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

4.1. MOTOR VEHICLE FUEL COMBUSTION

Ballschmiter et al. (1986) reported detecting CDD/CDFs in used motor oil and thus provided some of the first evidence that CDD/CDFs might be emitted by the combustion processes in gasoline- and diesel-fueled engines. Incomplete combustion and the presence of a chlorine source in the form of additives in the oil or the fuel (such as dichloroethane or pentachlorophenate) were speculated to lead to the formation of CDDs and CDFs. The congener patterns found in the used oil samples were characterized by Ballschmiter et al. (1986) as similar to the patterns found in fly ash and stack emissions from municipal waste incinerators.

Since 1986, several studies have been conducted to measure or estimate CDD/CDF concentrations in emissions from vehicles. Although there is no standard approved protocol for measuring CDD/CDFs in vehicle exhausts, researchers have developed and implemented several measurement approaches for collecting and analyzing vehicle exhausts. Other researchers have estimated vehicle exhaust emissions of CDD/CDFs indirectly from studies of tunnel air. The results of these two types of studies are summarized in chronological order in the following Section 4.1.1 and Section 4.1.2. Estimates of national annual CDD/CDF TEQ emissions from on-road motor vehicles fueled with leaded gasoline, unleaded gasoline, and diesel fuel are presented in Section 4.1.3 based on the results of these studies. It should be noted, however, that relatively few tests on emissions from diesel and unleaded gasoline fueled vehicles are available considering the variety and numbers of such vehicles currently in operation, and the range of operational, technical, and environmental conditions in which they are operated. As a result, the emission factors developed in this report for on-road motor vehicles are quite uncertain.

National emission estimates have not been generated in this report for off-road vehicles (i.e., construction and farm vehicles) or stationary sources using these fuel types because of lack of emission factor data; activity level information, however, is presented in this report for these potential source categories.

4.1.1. Tailpipe Emission Studies

Marklund et al. (1987) provided the first direct evidence of the presence of CDDs and CDFs in car emissions based on tailpipe measurements on Swedish cars. Approximately 20 to 220 pg of I-TEQ_{DF} from tetra- and penta-CDD/CDFs were reported per kilometer driven for four cars running on leaded gasoline. For this study, an unleaded gasoline was used to which was added tetramethyl lead (0.15 g/L or 0.57 grams per gallon) and dichloroethane (0.1 g/L as a scavenger). The fuel used may not have accurately represented commercial fuels at that time, which typically contained a mixture of chlorinated and brominated scavengers (Marklund et al., 1990). Also, the lead content of the fuel used (0.15 g lead/L), although the normal lead content for Swedish fuels at the time (Marklund et al., 1990), was higher than the lead content of leaded gasoline in the United States during the late 1980s (lowered to 0.10 g lead/gallon or 0.026 g lead/L effective January 1, 1986). Marklund et al. (1987) reported a striking similarity in the TCDF and PeCDF congener profiles in the car exhausts and those found in emissions from municipal waste incinerators. For two cars running on unleaded gasoline, CDD/CDF emissions were below the detection limit, which corresponded to approximately 13 pg of I-TEQ_{DF} per kilometer driven.

Table 4-1 presents a summary description of the results of the Marklund et al. (1987) study and subsequent studies (presented in chronological order) discussed below. Tables 4-2 and 4-3 present the results of tailpipe emission studies reported for diesel-fueled cars and trucks, respectively. Table 4-4 presents the results of studies using leaded gasoline-fueled cars, and Tables 4-5 and 4-6 present results of studies with cars fueled by unleaded gasoline. Figures 4-1, 4-2, and 4-3 present congener and congener group profiles for emissions from diesel-fueled vehicles, leaded gasoline-fueled vehicles, and unleaded gasoline-fueled vehicles, respectively.

Virtually no testing of vehicle emissions in the United States for CDD/CDFs has been reported. In 1987, the California Air Resources Board (CARB) produced a draft report on the testing of the exhausts of four gasoline-powered cars and three diesel fuel-powered vehicles (one truck, one bus, and one car) (CARB, 1987a). However, CARB indicated to EPA that the draft report should not be cited or quoted to support general conclusions about CDD/CDFs in motor vehicle exhausts because of the small sample size of the study and because the use of low rather than high resolution mass spectrometry in

the study resulted in high detection limits and inadequate selectivity in the presence of interferences (Lew, 1993). CARB did state that the results of a single sample from the heavy-duty diesel truck could be reported, because congeners from most of the homologue groups were present in the sample at levels that could be detected by the analytical method and there were no identified interferences in this sample. This test was conducted under steady state conditions (50 km/hr) for 6 hours with an engine with a fuel economy of 5.5 km/L. The TEQ emission factor of this one sample was equivalent to 7,290 pg I-TEQ_{DF}/L of fuel burned (7,190 pg TEQ_{DF}-WHO_{98}/L). Assuming a fuel economy of 5.5 km/L yields an emission factor of 1,325 pg I-TEQ_{DF}/km (1,307 pg TEQ_{DF}-WHO_{98}/km). Treating nondetected values as zeros yields TEQ emission factors of 3,720 pg I-TEQ_{DF}/L of fuel burned (or 676 pg I-TEQ_{DF}/km driven) and 3,280 pg TEQ_{DF}-WHO_{98}/L (or 596 pg TEQ_{DF}-WHO_{98}/km driven) (Lew, 1996).

Haglund et al. (1988) sampled exhaust gases from three different vehicles (two cars fueled with leaded and unleaded gasoline, respectively, and a heavy-duty diesel truck) for the presence of brominated dibenzo-p-dioxins (BDD) and brominated dibenzofurans (BDF). The authors concluded that the dibromoethane scavenger added to the tested gasoline probably acted as a halogen source. TBDF emissions measured 23,000 pg/km in the car with leaded gasoline and 240 pg/km in the car with unleaded gasoline. TBDD and PeBDF emissions measured 3,200 and 980 pg/km, respectively, in the car with leaded gasoline. All BDD/Fs were below detection limits in the diesel truck emissions.

Bingham et al. (1989) analyzed the exhausts of four cars using leaded gasoline (0.45 g/L tetramethyllead, 0.22 g/L dichloroethane, and 0.2 g/L dibromoethane), and the exhaust from one car using unleaded gasoline. Analytical results and detection limits were reported for only five of the 17 toxic CDD/CDF congeners. TEQ emission rates for the cars using leaded fuel, based on detected congeners only, ranged from 1 to 39 pg I-TEQ_{DF}/km. CDD/CDFs were not detected in the exhaust from the vehicle using unleaded fuel. The total I-TEQ_{DF} emission rate for this car using unleaded fuel, based on one-half the detection limits for the five reported congeners, was 20 pg I-TEQ_{DF}/km.

Marklund et al. (1990) tested Swedish cars fueled with commercial fuels, measuring CDD/CDF emissions before and/or after the muffler. Both new and old vehicles were tested. Three cars were tested using unleaded gasoline, and two cars were tested with leaded gasoline (0.15 g Pb/L and dichloroethane and dibromoethane scavengers).

CDD/CDFs were not detected in the fuels at a detection limit of 2 pg I-TEQ_{DF}/L, but were detected at a level of 1,200 pg I-TEQ_{DF}/L in the new semi-synthetic engine lube oil used in the engines. The test driving cycle employed (i.e., 31.7 km/hr as a mean speed; 91.2 km/hr as a maximum speed; and 17.9 percent of time spent idling) yielded fuel economies ranging from approximately 9 to 10 km/L or 22 to 24 miles/gallon in the various cars. The reported ranges of emission factors were:

- Leaded gas/before muffler: 2.4 to 6.3 pg I-TEQ_{DF}/km (or 21 to 60 pg I-TEQ_{DF}/L of fuel consumed);
- Leaded gas/in tailpipe: 1.1 to 2.6 pg I-TEQ_{DF}/km (or 10 to 23 pg I-TEQ_{DF}/L);
- Unleaded gas/catalyst-equipped/in tailpipe: 0.36 pg I-TEQ_{DF}/km (or 3.5 pg I-TEQ_{DF}/L); and
- Unleaded gas/before muffler: 0.36 to 0.39 pg I-TEQ_{DF}/km (or 3.5 pg I-TEQ_{DF}/L).

The TEQ levels in exhaust gases from older cars using leaded gasoline were up to six times greater when measured before the muffler than after the muffler. No muffler-related difference in new cars running on leaded gasoline or in old or new cars running on unleaded gasoline was observed.

Marklund et al. (1990) also analyzed the emissions from a heavy-duty diesel-fueled truck for CDD/CDFs. None were detected; however, the authors pointed out that the test fuel was a reference fuel and may not have been representative of commercial diesel fuel. Also, due to analytical problems, a much higher detection limit (about 100 pg I-TEQ_{DF}/L) was realized in this diesel fuel test than in the gasoline tests (5 pg I-TEQ_{DF}/L) conducted. Further uncertainty was introduced because the diesel emission samples were only collected prior to the muffler.

Hagenmaier et al. (1990) ran a set of tests using conditions comparable to the FTP-73 test cycle on gasoline- and diesel-fueled engines for light duty vehicles in Germany. The following average TEQ emission rates per liter of fuel consumed were reported:

- Leaded fuel: 1,080 pg I-TEQ_{DF}/L (1,287 pg TEQ_{DF}-WHO_{98}/L);
- Unleaded fuel (catalyst-equipped): 7.2 pg I-TEQ_{DF}/L (7.9 pg TEQ_{DF}-WHO_{98}/L);

- Unleaded fuel (not catalyst-equipped): 50.9 pg I-TEQ_{DF}/L (60.2 pg TEQ_{DF}-WHO_{98}/L); and
- Diesel fuel: 20.8 pg I-TEQ_{DF}/L (24.8 pg TEQ_{DF}-WHO_{98}/L).

