF	9.215–27.898 (14.776 average)	Pagano and Garner 2020

[a] Detection limit.

CDF levels have been measured in a multitude of environmental samples, including cork and wall paper (Frommberger 1991); foods of animal and vegetable origin (Furst et al. 1990; Glidden et al. 1990; Ryan et al. 1985b; Schecter et al. 1989b); commercial detergents and related products (Rappe et al. 1990b); coffee filters (Fricker and Hardy 1990; LeBel et al. 1992; Wiberg et al. 1989); several consumers products, including diapers, shopping bags, cigarette paper, tampons, and cotton (LeBel et al. 1992; Wiberg et al. 1989); paper products (LeBel et al. 1992; Keenan and Sullivan 1989); latex nipples (Gorski 1981); pine needles (Safe et al. 1992); marine mammals (Norstrom et al. 1990); and eggs of Great Blue Herons (Elliott et al. 1989). Comparison of data for bulk milk and milk in cartons indicates that 2,3,7,8-tetraCDF migrates in small amounts from some bleached paper cartons to bulk milk (Glidden et al. 1990; Ryan et al. 1992). The transfer of CDFs from cardboard and plastic-coated bleached paperboard milk cartons to bulk milk has been observed by other investigators (Beck et al. 1990b; Ryan et al. 1992). The mean concentrations of tetraCDF in bond paper composite, paper towel composite, and composite diaper pulp were 265, 33, and 8 ppt, respectively (Keenan and Sullivan 1989). The concentrations of 2,3,7,8-tetraCDF in bleached coffee filters, shopping bags, and tampons were 22, 7.6, and 0.9 ppt, respectively (Wiberg et al. 1989). On the other hand, no CDFs (detection limit ≤1 ppt) were detected in commercially available coffee filters in the United States (Fricker and Hardy 1990).

The percent migration of 2,3,7,8-tetraCDF from commercial articles of food contact products (e.g., milk packaged in cartons, coffee filters, paper cups and plates, popcorn bags) to foods may range from 0.1 to 35% under normal use conditions (Cramer et al. 1991). Therefore, the concentration of CDFs in packaged whole milk depends on the packaging material. Usually, commercial milk packaged in glass contains less CDFs than milk packaged in cartons (Rappe et al. 1990c). The mean concentration of 2,3,7,8-tetraCDF in whole milk packaged in cartons from California was 0.45 pg/g wet weight (Hayward et al. 1991). All other 2,3,7,8-substituted CDFs were either not detected or detected at very low levels (Hayward et al. 1991). Commercial milk from Sweden contained significant levels of other 2,3,7,8-substituted CDFs (Rappe et al. 1990c). The intake of CDDs/CDFs from all bleached paper food-contact articles was estimated to be 8.8 pg toxic equivalent/person/day (Cramer et al. 1991). However, with the reduction of CDD/CDF levels in paper pulp available at the present time, the exposure may be considerably less than this estimate (Cramer et al. 1991).

The levels of CDFs in the tissues of aquatic and terrestrial birds and in dolphins from contaminated areas are also available (Ankley et al. 1993; Jarman et al. 1993; Jones et al. 1993; Kuehl et al. 1991). Generally, CDDs/CDFs contribute a small portion of the total TCDD-equivalent toxicity in aquatic birds, while most of the TCDD-equivalent toxicity is contributed by non-ortho-substituted PCBs. In terrestrial birds, the contribution of CDDs/CDFs towards the total TCDD-equivalent toxicity is greater than in aquatic birds (Jones et al. 1993).

5.6 GENERAL POPULATION EXPOSURE

The general population is primarily exposed to CDFs by ingestion of foods containing these substances. Exposure may also occur through inhalation of air, ingestion of drinking water, and use of certain consumer products. Since the concentrations of CDFs in ambient air and drinking water are low (see Section 5.5), the intake of CDFs by inhalation and ingestion of drinking water would be low. It has been shown that inhalation exposure was not a major pathway of human exposure to CDFs (Travis and Hattemer-Frey 1989). The estimate that inhalation exposure contributes 2% of the total average human intake of CDDs/CDFs (Hattemer-Frey and Travis 1989) has been questioned as too low by other investigators (Goldfarb and Harrad 1991). The concentrations of CDD/CDF in foods consumed by a typical German were determined, and the intake of total CDD/CDF from food expressed as TEQ to 2,3,7,8-TCDD was estimated to be 1.2 pg TEQ/kg body weight/day (international dioxin toxic equivalent) (Fürst et al. 1990). The estimated intake of CDD/CDF from typical Canadian food was 1.5 pg TEQ/kg body weight/day (Birmingham et al. 1989a). From detailed determinations of the levels of TCDD/TCDF in air, water, soil, food, and consumer products in Canada, the estimated intakes of CDD/CDF were 0.07 pg TEQ/kg body weight/day from air, 0.002 pg TEQ/kg body weight/day from water, 0.02 pg TEQ/kg body weight/day from ingestion of soil, 2.328 pg TEQ/kg body weight/day from food, and 0.005 pg TEQ/kg body weight/day from consumer products (Birmingham et al. 1989b). Therefore, based on toxic equivalency, inhalation constitutes 2.9%, ingestion of drinking water constitutes 0.l%, ingestion of soil constitutes 0.8%, ingestion of food constitutes 96% and consumer products constitutes the residual 0.2% of the estimated total daily intake of TCDDs/TCDFs. The estimated daily intakes of 2,3,7,8-tetraCDF and 2,3,4,7,8-pentaCDF in the United States are 0.05 and 0.068 ng, respectively (Graham et al. 1986), but data for the daily intake of total CDFs and all of the 2,3,7,8-substituted CDFs from the different routes of exposure in the United States were not located. However, data for the daily intake of the combination of CDDs and CDFs from different exposure routes in Canada are available. The total average daily intake of CDDs/CDFs in industrialized countries is estimated at 1.9 pg TEQ/kg body weight/day (Fishbein 1992).