The major findings of a German study of emissions of halogenated dibenzodioxins and dibenzofurans from internal combustion engines running on commercial fuels were published in 1991 (Schwind et al., 1991), and the full detailed report was published in 1992 (Hutzinger et al., 1992). The study was conducted by the Universities of Stuttgart, Tübingen, and Bayreuth for the Federal Ministry for Research and Technology, the Research Association for Internal Combustion Engines, and the German Association for the Petroleum Industry and Coal Chemistry. Tests were conducted using engine test benches and rolling test benches under representative operating conditions. Tests were performed on leaded gasoline engines, unleaded gasoline engines, diesel car engines, and diesel truck engines. The reported range of CDD/CDF emission rates across the test conditions in units of pg TEQ per liter of fuel consumed are presented below. The results from those tests conducted under normal operating conditions with commercial fuels and for which congener-specific emission results were presented in Hutzinger et al. (1992) are listed in Tables 4-2 through 4-6.

- Leaded fuel: 52 to 1,184 pg I-TEQ_{DF}/L (72 to 1,417 pg TEQ_{DF}-WHO_{98}/L);
- Unleaded fuel (not catalyst-equipped): 96 to 177 pg I-TEQ_{DF}/L (102 to 181 pg TEQ_{DF}-WHO_{98}/L);
- Unleaded fuel (catalyst-equipped): 10 to 26 pg I-TEQ_{DF}/L (9.6 to 28.0 pg TEQ_{DF}-WHO_{98}/L);
- Diesel fuel (cars): 10 to 130 pg I-TEQ_{DF}/L (12 to 140 pg TEQ_{DF}-WHO_{98}/L); and
- Diesel fuel (trucks): 70 to 81 pg I-TEQ_{DF}/L (79 to 82 pg TEQ_{DF}-WHO_{98}/L).

Although no specific details on the methodology used were provided, Hagenmaier (1994) reported that analyses of emissions of a diesel-fueled bus run either on steady state or on the "Berlin cycle" showed no CDD/CDF present at a detection limit of 1 pg/L of fuel consumed for individual congeners.

Gullett and Ryan (1997) recently reported the results of the first program to sample diesel engine emissions for CDD/CDFs during actual highway and city driving. The exhaust emissions from a 1991 Freightliner diesel tractor with a 10.3 L, 6-cylinder Caterpillar engine, representative of the first generation of computerized fuel controlled vehicles manufactured in the United States, were sampled during both highway and city driving routes. The average emission factor for the three highway tests conducted (15.1 pg I-TEQ_{DF}/km; range 11.7-18.7 pg I-TEQ_{DF}/km; standard deviation of 3.5 pg I-TEQ_{DF}/km) was a factor of three below the average of the two city driving tests (49.9 pg I-TEQ_{DF}/kg; range 3.0-96.8 pg I-TEQ_{DF}/km). Detection limits were considered as zeros in the calculation of these emission factors. The average of all five tests was 29.0 pg I-TEQ_{DF}/km with a standard deviation of 38.3 pg I-TEQ_{DF}/km; this standard deviation reflects the 30-fold variation in the two city driving route tests.

4.1.2. Tunnel Emission Studies

Several European studies and one recent U.S. study evaluated CDD/CDF emissions from vehicles by measuring the presence of CDD/CDFs in tunnel air. This approach has the advantage that it allows random sampling of large numbers of cars, including a range of ages and maintenance levels. The disadvantage of this approach is that it relies on indirect measurements (rather than tailpipe measurements), which may introduce unknown uncertainties and make interpretation of the findings difficult. Concerns have been raised that the tunnel monitors are detecting resuspended particulates that have accumulated over time, leading to overestimates of emissions. Also, the driving patterns encountered in these tunnel studies are more or less steady state driving conditions rather than the transient driving cycle and cold engine starts that are typical of urban driving conditions and that may affect emission levels. Each of these studies is summarized below in chronological order.

Rappe et al. (1988) reported the CDD/CDF content of two air samples (60 m^3 per sample) collected from a tunnel in Hamburg, Germany, during January of 1986 to be 0.42 and 0.58 pg I-TEQ_{DF}/m^3 (0.44 and 0.59 pg TEQ_{DF}-WHO_{98}/m^3. Each sample was collected over a period of about 60 hours. The tunnel handled 65,000 vehicles per day of which 17 percent were classified as "heavy traffic." The congener-specific results of the two samples are presented in Table 4-7. Measurement of ambient air conducted in September

of 1986 at a nearby highway in Hamburg was reported to contain CDD/CDF levels two to six times lower than those measured in the tunnel.

Larssen et al. (1990) and Oehme et al. (1991) reported the results of a tunnel study in Olso, Norway, performed during April/May of 1988. Oehme et al. (1991) estimated total vehicle emissions by measuring CDD/CDF concentrations in tunnel inlet and outlet air of both the uphill and downhill lanes. Emission rates for light-duty and heavy-duty vehicle classes in the uphill and downhill lanes were estimated by counting the number of light-duty vs. heavy-duty vehicles passing through the tunnel on workdays and a weekend and assuming a linear relationship between the percentage of the light- or heavy-duty traffic and the overall emission rate. Thus, the linear relationship for each emission rate was based on only two points (i.e., the weekday and weekend measurements). The emission rates, in units of Nordic TEQ, estimated in this study are:

- Light-duty vehicles using gasoline (approximately 70-75 percent using leaded gas): uphill = 520 pg TEQ/km; downhill = 38 pg TEQ/km; mean = 280 pg TEQ/km; and
- Heavy-duty diesel trucks: uphill = 9,500 pg TEQ/km; downhill = 720 pg TEQ/km; mean = 5,100 pg TEQ/km.

The mean values are the averages of the emission rates corresponding to the two operating modes: vehicles moving uphill on a 3.5 percent incline at an average speed of 37 miles per hour and vehicles moving downhill on a 3.5 percent decline at an average speed of 42 miles per hour. Although Oehme et al. (1991) reported results in units of Nordic TEQ, the results in I-TEQ_{DF} should be nearly identical (i.e., about 3 to 6 percent higher), because the only difference between the two TEQ schemes is the toxic equivalency factor assigned to 1,2,3,7,8-PeCDF (0.1 in Nordic and 0.05 in I-TEQ_{DF}), a minor component of the toxic CDD/CDFs measured in the tunnel air. Table 4-7 presents the congener-specific differences in concentrations between the tunnel inlet and outlet concentrations.

Wevers et al. (1992) measured the CDD/CDF content of air samples taken during the winter of 1991 inside a tunnel in Antwerp, Belgium. During the same period, background concentrations were determined outside the tunnel. Two to four samples were collected from each location with two devices: a standard high volume sampler with a glass fiber filter and a modified two-phase high volume sampler equipped with a glass

fiber filter and a polyurethane foam plug (PUF). The I-TEQ_{DF} concentration in the air sampled with the filter/PUF device was 74 to 78 percent of the value obtained with the high volume sampler. However, the results obtained from both sets of devices indicated that the tunnel air had a CDD/CDF TEQ concentration about twice as high as the outside air (filter and PUF: 80.3 fg I-TEQ_{DF}/m^3 for tunnel air vs. 35 fg I-TEQ_{DF}/m^3 for outside air; filter only: 100 fg I-TEQ_{DF}/m^3 for tunnel air vs. 58 fg I-TEQ_{DF}/m^3 for outside air). The authors presented the congener-specific results for only one tunnel air measurement; these results are presented in Table 4-7.

During October/November 1995, Gertler et al. (1996, 1998) conducted a study at the Fort McHenry Tunnel in Baltimore, Maryland, with the stated objective of measuring CDD/CDF emission factors from in-use vehicles operating in the United States, with particular emphasis on heavy-duty vehicles. The air volume entering and leaving the tunnel bore that services most of the heavy-duty vehicles (i.e., approximately 25 percent of the vehicles using the bore are heavy-duty) was measured, and the air was sampled for CDD/CDFs during 7 sampling periods of 12-hour duration. Three of the samples were collected during daytime (i.e., 6 am to 6 pm) and four samples were collected during the night (i.e., 6 pm to 6 am). The air volume and concentration measurements were combined with information on vehicle counts (obtained from videotapes) and tunnel length to determine average emission factors. A total of 33,000 heavy-duty vehicles passed through the tunnel during the seven sample runs. Heavy-duty vehicles accounted for 21.2 to 28.8 percent of all vehicles passing through the tunnel for the seven sample runs. The emission factors calculated, assuming that all CDD/CDF emitted in the tunnel were from heavy-duty vehicles, are presented in Table 4-8. The average I-TEQ_{DF} emission factor was reported to be 172 pg I-TEQ_{DF}/km (182 pg TEQ_{DF}-WHO_{98}/km). The major uncertainties identified by the authors in the study were tunnel air volume measurement, sampler flow volume control, and analytical measurement of CDD/CDF.

EPA's Office of Mobile Sources (OMS) reviewed the Gertler et al. (1996) study (Lorang, 1996) and found the study to be technologically well done, with no major criticisms or comments on the test methodology or protocol. OMS found no reason to doubt the validity of the emission factor determined by the study. OMS did note that the particulate emission rate for heavy-duty vehicles measured in the study (0.32 g/mile) is lower than the general particulate emission rate used by EPA (i.e., about 1 g/mile) and,

thus, may underestimate CDD/CDF emissions under different driving conditions. OMS cautioned that the reported emission factor should be regarded only as a conservative estimate of the mean emission factor for the interstate trucking fleet under the driving conditions of the tunnel (i.e., speeds on the order of 50 miles/hour with the entering traffic slightly higher and the exiting traffic slightly lower.

Figure 4-4 graphically presents the results of the studies by Rappe et al. (1988), Oehme et al. (1991), Wevers et al. (1992), and Gertler et al. (1996, 1998). The figure compares the congener profiles (i.e., congener concentrations or emission factors normalized to total concentration or emission factor of 2,3,7,8-substituted CDDs and CDFs) reported in the four studies. The dominant congeners in the Rappe et al. (1988), Wevers et al. (1992), and Gertler et al. (1996, 1998) studies are OCDD, 1,2,3,4,6,7,8-HpCDD, OCDF, and 1,2,3,4,6,7,8-HpCDF. With the exception of OCDD, these congeners are also major congeners reported by Oehme et al. (1991). The Oehme et al. (1991) study also differs from the other two studies in that the total of 2,3,7,8-substituted CDFs dominates total 2,3,7,8-substituted CDDs (by a factor of 2), whereas just the opposite is observed in Rappe et al. (1988), Wevers et al. (1992), and Gertler et al. (1996, 1998).

4.1.3. National Emission Estimates

Estimates of national CDD/CDF TEQ emissions are presented in this section only for on-road vehicles utilizing gasoline or diesel fuel. Because emission factors are lacking for off-road uses (i.e., construction vehicles, farm vehicles, and stationary industrial equipment), no emission estimates could be developed at this time; however, activity level information for off-road uses is presented below.

Activity Information for On-Road Vehicles: The U.S. Federal Highway Administration, as reported in U.S. Department of Commerce (DOC) (1997), reports that 1,586-billion total vehicle miles (2,552 billion km) were driven in the United States during 1994 by automobiles and motorcycles. Because 1994 is the last year for which data are available, these data are used as a surrogate for 1995 activity levels. Trucks accounted for 840-billion vehicle miles (1,351 billion km), and buses accounted for 6.4 billion vehicle miles (10 billion km) (U.S. DOC, 1997). In 1992, diesel-fueled trucks accounted for 14.4 percent of total truck vehicle km driven; gasoline-fueled trucks accounted for the

remaining 85.6 percent (U.S. DOC, 1995b). Applying this factor (i.e., 14.4 percent) to the 1994 truck km estimate (i.e., 1,351 billion km) indicates that an estimated 195 billion km were driven by diesel-fueled trucks in 1994. It is assumed that all other vehicle km driven (3,718 billion km) (i.e., non-diesel trucks, all automobiles, all buses, and all motorcycles) were those of gasoline-powered vehicles; although it is recognized that a fraction of the buses and automobiles use diesel fuel, the exact numbers are not known. It is further assumed that all of these km were driven by unleaded gasoline-powered vehicles because in 1992, only 1.4 percent of the gasoline supply were leaded fuel (EIA, 1993); usage should have further declined by 1995, because use of leaded fuel in motor vehicles for highway use in the United States was prohibited as of December 31, 1995 (Federal Register, 1985a).

Similar information for 1987 is as follows. An estimated 3,092 billion km were driven in the United States of which trucks accounted for 887 billion km (U.S. DOC, 1995a). In 1987, diesel-fueled trucks accounted for 17.2 percent of total truck km driven (U.S. DOC, 1995b). Applying this factor (i.e., 17.2 percent) to the 1987 truck km estimate (i.e., 887 billion km) indicates that an estimated 153 billion km were driven by diesel-fueled trucks. It is assumed that all other vehicle km driven (2,939 billion km) were those of gasoline-powered vehicles. Leaded gasoline accounted for 24.1 percent of the gasoline supply in 1987 (EIA, 1993). Thus, it can be estimated that 708 billion km (i.e., 24.1 percent of 2,939 billion km) were driven by leaded gasoline-fueled vehicles. The remaining 2,231 billion km are estimated to have been driven by unleaded gasoline-fueled vehicles. These mileage estimates are given a high confidence rating because they are based on recent U.S. Bureau of the Census transportation studies.

Activity Information for Off-Road Uses: Although on-road vehicles are the largest consumers of diesel fuel (accounting for about 50 percent of U.S. sales), other sectors of the economy use significant volumes: farm use, railroad use, vessel bunkering, and other off-highway uses. The following paragraphs define each of these uses and present volumes of distillate fuel sales in each sector for reference years 1987 and 1995. For these sectors, the majority of "distillate fuel" sales are diesel fuels; a small fraction are fuel oils.

Farm use includes sales for use in tractors, irrigation pumps and other agricultural machinery, as well as that used for crops drying, smudge pot fuel and space heating of buildings. Sales in 1987 and 1995 were 2,999 and 3,476 million gallons, respectively (EIA, 1992; EIA, 1997a).

Railroad use includes sales to railroads, for any use, including diesel fuel for railroad locomotive engines and fuel used for heating buildings operated by railroads. Sales in 1987 and 1995 were 2,850 and 3,429 million gallons, respectively (EIA, 1992; EIA, 1997a).

Vessel bunkering includes sales for the fueling of commercial or private boats, such as pleasure craft, fishing boats, tug boats, and ocean-going vessels, including vessels operated by oil companies. Excluded are volumes sold to the U.S. Armed Forces. Sales in 1987 and 1995 were 1,865 and 2,339 million gallons, respectively (EIA, 1992; EIA, 1997a).

Off-highway use includes sales for use in: (1) construction equipment including earthmoving equipment, cranes, stationary generators, air compressors, etc.; and (2) sales for non-construction other off-highway uses such as logging. Sales in 1987 and 1995 were 1,560 and 2,173 million gallons, respectively (EIA, 1992; EIA, 1997a).

Emission Estimates: Using the results of the studies discussed in Section 4.1.1, separate annual national emission estimates are developed below for vehicles burning leaded gasoline, unleaded gasoline, and diesel fuel. Estimates are provided for the years 1987 and 1995. The emission estimates for reference year 1995 are based on activity data (i.e., kilometers driven) for calendar year 1994.

Leaded Gasoline: Literature indicates that CDD/CDF emissions do occur from vehicles using leaded gasoline and that considerable variation occurs depending, at least in part, on the types of scavengers used. Marklund et al. (1987) reported emissions ranging from 20 to 220 pg I-TEQ_{DF}/km from four cars fueled with a reference unleaded fuel to which lead (0.5 gplg) and a chlorinated scavenger were added. Marklund et al. (1990)

reported much lower emissions in the exhaust of cars (1.1 to 6.3 pg I-TEQ_{DF}/km) using a commercial leaded fuel (0.5 g/L) containing both dichloroethane and dibromoethane as scavengers. Marklund et al. (1990) attributed the difference in the emission measurements of the 1987 and 1990 studies to the different mix of scavengers used in the two studies, which may have resulted in preferential formation of mixed chlorinated and brominated dioxins and furans. Hagenmaier et al. (1990) reported TEQ emissions of 1,080 pg I-TEQ_{DF}/L of fuel (approximately 108 pg I-TEQ_{DF}/km or 129 pg TEQ_{DF}-WHO_{98}/km) from a car fueled with a commercial leaded fuel (lead content not reported). Bingham et al. (1989) reported emissions from four cars using gasoline with a lead content of 1.7 g/L in New Zealand to range from 1 to 39 pg I-TEQ_{DF}/km. The German study reported by Schwind et al. (1991) and Hutzinger et al. (1992) measured emissions of 52 to 1,184 pg I-TEQ_{DF}/L (approximately 5.2 to 118 pg I-TEQ_{DF}/km or 7.2 to 142 pg TEQ_{DF}-WHO_{98}/km) for cars under various simulated driving conditions. The tunnel study by Oehme et al. (1991) estimated that emissions from cars running primarily on leaded gasoline (i.e., 70 to 75 percent of the cars) ranged from 38 to 520 pg Nordic TEQ/km.

As shown in Table 4-4, the average emission factor reported for the tailpipe emission studies performed using commercial leaded fuel which reported analytical results for all 17 toxic CDD/CDF congeners (i.e., Marklund et al., 1990; Hagenmaier et al., 1990; and Schwind et al., 1991) is 450 pg I-TEQ_{DF}/L or 532 pg TEQ_{DF}-WHO_{98}/L. Assuming an average fuel economy of 10 km/L, these emission factors are approximately 45 pg I-TEQ_{DF}/km and 53 pg TEQ_{DF}-WHO_{98}/km. A low confidence rating is assigned to this emission factor because it is based on European fuels and emission control technologies, which may have differed from U.S. leaded-fuels and engine technology, and also because the factor is based is based on tests with only nine cars.

Combining the average emission factor developed above (45 pg I-TEQ_{DF}/km or 53 pg TEQ_{DF}-WHO_{98}/km, assuming not detected values are zero) with the estimate for km driven by leaded fuel-powered vehicles in 1987 (708 billion km) suggests that 31.9 g I-TEQ_{DF} (or 37.5 pg TEQ_{DF}-WHO_{98}) were emitted from vehicles using leaded fuels in 1987. Although there likely was minor use of unleaded fuel in 1995 in on-road vehicles, further use of leaded fuel in motor vehicles for highway use in the United States was prohibited as of December 31, 1995 (Federal Register, 1985a). In 1992, the last year for which data are available on consumption of leaded gasoline by on-road vehicles, only 1.4 percent

of the gasoline supply was leaded gasoline (EIA, 1993). If it is conservatively assumed that 1 percent of the total vehicle km driven in 1995 (i.e., 37.2 billion km of a total of 3,718 billion km) were driven by leaded fuel-powered vehicles, then combining the emission factor of 45 pg I-TEQ_{DF}/km (or 53 pg TEQ_{DF}-WHO_{98}/km) with this activity level estimate yields an annual emission of 1.7 g I-TEQ_{DF} (or 2.0 g TEQ_{DF}-WHO_{98}) in 1995.