The levels of CDFs as reported in the Fourth National Report on Human Exposure to Environmental Chemicals NHANES in blood serum levels in 1999–2000, 2001–2002, and 2003–2004 are shown in Table 5-13 (CDC 2021). After 2003–2004, CDF levels were measured in pooled samples. Pooled samples are used when larger sample volumes are needed to improve the sensitivity of the measurements and to reduce the number of samples being analyzed, balancing the cost of the analysis against a low frequency of detectable results. The weighted arithmetic means for age groups, races, and sexes for

1999–2004 surveys are presented in Table 5-14. Serum levels are presented as pg/g of total lipid or ppt on a lipid-weight basis. These compounds are lipophilic and concentrate in the body's lipids, including the lipid in serum. Serum levels reported per gram of total lipid reflect the amount of these compounds stored in body fat.

Table 5-13. Chlorodibenzofuran (CDF) Levels (pg/g Lipid) in the U.S. Population 1999–2004

Congener	1999–2000		2001–2002		2003–2004	
	Geometric Mean	90th percentile	Geometric Mean	90th percentile	Geometric Mean	90th percentile
1,2,3,4,6,7,8-HeptaCDF[a]	*[b]	14.7	9.64	21.3	*	14.6
1,2,3,4,7,8,9-HeptaCDF[c]	No data		*	<LOD	*	<LOD
1,2,3,4,7,8-HexaCDF[d]	*	<LOD	*	12.1	*	7.50
1,2,3,6,7,8-HexaCDF[e]	*	<LOD	*	10.4	*	14.0
1,2,3,7,8,9-HexaCDF[f]	*	<LOD	*	<LOD	*	<LOD
2,3,4,6,7,8-HexaCDF[g]	*	<LOD	*	<LOD	*	<LOD
OctaCDF[h]	*	<LOD	*	<LOD	*	<LOD
1,2,3,7,8-PentaCDF[i]	*	<LOD	*	<LOD	*	<LOD
2,3,4,7,8-PentaCDF[j]	*	<LOD	*	14.3	*	9.90
2,3,7,8-TetraCDF[k]	*	<LOD	*	<LOD	*	<LOD

[a] Asterisk indicates that a geometric mean was not calculated because the proportion of results below the limit of detection (LOD) was too high to provide a valid result.
[b] LODs for survey years 1999–2000, 2001–2002, and 2003–2004 were 13.5, 7.0, and 8.6 pg/g lipid, respectively.
[c] LODs for survey years 2001–2002 and 2003–2004 were 7.0 and 8.6 pg/g lipid, respectively.
[d] LODs for survey years 1999–2000, 2001–2002, and 2003–2004 were 12.7, 6.5, and 7.4 pg/g lipid, respectively.
[e] LODs for survey years 1999–2000, 2001–2002, and 2003–2004 were 12.6, 6.1, and 7.9 pg/g lipid, respectively.
[f] LODs for survey years 1999–2000, 2001–2002, and 2003–2004 were 12.7, 6.0, and 8.3 pg/g lipid, respectively.
[g] LODs for survey years 1999–2000, 2001–2002, and 2003–2004 were 12.9, 5.8, and 8.2 pg/g lipid, respectively.
[h] LODs for survey years 1999–2000, 2001–2002, and 2003–2004 were 35.6, 21.0, and 12.0 pg/g lipid, respectively.
[i] LODs for survey years 1999–2000, 2001–2002, and 2003–2004 were 13.2, 5.8, and 7.1 pg/g lipid, respectively.
[j] LODs for survey years 1999–2000, 2001–2002, and 2003–2004 were 12.7, 5.5, and 6.8 pg/g lipid, respectively.
[k] LODs for survey years 1999–2000, 2001–2002, and 2003–2004 were 11.9, 5.2, and 6.0 pg/g lipid, respectively.