Unleaded Gasoline: The literature documenting results of European studies indicates that CDD/CDF emissions from vehicles burning unleaded fuels are less than the emissions from vehicles burning leaded gas with chlorinated scavengers. It also appears, based on the limited data available, that catalyst-equipped cars have lower emission factors than noncatalyst-equipped cars. Marklund et al. (1987) did not detect CDD/CDF in emissions from two catalyst-equipped cars running on unleaded gasoline at a detection limit of 13 pg I-TEQ_{DF}/km. Marklund et al. (1990) reported emission factors of 0.36 and 0.39 pg I-TEQ_{DF}/km for two noncatalyst-equipped cars and an emission factor of 0.36 pg I-TEQ_{DF}/km for one catalyst-equipped car. Hagenmaier et al. (1990) reported an emission factor of 5.1 pg I-TEQ_{DF}/km for one noncatalyst-equipped car and 0.7 pg I-TEQ_{DF}/km for one catalyst-equipped car. Schwind et al. (1991) and Hutzinger et al. (1992) reported emission factors of 9.6 to 17.7 pg I-TEQ_{DF}/km for several noncatalyst-equipped cars tested under various conditions; the reported emission factor range for catalyst-equipped cars was 1.0 to 2.6 pg I-TEQ_{DF}/km.

All automobiles running on unleaded gasoline in the United States are equipped with catalysts. As shown in Table 4-6, the average emission factor reported for the tailpipe emission studies performed on catalyst-equipped cars (i.e., Hagenmaier et al. 1990; Schwind et al., 1991; and Hutzinger et al., 1992) is 14.9 pg I-TEQ_{DF}/L or 15.6 pg TEQ_{DF}-WHO_{98}/L. Assuming an average fuel economy of 10 km/L yields emission factors of 1.5 pg I-TEQ_{DF}/km and 1.6 pg TEQ_{DF}-WHO_{98}/km. A low confidence rating is assigned to this emission factor because the European fuels and emission control technology used may have differed from U.S. fuels and technology and also because the emission factor range is based on tests with only three catalyst-equipped cars.

Combining the calculated mean emission factor of 1.5 pg I-TEQ_{DF}/km (or 1.6 pg TEQ_{DF}-WHO_{98}/km) with the estimate derived above for vehicle km driven in 1995 by all gasoline-powered vehicles (3,718 billion km) suggests that 5.6 g of I-TEQ_{DF} (or 5.9 g

TEQ_{DF}-WHO_{98}) were emitted from vehicles using unleaded fuels in 1995. Applying the same emission factors to the estimate derived above for vehicle km driven in 1987 by unleaded gasoline-powered vehicles (2,231 billion km), suggests that 3.3 g of I-TEQ_{DF} (or 3.6 g TEQ_{DF}-WHO_{98}) may have been emitted in 1987.

Diesel Fuel: Few data are available upon which to base an evaluation of the extent of CDD/CDF emissions resulting from diesel fuel combustion. The limited data available address emissions only from on-road vehicles; no emissions data are available for off-road diesel uses (i.e., construction vehicles, farm vehicles, and stationary equipment). Two U.S. tailpipe studies are available: CARB (1987a) and Gullett and Ryan (1997). CARB (1987a) reported a relatively high emission factor of 676 pg I-TEQ_{DF}/km (not detected values assumed to be zero) for one tested heavy-duty truck with a fuel economy at 50 km/hr of 5.5 km/L. Gullett and Ryan (1997) reported a range of emission factors for one diesel truck tested on six highway or city driving routes, 3.0 to 96.8 pg I-TEQ_{DF}/km (mean of 29.0 pg I-TEQ_{DF}/km).

The results of several tailpipe studies conducted in Europe have also been published. Marklund et al. (1990) reported no emissions at a detection limit of 100 pg I-TEQ_{DF}/L (or 18 pg I-TEQ_{DF}/km assuming a fuel economy of 5.5 km/L) for one tested truck. Schwind et al. (1991) and Hutzinger et al. (1992) reported emission factors of 32 to 81 pg I-TEQ_{DF}/L (or 6 to 15 pg I-TEQ_{DF}/km assuming a fuel economy of 5.5 km/L) for a truck engine run under various simulated driving conditions. Hagenmaier (1994) reported no emissions from a bus at a detection limit of 1 pg/L of fuel consumed for individual congeners. For diesel-fueled cars, Hagenmaier et al. (1990) reported an emission factor of 24 pg I-TEQ_{DF}/L (or approximately 2.4 pg I-TEQ_{DF}/km) for one tested car. Schwind et al. (1991) and Hutzinger et al. (1992) reported emission factors of 5 to 13 pg I-TEQ_{DF}/km for a car engine run under various simulated driving conditions.

The tunnel study by Oehme et al. (1991) generated an estimated mean emission factor of 5,100 pg TEQ/km and a range of 720 to 9,500 pg TEQ/km (in units of Nordic TEQ) for diesel-fueled trucks. Insufficient information was provided in Oehme et al. (1991) to enable an exact calculation of emission in units of I-TEQ_{DF} or TEQ_{DF}-WHO_{98}. However, based on the information that was provided, the mean emission factor in units of I-TEQ is approximately 5,250 to 5,400 pg I-TEQ_{DF}/km. These indirectly estimated

emission factors are considerably larger than those reported from engine studies by Marklund et al. (1990), Schwind et al. (1991), and Hutzinger et al. (1992); the CARB (1987a) diesel truck emission factor falls at the low end of the range. Although aggregate samples were collected in this study representing several thousand heavy duty diesel vehicles, several characteristics of this study introduce considerable uncertainty with regard to using the study's results as a basis for estimating emissions in the United States. These factors include: (1) heavy-duty vehicles comprised only 3 to 19 percent of total vehicle traffic in the tunnel; (2) the majority of the light-duty vehicles were fueled with leaded gasoline the combustion of which, as noted above in Table 4-4, can release considerable amounts of CDD/CDFs; and (3) technology differences likely existed between the 1988 Norwegian and the 1987 and 1995 U.S. vehicle fleets.

The recent tunnel study conducted in Baltimore, Maryland, by Gertler et al. (1996, 1998) has the same disadvantages shared by all tunnel studies relative to tailpipe studies. Specifically, tunnel studies rely on indirect measurements (rather than tailpipe measurements), which may introduce unknown uncertainties, and the emission factors calculated from these studies reflect driving conditions by the vehicle fleet using the tunnel and not necessarily the overall vehicle fleet under other driving conditions. However, the Gertler et al. (1996, 1998) study does have strengths lacking in the Oehme et al. (1991) tunnel study. Also, the Gertler et al. (1996, 1998) study has benefits over the two U.S. diesel truck tailpipe studies. These include (1) the study is a recent study conducted in the United States and thus reflects current U.S. fuels and technology, (2) virtually no vehicle using the tunnel used leaded gasoline, (3) the tunnel walls and streets were cleaned 1 week prior to the start of sampling and, in addition, the study analyzed road dust and determined that resuspended road dust contributed only about 4 percent of the estimated emission factors, (4) heavy-duty vehicles comprised, on average, a relatively large percentage (25.7 percent) of vehicles using the tunnel, and (5) a large number of heavy-duty vehicles, approximately 33,000, passed through the tunnel during the sampling period, which generates confidence that the emission factor is representative of interstate trucks.

In consideration of the strengths and weaknesses of the available emission factor data from the tailpipe and tunnel studies, the mean TEQ emission factor reported by Gertler et al. (1996, 1998), 172 pg I-TEQ_{DF}/km (or 182 pg TEQ_{DF}-WHO_{98}/km), is assumed

to represent the best current estimate of the average emission factor for on-road diesel-fueled trucks. Because it may not be representative of emission rates for the entire fleet of diesel-fueled trucks under the wide array of driving conditions encountered on the road, this emission factor is assigned a low confidence rating.

Combining the calculated mean emission factors from Gertler et al. (1996, 1998) with the above estimate for vehicle kms driven in 1995 in the United States by diesel-fueled trucks (195 billion km) suggests that 33.5 g of I-TEQ_{DF} (or 35.5 g TEQ_{DF}-WHO_{98}) were emitted from trucks using diesel fuel in 1995. Combining the same emission factors to the estimate derived above for vehicle km driven in 1987 by diesel-fueled trucks (153 billion km) suggests that 26.3 g of I-TEQ_{DF} (or 27.8 g TEQ_{DF}-WHO_{98}) were emitted from diesel-fueled trucks in 1987.

4.2. WOOD COMBUSTION

In 1995, wood fuel (including black liquor solids) provided about 2.6 percent (or 2,350-trillion Btu) of the total primary energy consumed in the United States (EIA, 1997b). During 1987, wood energy consumption is estimated to have been 2,437 trillion Btu, or 3.2 percent of total primary energy consumed (EIA, 1997b). The industrial sector is the largest consumer of wood fuel, accounting for almost 72 percent of total wood fuel consumption in 1995 and 65 percent in 1987. The residential sector accounted for 25 percent of consumption in 1995 and 35 percent in 1987. The electric utility sector accounted for less than 1 percent of total consumption in both years. There are no accurate sources to provide reliable estimates of commercial wood energy use; consumption is thought to be between 20 and 40 trillion Btu, or 2 to 4 percent of total wood consumption (EIA, 1994, 1997b).

These energy consumption estimates, however, appear to include the energy value of black liquor solids, which are combusted in recovery boilers by wood pulp mills. In 1987 and 1995, the energy value of combusted black liquor solids were 950 trillion Btu and 1,078 trillion Btu, respectively (American Paper Institute, 1992; American Forest & Paper Association, 1997). Subtracting these black liquor energy value estimates from the national totals for wood fuel yields 1,487 trillion Btu in 1987 and 1,272 trillion Btu in 1995. Assuming that 1 kg of oven-dried wood (i.e., 2.15 kg of green wood) provides approximately 19,000 Btu (EIA, 1994), then an estimated 66.9 million and 78.3 million

metric tons of oven-dried wood equivalents were burned for energy purposes in 1995 and 1987, respectively. Of these totals, an estimated 31.4 million metric tons and 44.8 million metric tons were consumed by the residential sector in 1995 and 1987, respectively. An estimated 35.5 million metric tons and 33.5 million metric tons were consumed by the industrial sector in 1995 and 1987, respectively.

The following two subsections discuss the results of relevant emission studies for the residential and industrial sectors, respectively, and present annual TEQ emission estimates for the reference years 1987 and 1995.

4.2.1. Residential Wood Combustion

Four studies have provided direct measurement of CDD/CDFs in flue gas emissions from wood stoves and/or fireplaces (Schatowitz et al., 1993; Vikelsoe et al., 1993; Bremmer et al., 1994; Broker et al., 1992). The findings of each of these studies are summarized in the following paragraphs.

Schatowitz et al. (1993) measured the CDD/CDF content of flue gas emissions from several types of wood burners used in Switzerland: a household stove (6 kW), automatic chip furnaces (110 to 1,800 kW), and a wood stick boiler (35 kW). The emissions from combustion of a variety of wood fuels were measured (natural beech wood, natural wood chips, uncoated chipboard chips, waste wood chips from building demolition, and household paper and plastic waste). The results from the testing of the household stove are most relevant for assessing releases from residential combustion. The household stove was tested with the stove door both open and closed. The open door stove can be assumed to be representative of fireplaces because both have an uncontrolled draft. Although the congener/congener group analytical results were not reported, the following emission factors (dry weight for wood; wet weight for household waste) and emission rates (corrected to 13 volume% oxygen) for the household stoves and furnaces were reported.

Stoves

- Open door burn of beech wood sticks: 0.77 ng I-TEQ_{DF}/kg (0.064 ng I-TEQ_{DF}/Nm^3);

- Closed door burn of beech wood sticks: 1.25 ng I-TEQ$_{DF}$/kg (0.104 ng I-TEQ$_{DF}$/Nm^3); and
- Closed door burn of household waste: 3,230 ng I-TEQ$_{DF}$/kg (114.4 ng I-TEQ$_{DF}$/Nm^3).

Furnaces

- Natural wood chips: 0.79 to 2.57 ng I-TEQ$_{DF}$/kg
- Chipboard chips (uncoated): 0.29 to 0.91 ng I-TEQ$_{DF}$/kg
- Waste wood chips from building demolition: 26.0 to 173.3 ng I-TEQ$_{DF}$/kg

Vikelsoe et al. (1993) studied emissions of CDD/CDF congener groups from residential wood stoves in Denmark. The wood fuels used in the experiments were seasoned birch, beech, and spruce, equilibrated to 18 percent absolute moisture. Four different types of stoves (including one experimental stove) were evaluated under both normal and optimal (i.e., well controlled with CO emission as low as possible) operating conditions. Widely varying total CDD/CDF emissions were found for the 24 different fuel/stove type/operating condition combinations. The emissions from spruce were about twice as high as the emissions from birch and beech. Surprisingly, the optimal operating condition led to significantly higher CDD/CDF emissions for two stove types, but not for the other stoves. The predominant congener group for all experiments was TCDF. The weighted average (considering wood and stove types) emission factor and flue gas concentration for wood stoves were reported to be 1.9 ng Nordic-TEQ/kg and 0.18 ng Nordic-TEQ/Nm^3, respectively. Because Vickelsoe et al. (1993) did not measure congener levels, the reported emission factor and emission rate were estimated by assuming the same congener distribution in each congener group that had been found for municipal waste incinerators.

Bremmer et al. (1994) reported results of testing performed with a cast-iron, wood burning stove with a combustion chamber lined with fire refractory clay. Measurements were conducted at three loads (maximum, average, and minimum) using clean wood as fuel. The emission factors ranged from 1.0 to 3.3 ng I-TEQ$_{DF}$/kg (average of about 2.2 ng I-TEQ$_{DF}$/kg). Bremmer et al. (1994) also reported results of testing conducted at a

fireplace of a type that is common in The Netherlands. The measured emission factors from burning of clean wood ranged from 13.0 to 28.5 ng I-TEQ_{DF}/kg (average of about 20 ng I-TEQ_{DF}/kg). Bremmer et al. (1994) noted that the measured emission factors for fireplaces were considerably higher than those reported by others (see Broker et al., 1992, below) and they, therefore, assigned "great uncertainty" to the emission factors.

Broker et al. (1992) reported results of a series of three tests with a wood stove and a fireplace. The average of the minimum and maximum emission factors measured for the woodstove tests ranged from 0.53 to 0.94 ng I-TEQ_{DF}/kg, respectively. The geometric mean of these two average values is 0.71 ng I-TEQ_{DF}/kg. The average of the minimum and maximum emission factors measured for the fireplace tests ranged from 0.20 to 1.06 ng I-TEQ_{DF}/kg, respectively. The geometric mean of these two average values is 0.46 ng I-TEQ_{DF}/kg.

Based on the results reported by Schatowitz et al. (1993), Vikelsoe et al. (1993), Bremmer et al. (1994), and Broker et al. (1992), 2 ng I-TEQ_{DF}/kg appear to be a reasonable average emission factor for residential burning of clean wood in fireplaces and stoves. Although the cited studies were conducted in Europe, residential wood burning practices are probably sufficiently similar to apply to the United States. Nevertheless, a low confidence rating was assigned to this estimate on the basis that it is derived from only four direct measurement studies. With the exception of the Broker et al. (1992) study, none of the cited studies presented results for the individual 2,3,7,8-substituted congeners. The Broker et al. (1992) study reported congener-specific results for only one of the test runs. Consequently, the data are not available from which to derive a corresponding emission factor for TEQ_{DF}-WHO_{98}. For purposes of this inventory, an emission factor of 2 ng TEQ_{DF}-WHO_{98}/kg is assumed.

Several studies have reported that combustion of non-clean wood in stoves and fireplaces can result in significantly higher CDD/CDF emission factors. The results of Schatowitz et al. (1993) for combustion of household waste in stoves and demolition waste in wood furnaces are presented above. A few researchers (e.g., Vikelsoe et al, 1993) have reported high CDD/CDF emission rates when PCP-contaminated wood is combusted in residential wood stoves and furnaces. The European Inventory (Quab and Fermann, 1997) used the results of these studies to derive best estimates of CDD/CDF emission factors for combustion of "slightly contaminated wood (excluding PCP)" and

"PCP-contaminated wood" to be 50 and 500 ng I-TEQ_{DF}/kg, respectively. Although it is likely that there is some residential combustion of these types of wood in the United States, there are no corresponding activity level data upon which to base a national annual estimate of emissions.

In 1987, 22.5 million households in the United States burned wood (EIA, 1991). Of these households, wood was used in 1987 as the primary heating fuel in 5 million households and as a secondary source for aesthetic purposes (i.e., fireplaces) in 17.4 million households (EIA, 1991; EIA, 1997b). Lower numbers were reported for 1995; wood was reported to be used as the primary fuel in 3.53 million households (EIA, 1997b). More rural low-income households consume wood as a primary heating fuel than do other sectors of the population. The majority of these households use wood-burning stoves as the primary heating appliance. Although fireplaces are the most common type of wood-burning equipment in the residential sector, only 7 percent of fireplace users report use of fireplaces for heating an entire home (EIA, 1991; EIA, 1994).

Residential wood consumption in 1995 was 596 trillion Btu (31.4 million metric tons), or 25 percent of total U.S. wood energy consumption (EIA, 1997b). In 1987, residential wood consumption was 852 trillion Btu (44.8 million metric tons), or 35 percent of total U.S. consumption (EIA, 1997b). These production estimates are given high confidence ratings because they are based on recent government survey data.

Combining the best estimate of the emission factor (2 ng I-TEQ_{DF}/kg wood) with the mass of wood consumed by residences in the years 1995 and 1987 indicates that the annual I-TEQ_{DF} air emissions from this source were approximately 62.8 grams in 1995 and 89.6 grams in 1987.

4.2.2. Industrial Wood Combustion

Emissions Data - Congener-specific measurements of CDD/CDFs in stack emissions from industrial wood-burning furnaces were measured by the California Air Resources Board at four facilities in 1988 (CARB, 1990b; CARB, 1990e; CARB, 1990f; CARB, 1990g). Measurements of CDD/CDF congener groups and 2,3,7,8-TCDD and 2,3,7,8-TCDF were reported for one facility by EPA (U.S. EPA, 1987a). The National Council of the Paper Industry for Air and Stream Improvement (NCASI) (1995) presented congener-specific emission factors for five boilers tested during burns of bark/wood residue. The

average congener emission factors derived from the four CARB and five NCASI studies are presented in Table 4-9. Average congener and congener group profiles are presented in Figure 4-5a for the four CARB studies and in Figure 4-5b for the five NCASI studies.

In CARB (1990b), CDD/CDFs were measured in the emissions from a quad-cell wood-fired boiler used to generate electricity. The fuel consisted of coarse wood waste and sawdust from nonindustrial logging operations. The exhaust gas passed through a multicyclone before entering the stack. From this study, average emission factors for total CDD/CDF and I-TEQ_{DF} are calculated to be 48.1 and 0.64 ng/kg of wood burned, respectively.

In CARB (1990e), CDD/CDFs were measured in the emissions from two spreader stoker wood-fired boilers operated in parallel by an electric utility for generating electricity. The exhaust gas stream from each boiler is passed through a dedicated ESP after which the gas streams are combined and emitted to the atmosphere through a common stack. Stack tests were conducted both when the facility burned fuels allowed by existing permits and when the facility burned a mixture of permitted fuel supplemented by urban wood waste at a ratio of 70:30. From this study, average emission factors for total CDD/CDF and I-TEQ_{DF} are calculated to be 29.2 and 0.82 ng/kg of wood burned, respectively.

In CARB (1990f), CDD/CDFs were measured in the emissions from a twin fluidized bed combustors designed to burn wood chips for the generation of electricity. The air pollution control device (APCD) system consisted of ammonia injection for controlling nitrogen oxides, and a multiclone and electrostatic precipitator for controlling particulate matter. During testing, the facility burned wood wastes and agricultural wastes allowed by existing permits. From this study, average emission factors for total CDD/CDF and I-TEQ_{DF} are calculated to be 47.9 and 1.32 ng/kg of wood burned, respectively.