Source: CDC 2021

Table 5-14. Chlorodibenzofuran (CDF) Levels (pg/g Lipid) in the U.S. Population 2005–2010

	2005–2006				2007–2008				2009–2010			
	Age (years)											
Congener	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+
1,2,3,4,6,7,8-HeptaCDF[a]												
Non-Hispanic Whites												
Males	12.5	7.09	8.33	8.16	12.0	8.07	7.42	7.24	7.93	6.63	7.00	6.32
Females	7.63	6.94	6.85	7.74	8.74	8.22	7.00	8.12	7.84	6.26	4.96	6.30
Non-Hispanic Blacks												
Males	10.8	8.24	7.85	10.6	10.2	7.61	7.10	7.78	7.62	5.58	6.14	5.43
Females	8.80	6.20	6.35	10.5	8.73	7.86	9.30	8.95	7.11	5.24	5.09	7.45
Mexican Americans												
Males	9.25	6.57	7.45	7.18	8.38	8.14	6.77	6.33	8.90	7.22	5.63	7.47
Females	5.61	6.00	8.74	6.28	8.97	7.42	6.36	6.66	5.49	6.11	6.64	8.50
All Hispanics												
Males	ND	ND	ND	ND	ND	ND	ND	ND	9.87	7.48	5.43	7.24
Females	ND	ND	ND	ND	ND	ND	ND	ND	5.81	5.76	6.65	7.04
1,2,3,4,7,8,9-HeptaCDF[b]												
Non-Hispanic Whites												
Males	*[c]	*	*	*	*	*	*	*	*	*	*	*
Females	*	*	*	*	*	*	*	*	*	*	*	*
Non-Hispanic Blacks												
Males	*	*	*	*	*	*	*	*	*	*	*	*
Females	*	*	*	*	*	*	*	*	*	*	*	*

Table 5-14. Chlorodibenzofuran (CDF) Levels (pg/g Lipid) in the U.S. Population 2005–2010

	2005–2006				2007–2008				2009–2010			
	Age (years)											
Congener	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+
Mexican Americans												
Males	*	*	*	*	*	*	*	*	*	*	*	*
Females	*	*	*	*	*	*	*	*	*	*	*	*
All Hispanics												
Males	ND	ND	ND	ND	ND	ND	ND	ND	*	*	*	*
Females	ND	ND	ND	ND	ND	ND	ND	ND	*	*	*	*
1,2,3,4,7,8-HexaCDF[d]												
Non-Hispanic Whites												
Males	2.18	2.51	4.55	5.40	2.58	3.13	3.78	4.80	2.03	2.50	4.11	4.31
Females	1.71	2.36	3.58	5.54	1.76	2.29	3.24	5.29	1.61	2.09	2.77	4.06
Non-Hispanic Blacks												
Males	1.79	2.61	3.33	5.35	1.87	2.68	3.69	4.49	1.45	1.59	2.52	3.36
Females	1.25	2.14	3.37	8.98	1.53	2.17	3.61	6.68	1.46	1.76	2.94	6.00
Mexican Americans												
Males	1.67	2.29	3.28	4.09	1.30	2.70	2.97	3.52	1.74	2.52	2.94	5.04
Females	1.30	1.83	3.15	4.45	*	2.06	2.71	4.69	1.10	1.60	2.74	4.68
All Hispanics												
Males	ND	ND	ND	ND	ND	ND	ND	ND	1.73	2.28	2.88	4.30
Females	ND	ND	ND	ND	ND	ND	ND	ND	1.19	1.65	2.75	4.35
1,2,3,6,7,8-HexaCDF[e]												
Non-Hispanic Whites												
Males	2.46	2.68	4.91	5.44	3.09	2.98	3.97	4.82	2.21	2.71	4.62	4.41
Females	1.91	2.43	3.68	5.51	1.71	2.44	3.30	5.04	1.70	2.30	3.08	4.58

Table 5-14. Chlorodibenzofuran (CDF) Levels (pg/g Lipid) in the U.S. Population 2005–2010

	2005–2006				2007–2008				2009–2010			
	Age (years)											
Congener	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+
Non-Hispanic Blacks												
Males	1.81	2.28	3.00	5.27	2.04	2.32	3.42	4.38	1.62	1.66	2.68	3.73
Females	1.26	2.02	2.97	7.44	1.19	2.21	3.17	5.96	1.57	1.80	2.93	5.43
Mexican Americans												
Males	1.68	2.25	3.18	4.31	1.80	2.09	3.00	4.01	1.99	2.49	2.95	4.80
Females	1.42	1.87	2.88	4.10	*	2.13	2.82	4.74	1.47	1.76	2.88	4.61
All Hispanics												
Males	ND	ND	ND	ND	ND	ND	ND	ND	1.97	2.25	2.93	4.19
Females	ND	ND	ND	ND	ND	ND	ND	ND	1.48	1.78	2.91	4.27
1,2,3,7,8,9-HexaCDF[f]												
Non-Hispanic Whites												
Males	*[c]	*	*	*	*	*	*	*	*	*	*	*
Females	*	*	*	*	*	*	*	*	*	*	*	*
Non-Hispanic Blacks												
Males	*	*	*	*	*	*	*	*	*	*	*	*
Females	*	*	*	*	*	*	*	*	*	*	*	*
Mexican Americans												
Males	*	*	*	*	*	*	*	*	*	*	*	*
Females	*	*	*	*	*	*	*	*	*	*	*	*
All Hispanics												
Males	ND	ND	ND	ND	ND	ND	ND	ND	*	*	*	*
Females	ND	ND	ND	ND	ND	ND	ND	ND	*	*	*	*