In CARB (1990g), CDD/CDFs were measured in the emissions from a quad-cell wood-fired boiler. During testing, the fuel consisted of wood chips and bark. The flue gases passed through a multicyclone and an ESP before entering the stack. From this study, average emission factors for total CDD/CDF and I-TEQ_{DF} are calculated to be 27.4 and 0.50 ng/kg of wood burned, respectively.

NCASI (1995) presented stack emission test results for five boilers burning bark or wood residues. One of these facilities, equipped with a multicyclone, normally burns bark

in combination with sludge and coal. One other facility, equipped with an ESP, normally fires pulverized coal. The other three facilities were spreader stokers equipped with multicyclones or ESPs. Although stack gas flow rates were obtained during these tests, accurate measurements of the amounts of bark/wood fired were not made and had to be estimated by NCASI (1995) from steam production rates. The average TEQ emission factor for these facilities was 0.40 ng I-TEQ_{DF}/kg of feed (or 0.46 ng TEQ_{DF}-WHO_{98}/kg).

The mean of the emission factors derived from the four CARB studies and five NCASI studies, 0.56 ng I-TEQ_{DF}/kg wood (assuming nondetected values are zero) (or 0.60 ng TEQ_{DF}-WHO_{98}/kg wood), is used in this report as most representative of industrial wood combustion. This emission factor was assigned a medium confidence rating.

It should be noted, however, that these mean emission factors may not be appropriate emission factors to apply to the combustion of waste wood containing elevated chlorine content. NCASI (1995) concluded that CDD/CDF emissions from facilities burning salt-laden wood residue may be considerably higher than from those burning salt-free wood. Similarly, Umweltbundesamt (1996) reported the results of stack gas testing at approximately 30 facilities of varying design type as well as type of wood fuel combusted and noted that elevated CDD/CDF emissions were observed when the combustion conditions were poor, as evidenced by elevated carbon monoxide emissions, and/or when the fuel contained elevated chlorine levels. Umweltbundesamt (1996) attributed the correlation between elevated CDD/CDF emissions and elevated chlorine content of the fuel to the fire retardant effects of chlorine, which may have inhibited complete combustion. The chlorine content of untreated wood and bark were reported to range from 0.001 to 0.01 percent by weight and 0.01 to 0.02 percent by weight, respectively. Chipboard can contain up to 0.2 percent chlorine by weight because of binding agents used to manufacture the chipboard. Preservative-treated wood and PVC-coated wood were reported to contain chlorine contents as high as 1.2 and 0.3 percent by weight, respectively.

The facility tested by EPA in 1987 was located at a lumber products plant that manufactures overlay panels and other lumber wood products. Nearly all the wood fed to the lumber plant had been stored in sea water adjacent to the facility and, therefore, had a significant concentration of inorganic chloride. The wood-fired boiler tested was a three-cell dutch oven equipped with a waste heat boiler. The feed wood was a mixture of bark,

hogged wood, and green and dry planar shavings. The exhausted gases from the boiler passed through a cyclone and fabric filter prior to discharge from the stack. From this study, an average emission factor for total CDD/CDF of 1,020 ng/kg of wood burned (range: 552 to 1,410 ng/kg) was reported for the three collected samples. An average emission factor for I-TEQ_{DF} of 17.1 ng/kg of wood burned (range: 7.34 to 22.8 ng/kg) was estimated by EPA using measured congener group concentrations and concentrations of 2,3,7,8-TCDD and 2,3,7,8-TCDF. Similar emission factors were reported by Lutke et al. (1998) for testing conducted during the 1990s at four Canadian coastal, salt-laden wood power boilers: 1.4, 2.6, 17.4, and 27.6 ng I-TEQ_{DF}/kg wood combusted. The overall average of the five tested Canadian and U.S. facilities is 13.2 ng I-TEQ_{DF}/kg of wood combusted. The confidence rating assigned to this emission factor is low because it is based on reporting of limited congener data at one U.S. facility and testing at four non-U.S. sources and because the fraction of salt-laden wood combusted across facilities is likely to be highly variable.

Activity Level Information - As discussed in Section 4.2, industrial wood consumption in 1995 totaled 35.5 million metric tons. A similar amount, 33.5 million metric tons, was burned for fuel in industrial furnaces in 1987. The majority of wood fuel consumed in the industrial sector consists of wood waste (i.e., chips, bark, sawdust, and hogged fuel). Consumption in the industrial sector is dominated by two industries: the Paper and Allied Products industry and the Lumber and Wood Products industry (EIA, 1994). These activity level estimates are assigned a high confidence rating because they are based on recent government survey data.

As noted above, the emission factor associated with combustion of salt-laden wood appears to be greater than that associated with combustion of non-salt-laden wood. However, activity level data on combustion of salt-laden wood are not normally collected. Nonetheless, attempts have been made to estimate this activity level. NCASI combined the results from a 1995 survey of combustion units in the pulp and paper industry with an ad hoc telephone survey of mills in the Pacific Northwest (i.e., Oregon and Washington) to produce a conservative (i.e., high end) estimate of the amount of salt-laden wood combusted at U.S. pulp and paper mills in 1995: 254,000 metric tons (or 0.7 percent of the estimated 35.5 million metric tons of industrial wood consumed that year). NCASI

suspects that a similar fraction of industrial wood combustion in 1987 by pulp and paper mills was salt-laden (Gillespie, 1998).

For purposes of the NCASI survey, salt-laden wood was defined as wood that had been transported, stored, or otherwise exposed to saltwater prior to being processed as fuel. None of the three responding mills in Oregon reported use of salt-laden wood. Eight of the 13 responding mills in Washington reported some combustion of salt-laden wood. The estimated percentage of salt-laden wood to total wood consumption in the Washington mills was 17 percent.

As noted above, the majority of industrial wood combustion (i.e., 97 percent) occurs in two industries: the Paper and Allied Products industry and the Lumber and Wood Products industry. The relative amounts of wood combusted by each of these two industries were the same in 1990 and 1992, the only years for which these statistics are readily available (EIA, 1991, 1994). Therefore, it can be assumed that the percentage of total wood combusted nationally by the Lumber and Wood Products industry that is salt-laden is the same percentage as that reported by the Paper and Allied Products industry, 0.7 percent. Therefore, the total percentage of wood combusted by industry that is salt-laden is 1.4 percent. On a mass basis, this equates to 0.5 million metric tons in 1995 and 0.5 million metric tons in 1987. These activity level estimates are assigned a low confidence rating.

Emission Estimates - Applying the average TEQ emission factor from the four CARB and five NCASI studies (0.56 ng I-TEQ_{DF}/kg wood or 0.60 ng TEQ_{DF}-WHO_{98}/kg wood) to the estimated quantities of non-salt-laden wood burned by industrial facilities in 1995 (35 million metric tons) and 1987 (33 million metric tons) yields estimated TEQ emissions to air of 19.6 g I-TEQ_{DF} (or 21.0 g TEQ_{DF}-WHO_{98}) in 1995 and 18.5 g I-TEQ_{DF} (or 19.8 g TEQ_{DF}-WHO_{98}) in 1987.

Applying the average TEQ emission factor from the five studies on boilers combusting salt-laden wood (13.2 ng I-TEQ_{DF}/kg wood) to the estimated quantities of salt-laden wood burned by industrial facilities in 1995 (0.5 million metric tons) and 1987 (0.5 million metric tons) yields estimated TEQ emissions to air of 6.6 g TEQ in both 1995 and 1987.

Total emissions are estimated to have been 26.2 and 25.1 g I-TEQ_{DF} in 1995 and 1987, respectively. Total emissions of TEQ_{DF}-WHO_{98} are estimated to have been 27.6

and 26.4 g in 1995 and 1987, respectively. As noted above, these emissions are based on tests conducted at nine facilities in two industries. These two industries account for 97 percent of total industrial wood fuel combustion. The remaining 3 percent of industrial combustion and the combustion of wood by the commercial sector (for which no reliable activity level estimates are available) may not be well represented by the emission factors used above, particularly if poorly controlled combustors or treated wood (e.g., treated with PCP or plastics) are combusted.

4.2.3. Solid Waste from Wood Combustion

The measurement of CDDs and CDFs in chimney soot and bottom ash from wood-burning stoves and fireplaces has been reported by several researchers (Bumb et al., 1980; Nestrick and Lamparski, 1982 and 1983; Clement et al., 1985b; Bacher et al., 1992; Van Oostam and Ward, 1995; and Dumler-Gradl et al., 1995a).

Bumb et al. (1980) detected TCDDs (ND to 0.4 μg/kg), HxCDDs (0.2 to 3 μg/kg), HpCDDs (0.7 to 16 μg/kg), and OCDD (0.9 to 25 μg/kg) in residues from the wall of a home fireplace and from the firebrick of another home fireplace; for lack of a suitable analytical method, analysis was not performed for PeCDDs. Neither of the fireplaces sampled by Bumb et al. (1980) had burned preservative-treated wood.

Nestrick and Lamparski (1982, 1983) expanded the research of Bumb et al. (1980) by conducting a survey of CDD concentrations in chimney soot from residential wood-burning units in three different rural areas of the United States. Samples were collected from the base of six chimneys in each of the three study areas. Samples were not collected from units where any type of treated or manufactured wood had been burned. For lack of a suitable analytical method, analysis was not performed for PeCDDs. The results of this survey are summarized in Table 4-10. There was wide variation in the results across soot samples with standard deviations for congeners and congener groups often equal to or exceeding the mean value; however, CDDs in each congener group were detected in the soot from almost all sampled units. Nestrick and Lamparski (1982, 1983) concluded that the results do not appear to present any easily discernible patterns with respect to geographic region, furnace operational parameters, or wood fuel type. Nestrick and Lamparski (1982, 1983) attribute the wide variability observed to differences in

design of the different units, which affected the sampling point and/or the conditions at the sampling point, and/or possible contamination of the fuel wood.

Clement et al. (1985b) analyzed chimney soot and bottom ash from residential woodstoves and fireplaces in Canada. The CDD/CDF congener concentrations are presented in Table 4-10 (soot) and Table 4-11 (bottom ash). CDD/CDF congeners were detected in all samples analyzed, although the relative amounts of the different congener groups varied considerably and inconsistently within the type of wood burning unit and between ash and soot samples from the same unit. Clement et al. (1985b) also presents total CDD/CDF concentration data for bottom ashes from outside open-air burning of wood. No analyses were reported for individual congeners. The results for the congener groups are presented below. Clement et al. (1985b) did not present the quantities of ashes produced by the outside open-air burning test, hence it is not possible to readily determine the quantities of CDD/CDF disposed.

Congener group	Concentration (μg/kg)	Congener group	Concentration (μg/kg)
TCDDs	0.8	TCDFs	2.2
PeCDDs	4.2	PeCDFs	7.6
HxCDDs	7.2	HxCDFs	8.2
HpCDDs	11	HpCDFs	11
OCCDs	10	OCDFs	1.7

Bacher et al. (1992) characterized the full spectrum (i.e., mono- through octa-substitution) of chlorinated and brominated dibenzo-p-dioxin and dibenzofuran congeners in the soot from an old farmhouse in southern Germany. The chimney carried smoke from an oven that had used untreated wood at the rate of about 5 m^3 per year for more than 10 years. The sample was taken during the annual cleaning by a chimney sweep. The only BDF detected was mono-BDF (230 ng/kg). No BDDs, BCDDs, or BCDFs were detected at a detection limit of 20 ng/kg. The results for the tetra- through octa- CDDs and CDFs are presented in Table 4-10. The results indicate that CDFs dominate the CDDs in each congener group except octa. Also, the lower chlorinated congener groups dominate the higher chlorinated congener groups for both the CDDs and CDFs. The TEQ

content of the chimney soot was 720 ng I-TEQ_{DF}/kg (755 ng TEQ_{DF}-WHO_{98}/kg) of which less than 30 percent was due to CDDs.

Van Oostdam and Ward (1995) analyzed soot from two wood stoves in British Columbia, Canada. The average TEQ concentrations were 211 ng I-TEQ_{DF}/kg and 246 ng TEQ_{DF}-WHO_{98}/kg. The congener-specific results are presented in Table 4-10. The soot from a wood stove burning salt-laden wood in a coastal area was found to have an I-TEQ_{DF} content of 7,706 ng I-TEQ_{DF}/kg or 20 to 90 times greater than the concentrations found in the soot from the other two tested stoves.

Dumler-Gradl et al. (1995a) analyzed chimney soot samples collected by chimney sweeps from 188 residences in Bavaria. The summary results of the survey, the largest published survey of its kind to date, are presented in Table 4-12. As was observed by Nestrick and Lamparski (1982, 1983) and Clement et al. (1985b), CDD/CDFs were detected in all samples; however, there was wide variability in total TEQ concentrations within and across unit type/fuel type combinations.

Washington (1998) reports CDD/CDF congener data for ash from hog fuel boilers at three paper mills. The data are compiled and evaluated to determine a total I-TEQ concentrations and loading. Non-detect values were included as either zero, ½ DL or at the DL. The results are as follows, assuming that non-detect values are at zero concentration:

Location	Type of Residual	I-TEQ_{DF} (ng/kg)	I-TEQ_{DF} (mg/day)
Daishowa America, Port Angeles	Mixed Ash	0.31	0.012
Ft. James	Fly Ash	35.4	0.544
Rayonier	Filter Ash Vacuum Filter & Grate Filter Ash Fly Ash	12,640 1,150 2,299 225	68.9 6.27 12.5 1.23

Pohlandt (1994) presents CDD/CDF concentration data for various ashes ("bottom", "furnace", "boiler", "fly") from 12 wood burning boilers. The "fly ash" samples from two wood working industry boilers appear to have the greatest concentrations of CDD/CDF. Table 4-13 list the average congener concentration for those two boilers.

Three boiler bottom ash samples contain detectable amounts of only total HpCDD/HpCDF and OCDD/OCDF. All the other boiler samples were from boilers that burned copper/chrome/boron impregnated woods. These samples had total TEQs (assumed to be I-TEQs) ranging from 0.07 - 89 ppt, the highest being the fly ash samples (52 and 89). Pohlandt (1994) did not report the quantities produced by the boilers that were tested, hence it is not possible to readily determine the quantities of CDD/CDF disposed.

Carpenter (2001) reported the results of analyses of two ash samples from wood burning facilities in New Hampshire. Both samples are from the burning of clean (i.e., untreated) wood chips, sawdust and bark. The first sample is a combination of fly ash and bottom ash. The second sample is only fly ash, but it is a combination of fly ash from two wood burning boilers. For the first sample, none of the 2,3,7,8-substituted congeners were detected at detection limits that ranged from 0.98 ng/kg for 2,3,7,8-TCDD and 2,3,7,8-TCDF to 9.80 ng/kg for OCDD and OCDF. (All other congeners had a detection limit of 4.90 ng/kg.) For the second sample, except for two congeners, all congeners were below detection limits (which ranged from 0.379 to 0.831 ng/kg). The two congeners that exceeded detection limits were OCDD at 1.261 ng/kg, and 1,2,3,4,6,7,8-HpCDF at 1.022 ng/kg. For this sample, assuming that the non-detect congeners are not present, I-TEQ_{DF} concentration is 0.011 ng/kg. The quantities of the ash produced were not reported.

In a CARB report of emissions from a wood waste fired incinerator (CARB, 1990b) data are given for CDDs and CDFs for four ash samples. The concentrations of 2,3,7,8-substituted CDD/CDF congeners for each of those four tests were *all* below the method detection limits (MDLs) except for OCDD, which was detected in three samples at concentrations of 14,18, and 32 ng/kg, and 2,3,7,8-TCDF, which was detected in one sample at a concentration of 2.2 ng/kg. The method detection limits for each CDD and CDF congener ranged from 0.63 ppt (for 2,3,7,8-TCDD) to 9.5 ppt (for HpCDF congeners). Total CDD and total CDF values are given for each of the four samples. However, those values assume that non-detected congeners are at the MDL level. Consequently, the total CDD and total CDF values are biased high. The average of the four total CDD values is 28.8 ng/kg (with a range of 20.3 - 44.0). The average of the four total CDF values is 21.9 ng/kg (with a range of 16.0 - 26.9).

In another CARB report (CARB, 1990e), data are presented for CDDs and CDFs for several samples of Electrostatic Precipitator (ESP) waste ash from a wood-fired boiler. The report provides sample results for two weeks of sampling conducted at the facility. During the first week, the boiler burned fuels that were allowed by the facility permit; during the second week, the boiler burned a mixture containing 70 percent permitted fuel and 30 percent urban wood wastes. For the six samples collected over the three days of the first week, many of the concentrations of CDD/CDF congeners in the ESP ash were below the detection limits. CARB reports the CDD concentrations in ESP waste ash ranged from 24 to 264 ng/kg, and the CDF concentrations ranged from 12 to 151 ng/kg. However, those values assume that non-detected congeners are present at the detection level. One sample does not have any non-detect values for CDDs. The total CDD concentration for this sample is 264 ng/kg, or about 8.3 ng/kg I-TEQ_{DF} and 11.4 ng/kg WHO-TEQs. The I-TEQ_{DF} and TEQ_{DF}-WHO_{98} CDF concentrations for this sample are both less than 1.5 ng/kg. These values are less than 1 ng/kg for the other five samples. All of the samples have some non-detects for the CDF analysis.

Six samples were also collected over three days during the second week of sampling, when the 70/30 permitted/urban wood waste mix was burned. For the samples from the second week, the CDD concentrations in ESP waste ash ranged from 1,365 to 3,190 ng/kg, and the CDF concentrations ranged from 2,866 to 11,282 ng/kg. CARB (1990e) assumes that non-detected congeners are present at the detection level. However, this is a reasonable estimate for this data set because there is only one non-detect value. Table 4-14 presents the average congener concentrations for these samples.

CARB (1990e) did not present quantities of ESP ashes produced by the boiler, therefore, it is not possible to readily determine the quantities of CDD/CDF disposed.

Appendix II of Luthe (1998) reports TEQ concentrations (assumed to be I-TEQ_{DF}) in ashes collected from air pollution control devices from "salt-laden" wood steam boilers. The I-TEQ_{DF} content of ashes from three for primary multiclone hoppers varied significantly, 0.0978, 0.186, and 9.375 μg/kg. For the secondary multiclone hoppers, two samples of ash were taken. The secondary multiclone removes dust from the primary multiclone emissions; and therefore, the ash is finer than primary dust). The I-TEQ_{DF} for the ash were 1.073 and 20.879 μg/kg. The I-TEQ_{DF} for two samples taken from the

electrostatic precipitator, which collects dust from the secondary multiclone emissions, and is, therefore, finer than multiclone dust, are 3.926 and 8.044 μg/kg. No data are given for individual congeners. In fact, because the reference discusses only "dioxins", it is unclear whether the TEQ data are for CDDs, or CDDs plus CDFs. Quantities of collected ash are not given.

Also for the burning of salt-laden wood in paper mill boilers, Table II of Luthe (1996) presents data for the "TEQs [assumed to be I-TEQs] on particulates from secondary collection device" for four different paper mills. Eight data points are given (two for each mill), the average of which is 3.6 μg/kg. The range of values is 1.3 to 8.0 μg/kg. As with Luthe (1998), no data are given for individual congeners. It is also unclear whether the TEQ data are for CDDs, or CDDs plus CDFs. Quantities of collected ash are not given.