Table 5-14. Chlorodibenzofuran (CDF) Levels (pg/g Lipid) in the U.S. Population 2005–2010

	2005–2006				2007–2008				2009–2010			
	Age (years)											
Congener	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+
2,3,4,6,7,8-HexaCDF[g]												
Non-Hispanic Whites												
Males	0.555	0.882	1.40	1.31	*	0.782	1.08	1.09	0.743	0.960	1.38	1.19
Females	*	0.714	1.00	1.18	*	*	*	0.803	0.685	0.910	1.00	1.01
Non-Hispanic Blacks												
Males	0.418	1.23	0.794	0.969	*	*	0.6950	0.699	0.404	0.648	0.677	0.750
Females	*	0.528	0.773	1.11	*	*	*	*	0.540	0.601	0.821	0.955
Mexican Americans												
Males	0.481	0.825	1.15	1.16	*	*	*	*	0.836	1.13	1.08	1.52
Females	*	0.784	1.09	0.926	*	*	*	*	0.438	0.733	1.13	1.27
All Hispanics												
Males	ND	ND	ND	ND	ND	ND	ND	ND	0.760	0.971	1.12	1.45
Females	ND	ND	ND	ND	ND	ND	ND	ND	0.437	0.710	1.07	1.12
OctaCDF[h]												
Non-Hispanic Whites												
Males	*	1.80	1.44	*	3.27	2.48	2.07	2.08	*	*	*	*
Females	1.83	*	1.55	1.95	2.92	1.96	2.17	2.14	*	*	*	*
Non-Hispanic Blacks												
Males	*	*	2.25	2.72	3.08	4.10	1.90	2.15	*	*	*	*
Females	2.95	3.42	3.09	3.28	2.11	2.86	2.93	2.37	*	*	*	*
Mexican Americans												
Males	*	*	*	*	2.65	2.90	1.88	1.77	*	*	*	*
Females	*	*	2.06	*	3.11	3.04	2.78	2.63	*	*	*	*

Table 5-14. Chlorodibenzofuran (CDF) Levels (pg/g Lipid) in the U.S. Population 2005–2010

	2005–2006				2007–2008				2009–2010			
	Age (years)											
Congener	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+
All Hispanics												
Males	ND	ND	ND	ND	ND	ND	ND	ND	*	*	*	*
Females	ND	ND	ND	ND	ND	ND	ND	ND	*	*	*	*
1,2,3,7,8-PentaCDF[i]												
Non-Hispanic Whites												
Males	*[c]	*	*	*	*	*	*	*	*	*	*	*
Females	*	*	*	*	*	*	*	*	*	*	*	*
Non-Hispanic Blacks												
Males	*	*	*	*	*	*	*	*	*	*	*	*
Females	*	*	*	*	*	*	*	*	*	*	*	*
Mexican Americans												
Males	*	*	*	*	*	*	*	*	*	*	*	*
Females	*	*	*	*	*	*	*	*	*	*	*	*
All Hispanics												
Males	ND	ND	ND	ND	ND	ND	ND	ND	*	*	*	*
Females	ND	ND	ND	ND	ND	ND	ND	ND	*	*	*	*
2,3,4,7,8-PentaCDF[j]												
Non-Hispanic Whites												
Males	2.26	3.45	5.82	8.03	3.20	3.76	5.40	7.32	2.51	3.31	6.16	7.33
Females	1.79	2.70	4.56	8.49	1.97	2.99	4.59	7.82	1.77	2.46	4.22	8.19
Non-Hispanic Blacks												
Males	1.84	3.48	3.86	7.19	2.01	2.61	4.78	6.78	1.35	2.13	3.98	5.62
Females	1.19	2.13	3.98	12.7	1.41	2.09	1.58	9.57	1.39	1.70	4.13	9.52

Table 5-14. Chlorodibenzofuran (CDF) Levels (pg/g Lipid) in the U.S. Population 2005–2010

	2005–2006				2007–2008				2009–2010			
	Age (years)											
Congener	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+
Mexican Americans												
Males	1.67	2.65	3.82	5.90	2.36	3.03	4.45	5.61	2.01	2.82	3.92	8.07
Females	1.00	2.05	3.51	6.10	1.37	2.10	3.79	7.29	*	1.92	3.61	7.10
All Hispanics												
Males	ND	ND	ND	ND	ND	ND	ND	ND	1.96	2.54	4.17	7.10
Females	ND	ND	ND	ND	ND	ND	ND	ND	*	1.96	3.62	6.83
2,3,7,8-TetraCDF[k]												
Non-Hispanic Whites												
Males	*[c]	*	*	*	*	*	0.502	*	*	*	*	*
Females	*	*	*	*	*	*	*	*	*	*	*	*
Non-Hispanic Blacks												
Males	*	*	*	*	*	*	*	*	*	*	*	*
Females	*	*	*	*	*	*	*	*	*	*	*	*
Mexican Americans												
Males	*	*	*	*	*	*	*	*	*	*	*	*
Females	*	*	*	*	*	*	*	*	*	*	*	*

Table 5-14. Chlorodibenzofuran (CDF) Levels (pg/g Lipid) in the U.S. Population 2005–2010

	2005–2006				2007–2008				2009–2010			
	Age (years)											
Congener	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+	12–19	20–39	40–59	60+
All Hispanics												
Males	ND	ND	ND	ND	ND	ND	ND	ND	*	*	*	*
Females	ND	ND	ND	ND	ND	ND	ND	ND	*	*	*	*

[a] Limits of detection (LODs) for survey years 2005–2006, 2007–2008, and 2009–2010 were 0.23, 0.05, and 2.69 pg/g lipid, respectively.
[b] LODs for survey years 2005–2006, 2007–2008, and 2009–2010 were 0.23, 0.33, and 0.49 pg/g lipid, respectively.
[c] Asterisk indicates that a weighted arithmetic mean was not calculated because the proportion of results below the LOD was too high to provide a valid result.
[d] LODs for survey years 2005–2006, 2007–2008, and 2009–2010 were 0.27, 0.39, and 0.78 pg/g lipid, respectively.
[e] LODs for survey years 2005–2006, 2007–2008, and 2009–2010 were 0.1, 0.14, and 0.27 pg/g lipid, respectively.
[f] LODs for survey years 2005–2006, 2007–2008, and 2009–2010 were 0.23, 0.35, and 0.52 pg/g lipid, respectively.
[g] LODs for survey years 2005–2006, 2007–2008, and 2009–2010 were 0.13, 0.2, and 0.3 pg/g lipid, respectively.
[h] LODs for survey years 2005–2006, 2007–2008, and 2009–2010 were 1.17, 1.14, and 3.68 pg/g lipid, respectively.
[i] LODs for survey years 2005–2006, 2007–2008, and 2009–2010 were 0.47, 0.81, and 1.2 pg/g lipid, respectively.
[j] LODs for survey years 2005–2006, 2007–2008, and 2009–2010 were 0.39, 0.38, and 1.3 pg/g lipid, respectively.
[k] LODs for survey years 2005–2006, 2007–2008, and 2009–2010 were 0.3, 0.45, and 0.68 pg/g lipid, respectively.

ND = no data

Source: CDC 2021

LaKind et al. (2009) analyzed data from three NHANES sampling periods spanning 1999–2004 to assess whether there are discernable temporal trends in the United States for exposure to CDFs and CDDs. The authors reported serum CDD/CDF data from 1999 to 2004 suggest that levels of these compounds in the serum of the U.S. population are declining as controls on the emission of these substances have increased. The authors concluded that PCDD/PCDF levels decreased by 56% for the 12–19-year-old group and 38% for the 20–39-year-old group, with a slight nonsignificant decrease for the 40–59-year-old group and a slight significant increase for adults ≥60 years old.

Bloom et al. (2006) analyzed serum levels of CDFs among licensed anglers between 18 and 40 years of age, residing in 16 New York counties proximally to Lake Erie and Lake Ontario. The detection frequency of the most common CDF congeners ranged from 42 to 100% in the serum of the study participants with the exception of 1,2,3,7,8,9-hexaCDF, which was not detected in the serum of any of the study participants.

Xu et al. (2022) summarized the results of pooled samples of serum of women (postpartum, pregnant, and nonpregnant) from Northern Norway during the period of 2007–2009 and in 2019, respectively. The detection frequency was zero percent over both periods for 2,3,7,8-teraCDF, 1,2,3,7,8-pentaCDF, 1,2,3,4,7,8-hexaCDF, 2,3,4,6,7,8-hexaCDF, 1,2,3,7,8,9-hexaCDF, 1,2,3,4,7,8,9-heptaCDF, and octaCDF. The detection frequency decreased from 100 to 75% for 2,3,4,7,8-pentaCDF and 1,2,3,4,6,7,8-heptaCDF from the earlier period to 2019 sampling. The detection frequency of 1,2,3,6,7,8-hexaCDF was 0% in 2007–2009 but increased to 25% in 2019.

Occupational exposure to CDFs may occur. For example, the level of CDFs in the blood of workers in the sawmill industry (exposure to 2,3,4,6-tetrachlorophenolate), textile industry (PCP exposure during fabric impregnation), and leather industry (PCP exposure during tanning) were measured, and the pattern of CDFs in the blood of exposed workers correlated with the CDFs in the exposed compounds (Rappe and Buser 1981). The intake from dermal exposure to CDD/CDF for workers in pulp mill (exposing hands in wet pulp) can be ≤7 pg TEQ/day (Kelada 1990). The concentrations of CDFs in adipose tissues of workers of a chemical plant (producing chlorophenols and 2,4,5-trichlorophenol among other chemicals) was much higher than those of a control population (Beck et al. 1989). Small, but significantly ($p<0.05$) higher, levels of 2,3,4,7,8-pentaCDF and 1,2,3,4,7,8-hexaCDF were found in the lipid-adjusted serum of workers in a pesticide plant (2,4,5-trichlorophenol or its derivatives) compared to the levels in a control group (Piacitelli et al. 1992). Occupational exposure to CDFs may also occur in factories manufacturing and repairing transformers and capacitors, in factories with heat exchange systems containing PCBs, in factories using casting waxes containing PCBs, or in industrial incinerators where materials containing chlorinated phenols, PCBs, and PCB ethers are incinerated (Rappe et al. 1979). The concentrations of CDDs/CDFs expressed as 2,3,7,8-TCDD TEQ in air of a municipal incinerator and an electrical transformer metal reclamation plant were significantly higher than ambient levels for these compounds (Crandall et al. 1992). However, no significant risk of exposure to tetraCDFs was found in modem resource recovery plants in Bristol, Connecticut, and Hillsborough County, Florida (Hahn et al. 1989).

Numerous data are available regarding the levels of CDFs in body tissue and fluids of exposed and background (no obvious source of exposure) populations (Nagayama et al. 1977; Ryan 1986; Schecter et al. 1987; Tiernan et al. 1984; Young 1984). CDFs are lipophilic and tend to concentrate in fatty tissues. A positive correlation between 2,3,4,7,8-pentaCDF, 1,2,3,4,7,8-hexaCDF, and 2,3,4,6,7,8-hexaCDF in adipose tissue and age of donor (higher concentrations at older age) was found (LeBel et al. 1990). A similar correlation between 1,2,3,4,7,8-/1,2,3,6,7,8-hexaCDF and age of donor was also reported among the urban population in California (CARB 1989). No significant correlation between either the level of 2,3,7,8-tetraCDF, 1,2,3,4,6,7,8-heptaCDF, and octaCDF in adipose tissue and age of donor or between any CDFs and sex was discernable (Le Be1 et al. 1990). The latter findings differ from the case of 2,3,7,8-TCDD where higher concentrations of 2,3,7,8-TCDD were detected in female donors than in male donors and a positive correlation between 2,3,7,8-TCDD levels and age of donors was found (Patterson et al. 1986). The average levels of 2,3,7,8-substituted CDFs in human fat of exposed and background populations of different countries have been reviewed (Jensen 1987). Data for the background levels of 2,3,7,8-substituted CDFs in human adipose tissues from different countries are given in Table 5-15. A comparative study of CDF content in liver and adipose tissue of control humans (Germany) showed that on a fat basis, the concentrations of CDFs were higher in the liver than in adipose tissue (Beck et al. 1990b; Thoma et al. 1990). Ten CDF congeners were detected in milk samples collected from 75 mothers in Spain, with 2,3,4,7,8-pentaCDF being the most frequently detected congener (92% detection frequency) and 1,2,3,4,7,8,9-heptaCDF being the least frequently detected congener (29%) (Hernández et al. 2020). 2,3,4,7,8-PentaCDF also had the greatest mean value (1.83 pg/g) of the congeners studied. 2,3,7,8-TetraCDF, 1,2,3,4,6,7,8-heptaCDF, and 1,2,3,7,8-pentaCDF were not detected in amniotic fluid collected from four healthy pregnancies in the United Kingdom; however, 1,2,3,4,7,8-hexaCDF was detected in a sample at a concentration of 45 ng/L (Dusza et al 2022).

Table 5-15. Levels of Chlorodibenzofurans (CDFs) in Human Adipose Tissue

	Sample source and mean concentrations (ppt on fat basis)				
Congener	Japan[a]	Sweden[a]	Germany[a]	Canada[b]	United States[c]
2,3,7,8-TetraCDF	9	3.9	0.9	3.3	9.1[d]
2,3,4,7,8-PentaCDF	25	54	44	33.3	40[e]
1,2,3,4,7,8-HexaCDF	15	6	10	37[f]	9.
1,2,3,6,7,8-HexaCDF	14	5	6.7	37[f]	5.4
2,3,4,6,7,8-HexaCDF	8	2	3.8	5.2	1.8
1,2,3,4,6,7,8-HeptaCDF	No data	11	19.5	37.1	21[e]
OctaCDF	No data	4	<1	12	60[d]

[a] Rappe et al. 1987.
[b] LeBel et al. 1990.
[c] Derived from Rappe 1989, unless otherwise stated.
[d] Stanley et al. 1986.
[e] EPA 1989a.
[f] These isomers were not separated.

Several studies indicate that the levels of CDFs in the adipose tissue of exposed populations exceed the levels detected in background or control populations. For example, adipose tissue levels of CDFs in an exposed patient of the Binghamton State Office Building fire (Schecter and Ryan 1989; Schecter et al. 1985a, 1985b, 1986), Yusho victims in Japan (Miyata et al. 1989; Ryan et al. 1987a), and three patients with fatal PCP poisoning (Ryan et al. 1987b) are all higher than control populations. However, no conclusive evidence of higher CDF exposure was found in seven people exposed during the Missouri dioxin episode and in Vietnam veterans (Kang et al. 1991; Needham et al. 1987). Certain municipal incinerator workers, such as those engaged in ash cleaning are exposed to higher levels of CDFs. The whole blood level of total CDFs in pooled blood of 56 such workers was 102.8 ppt (on lipid basis) compared to 47.0 ppt in pooled blood of 14 control subjects (Schecter et al. 1991a). The concentrations of 2,3,7,8-tetraCDF, 1,2,3,7,8-pentaCDF, 1,2,3,4,7,8-hexaCDF, 1,2,3,7,8,9-hexaCDF, 2,3,4,6,7,8-hexaCDF, 1,2,3,4,7,8,9-heptaCDF, and octaCDF were also higher in the pooled blood of workers compared to pooled blood of control subjects. The estimated BCF for 2,3,7,8-tetraCDF in human fat (on lipid basis) was 591 and was higher than other chlorinated aromatics including PCBs, octachlorostyrene, OCDD, and octaCDF (Geyer et al. 1987).

Data are available on the levels of CDFs in human milk from different countries (Dewailly et al. 1991; Schecter and Gasiewicz 1987a, 1987b; Schecter et al. 1989c). In general, CDF levels seem to be lower in the less industrialized countries than in more industrialized countries. Certain differences in specific isomers may exist in different countries, reflecting sources of contamination (Schecter et al. 1989d). The levels of CDFs in human milk derived from different countries are shown in Table 5-16. Levels of CDFs in human milk from other countries including South and North Vietnam and the former Soviet Union are also available (Schecter et al. 1989c, 1990c). From these data, it appears that the most prevalent congener in human milk is 2,3,4,7,8-pentaCDF, followed by 1,2,3,4,7,8-hexaCDF. In one study, no correlation was found between consumption of contaminated fish and accumulation of CDFs in the milk from nursing mothers (Hayward et al. 1989). During the breastfeeding period, the level of CDFs in milk lipid is highest in the first week and slowly decreases thereafter (Beck et al. 1992; Fürst et al. 1989). The level of CDFs in breast milk is highest for women having their first child and distinctly lower for women having their second and third child (Beck et al. 1992).

Table 5-16. Levels of Chlorodibenzofurans (CDFs) in Human Milk

	Sample source and mean concentrations (ppt on fat basis)			
Congener	Sweden[a]	West Germany[b]	United States[c]	Japan[d]
2,3,7,8-TetraCDF	4.2	1.7	2.85	2.9
1,2,3, 7,8-PentaCDF	<1.0	0.5	0.45	1.0
2,3,4,7,8-PentaCDF	21.3	26.7	7.3	23.0
1,2,3,4,7,8-HexaCDF	4.7	7.8	5.55	3.9
1,2,3,6,7,8-HexaCDF	3	6.5	3.2	2.5
2,3,4,6,7,8-HexaCDF	1.4	3.4	1.85	1.9
1,2,3,4,6,7,8-HeptaCDF	7.4	5.5	4.05	3.3
OctaCDF	3.2	1.4	4.1	<2.0

[a] Rappe et al. 1987.
[b] Fürst et al. 1992.
[c] Schecter et al. 1991b.
[d] Rappe 1992.

The levels of CDFs in human whole blood from various countries are listed in Table 5-17. Plasma levels of CDFs in people from different countries have been measured; the individual congener concentrations on a fat basis in control populations (not exposed to obvious sources of CDFs) vary from a minimum of <0.1 ppt for 2,3,7,8-tetraCDF to a maximum of 80 ppt for 2,3,4,7,8-pentaCDF (Chang et al. 1990; Nygren et al. 1988; Rappe 1991; Schecter 1991). The highest 2,3,4,7,8-pentaCDF concentration was found in a high fish-consuming population around the Baltic Sea (Svensson et al. 1991). The most prevalent congener in human plasma lipids in the United States was 1,2,3,4,6,7,8-heptaCDF, followed by 1,2,3,7,8- and 2,3,4,7,8-pentaCDF. This pattern was reversed in the plasma lipids of Swedish people, where 2,3,4,7,8-pentaCDF was the prevalent congener followed by 1,2,3,4,6,7,8-heptaCDF (Chang et al. 1990). A similar pattern of high 2,3,4,7,8-pentaCDF level in blood was observed in human blood from

Germany (Schecter et al. 1991c). Using a multivariate analysis, the concentration of CDFs in the plasma of exposed Vietnam veterans from the United States were determined to be slightly higher than matched controls (Nygren et al. 1988). It was also determined that higher chlorinated CDFs do not appear to partition according to the lipid content of whole blood. As the degree of chlorination increases, the percent associated with the protein fraction also increases. Therefore, it was concluded that partitioning of higher chlorinated CDFs is not dependent on lipid content, but on specific binding to the protein fraction of serum and whole blood (Patterson et al. 1989; Schecter et al. 1991c).

Table 5-17. Mean Levels of Chlorodibenzofurans (CDFs) in Human Whole Blood (ppt Lipid) from Various Countries

	Germany		United States	Vietnam		
Congener	N=85	SD	N=100[a]	Ho Chi Minh City N=50[a]	Dong Nai N=33[a]	Hanoi N=32[a]
2,3,7,8-TetraCDF	2.5	1.8	3.1	4.6	3.9	26
1,2,3,7,8-PentaCDF	ND		2.8	3.2	2.9	<1.1
2,3,4,7,8-PentaCDF	36.8	18.8	13.0	21	22	8.6
Total pentaCDF	36.8		15.8	24.2	24.	9.2
1,2,3,4,7,8-HexaCDF	17.5[b]		15.0	14.0	27.0	6.5
1,2,3,6,7,8-HexaCDF	13.7[b]		14.0	11.0	27.0	6.4
1,2,3,7,8,9-hexaCDF	ND[b]		ND (1.2)[c]	ND (1.4)[c]	ND (1.2)[c]	ND (1.1)[c]
2,3,4,6,7,8-hexaCDF	ND[b]		3.6	3.3	5	1.8
Total hexaCDF	32.1[b]	20.8	32.6	28.3	59	14.7
1,2,3,4,6,7,8-HeptaCDF	23.8[b]		36.0	22	31	12
1,2,3,4,7,8,9-HeptaCDF	ND[b]		ND (1.8)[c]	2.6	2.7	<1.2
Total heptaCDF	24.1[b]	12.0	3	24.6	33.7	12.6
OctaCDR	5.5	3.5	4.2	ND (5.5)[c]	11.0	<3.0

[a] These samples were pooled into one.
[b] These values are derived from Papke et al. 1989.
[c] The values in the parenthesis are the detection limits.

ND = not detected; SD = standard deviation

Source: Schecter 1991

5.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Workers in industries that manufacture or use chemicals contaminated with CDFs are one segment of the population at high risk for CDF exposure (see Section 5.6). Persons working in the hazardous waste industry or first responders to incidents where CDFs may have been released (e.g., World Trade Center first responders) will be exposed to higher levels than the general population. Although production of

PCBs ceased in the United States over 40 years ago, the use of PCBs is still authorized in transformers and other electrical equipment and accidents involving PCB capacitors and transformers may entail high exposures to CDFs. A study was conducted with 36 firefighters assigned to interior, exterior, and overhaul job assignments, before and after responding to controlled residential fire scenarios. Compared to the general population, firefighters were shown to have statistically significantly higher pre-fire geometric mean serum concentrations of 2,3,4,7,8-pentaCDF, and significantly higher pre- and post-fire geometric mean serum concentrations of 1,2,3,4,7,8-hexaCDF, 1,2,3,6,7,8-hexaCDF, and 2,3,4,6,7,8-hexaCDF.

Among the general population, especially in more industrial countries, higher exposures to CDFs may occur among populations that consume high amounts of fatty fish contaminated with high levels of CDFs (Bloom et al. 2006; Svensson et al. 1991). Several 2,3,7,8-substituted CDFs are present in human milk at concentrations much higher than those in cow milk (Vainio et al. 1989). Therefore, consumption of human milk containing high levels of CDFs may pose a risk to infants consuming breast milk (Schecter and Gasiewicz 1987a, 1987b). Because of the relatively short period of intake and the accepted benefits of breastfeeding, the World Health Organization did not recommend limitations on breastfeeding (Vainio et al. 1989). Another population group that may be exposed to higher concentrations of CDFs includes people who live adjacent to uncontrolled landfill sites with soils containing high concentrations of CDFs. Attic dust and blood levels of dioxin-like compounds were analyzed in a community near a wood treatment facility in southern Alabama (Hensley et al. 2007). It was determined that concentrations of CDDs/CDFs measured in the blood samples of exposed community members exceeded the 1999–2002 NHANES 90th percentile for total dioxin TEQ levels found in the general U.S. adult population.

It is possible that persons residing near emission sources such as hazardous waste incinerators may have the potential for greater exposure to CDFs than the general population; however, recent studies have suggested that the impact that these facilities create for local populations is low. Nadal et al. (2019) analyzed the temporal trends of total CDDs/CDFs in the plasma of residents living in the vicinity of a hazardous waste incinerator that was constructed in 1998 in Catalonia, Spain. Over a 2-decade period (1998–2018), they reported between a 59 and 80% decrease in plasma CDD/CDF levels for these residents depending upon age and gender. They concluded that these decreases were due to reduced dietary intakes of these substances and that the incinerator did not create measurable risk to the health of the population living in the vicinity of the facility. A comprehensive review of 82 studies regarding the biomonitoring of individuals residing near, or working at, hazardous waste incinerators suggested that there was only a low impact on the internal dose of CDD/CDF levels due to emissions from solid waste incinerators (Campo et al. 2019). Similarly, biomonitoring data of a population near a large waste incinerator located in Turin, Italy showed no significant differences in the serum levels of PCDD/PCDFs, and PCBs measured in the population group residing near the plant after 3 years of operation with respect to a control group (Iamiceli et al. 2021).