Table 5-16 of U.S.EPA (1987a) contains data indicating that the bottom ash from wood combustion (it is not indicated whether the combustion source was a boiler) from one source contained 140 ng/kg of 2,3,7,8-TCDD, 138,200 ng/kg of CDDs, and 7,400 ng/kg of CDFs. For a second wood combustion source, the ash contained no detectable 2,3,7,8-TCDD, but did contain about 125 ng/kg of CDDs and non detectable levels of CDFs. The baghouse dust from the second source contained 100 ng/kg of 2,3,7,8-TCDD, 1,143,600 ng/kg of CDDs, and 315,600 ng/kg of CDFs. Specific data for congeners and for ash/dust quantities were not given.

4.3. OIL COMBUSTION

Two major categories of fuel oil are burned by combustion sources: distillate oils and residual oils. These oils are further distinguished by grade numbers, with Nos. 1 and 2 being distillate oils; Nos. 5 and 6 being residual oils; and No. 4 either distillate oil or a mixture of distillate and residual oils. No. 6 fuel oil is sometimes referred to as Bunker C. Distillate oils are more volatile and less viscous than residual oils. They have negligible nitrogen and ash contents and usually contain less than 0.3 percent sulfur (by weight). Distillate oils are used mainly in domestic and small commercial applications. Being more viscous and less volatile than distillate oils, the heavier residual oils (Nos. 5 and 6) must be heated for ease of handling and to facilitate proper atomization. Because residual oils are produced from the residue remaining after the lighter fractions (gasoline, kerosene, and

distillate oils) are removed from the crude oil, they contain significant quantities of ash, nitrogen, and sulfur. Residual oils are used mainly in utility, industrial, and large commercial application (U.S. EPA, 1995b).

4.3.1. Residential/Commercial Oil Combustion

No testing of the CDD/CDF content of air emissions from residential/commercial oil-fired combustion units in the United States could be located. However, U.S. EPA (1997b) has estimated CDD/CDF congener group and I-TEQ$_{DF}$ emission factors based on average CDD/CDF concentrations reported for soot samples from 21 distillate fuel oil-fired furnaces used for central heating in Canada, and a particulate emission factor for distillate fuel oil combustors (300 mg/L of oil) obtained from AP-42 (U.S. EPA, 1995b). The I-TEQ$_{DF}$ emission factor estimate in U.S. EPA (1997b) was derived using the calculated emission factors for 2,3,7,8-TCDD, 2,3,7,8-TCDF, and the 10 congener groups. These emission factors are presented in Table 4-15, and the congener group profile is presented in Figure 4-6.

Because there are no direct measurements of CDD/CDF emissions in stack gases from U.S. residential oil-fired combustors and because of uncertainties associated with using chimney soot data to estimate stack emissions, no national emission estimates for this category are proposed at this time. However, a preliminary estimate of potential national TEQ emissions from this source category can be made using the emission factor presented in Table 4-13 (150 pg I-TEQ$_{DF}$/L of oil combusted). Distillate fuel oil sales to the residential/commercial sector totaled 39.7 billion liters in 1995 (EIA, 1997a). Application of the emission factor of 150 pg I-TEQ$_{DF}$/L to this fuel oil sales estimate results in estimated emissions of 6.0 g I-TEQ$_{DF}$ in 1995. This estimate should be regarded as a preliminary indication of possible emissions from this source category; further testing is needed to confirm the true magnitude of the emissions.

4.3.2. Utility Sector and Industrial Oil Combustion

Preliminary CDD/CDF emission factors for oil-fired utility boilers developed from boiler tests conducted over the past several years are reported in U.S. EPA (1997b). The data are a composite of various furnace configurations and APCD systems. Table 4-16 lists the median emission factors presented in U.S. EPA (1997b). The congener and

congener group profiles based on these data are presented in Figure 4-7. The median I-TEQ_{DF} emission factor was reported to be 314 pg/L of oil burned (or 366 pg TEQ_{DF}-WHO_{98}/L).

In 1993, the Electric Power Research Institute (EPRI) sponsored a project to gather information of consistent quality on power plant emissions. This project, the Field Chemical Emissions Measurement (FCEM) project, included testing of two cold side ESP-equipped oil-fired power plants for CDD/CDF emissions (EPRI, 1994). The averages of the congener and congener group emission factors reported for these two facilities are presented in Table 4-16. The average TEQ emission factors are 83.1 pg I-TEQ_{DF}/L and 93.6 pg TEQ_{DF}-WHO_{98}/L of oil burned (when nondetected values are treated as zero).

The TEQ emission factors reported in EPRI (1994) are a factor of three to four less than the median TEQ emission factor reported in U.S. EPA (1997b). For purposes of this assessment, emission factors of 200 pg I-TEQ_{DF}/L and 230 pg TEQ_{DF}-WHO_{98}/L (i.e., the average of the EPA median and EPRI mean emission factors) are assumed to be current best estimates of the average TEQ emission factors for utility/industrial oil burning. These estimated emission factors are assigned a low confidence rating.

The emission factors derived above were based on combustion of virgin oil by utility boilers. Significantly greater emission factors have been reported by Bremmer et al. (1994) for combustion of used oil by smaller combustion units in The Netherlands. Flue gases from a garage stove consisting of an atomizer fueled by spent lubricating oil from diesel engines (35 mg Cl^-/kg) were reported to contain 0.1 ng I-TEQ_{DF}/Nm^3 (or 2,000 pg I-TEQ_{DF}/kg of oil burned). The flue gases from a hot water boiler consisting of a rotary cup burner fueled with the organic phase of rinse water from oil tanks (340 mg Cl^-/kg) contained 0.2 ng I-TEQ_{DF}/Nm^3 (or 4,800 pg I-TEQ_{DF}/kg of oil burned). The flue gases from a steam boiler consisting of a rotary cup burner fueled by processed spent oil (240 mg Cl^-/kg) contained 0.3 ng I-TEQ_{DF}/Nm^3 (or 6,000 pg I-TEQ_{DF}/kg of oil burned). The emission factor for a ferry burning heavy fuel oil containing 11 ng/kg organic chlorine was 3,200 to 6,500 pg I-TEQ_{DF}/kg of oil burned. From these data, Bremmer et al. (1994) derived an average emission factor for combustion of used oil of 4,000 pg I-TEQ_{DF}/kg of oil burned. Bremmer et al. (1994) also reported measuring CDD/CDF emissions from a river barge and a container ship fueled with gas oil (less than 2 ng/kg of organic chlorine). The exhaust gases contained from 0.002 to 0.2 ng I-TEQ_{DF}/Nm^3. From these data, Bremmer et al.

(1994) derived an average emission factor for inland oil-fueled vessels of 1,000 pg I-TEQ_{DF}/kg oil burned. The applicability of these emission factors to used oil combustors in the United States is uncertain. Therefore, estimates of potential emissions from used oil combustion in the United States are not being developed at this time.

Residual fuel oil sales totaled 46.6 billion liters in 1995 and 77.3 billion liters in 1987 (EIA, 1992, 1997a). Vessel bunkering was the largest consumer (48 percent of sales) followed by electric utilities and the industrial sector. A high confidence rating is assigned to these production estimates. Application of the TEQ emission factor of 200 pg I-TEQ_{DF}/L (230 pg TEQ_{DF}-WHO_{98}/L) to these residual fuel oil sales results in estimated TEQ emissions of 9.3 g I-TEQ_{DF} (10.7 g TEQ_{DF}-WHO_{98}) in 1995 and 15.5 g I-TEQ_{DF} 1987 (17.8 g TEQ_{DF}-WHO_{98}) in 1987.

4.4. COAL COMBUSTION

During 1995, coal consumption accounted for approximately 22 percent of the energy consumed from all sources in the United States (U.S. DOC, 1997). In 1995, 872 million metric tons of coal were consumed in the United States. Of this total, 88.4 percent (or 771 million metric tons) were consumed by electric utilities, 11.0 percent (or 96 million metric tons) were consumed by the industrial sector (including consumption of 30 million metric tons by coke plants), and 0.6 percent (or 5.3 million metric tons) were consumed by residential and commercial sources (EIA, 1997b). Comparable figures for 1987 are: total consumption, 759 million metric tons; consumption by electric utilities, 651 million metric tons; consumption by coke plants, 33.5 million metric tons; consumption by other industries, 68.2 million metric tons; and consumption by the residential and commercial sectors, 6.3 million metric tons (EIA, 1995c). These production estimates are assigned a high confidence rating because they are based on detailed studies specific to the United States.

The following two subsections discuss the results of relevant emission studies for the utility/industrial and residential sectors, respectively, and present annual TEQ emission estimates for the reference years 1987 and 1995.

4.4.1. Utilities and Industrial Boilers

Until fairly recently, few studies had been performed to measure CDD/CDF concentrations in emissions from coal-fired plants, and several of these studies did not have the congener specificity and/or detection limits necessary to fully characterize this potential source (U.S. EPA, 1987a; NATO, 1988; Wienecke et al., 1992). The results of more recent testing of coal-fired utility and industrial boilers in The Netherlands (Bremmer et al., 1994), the United Kingdom (Cains and Dyke, 1994; CRE, 1994), Germany (Umweltbundesamt, 1996), and the United States (Riggs et al., 1995; EPRI, 1994) have achieved lower detection limits.

Bremmer et al. (1994) reported the results of emission measurements at two coal-fired facilities in The Netherlands. The emission factor reported for a pulverized coal electric power plant equipped with an ESP and a wet scrubber for sulfur removal was 0.35 ng I-TEQ_{DF}/kg of coal fired (or 0.02 ng I-TEQ_{DF}/Nm^3 at 11 percent O_2). The emission factor reported for a grass drying chain grate stoker equipped with a cyclone APCD was 1.6 ng I-TEQ_{DF}/kg of coal fired (or 0.16 ng I-TEQ_{DF}/Nm^3 at 11 percent O_2).

Cains and Dyke (1994) reported an emission factor of 102 to 109 ng I-TEQ_{DF}/kg of coal at a small-scale facility in the United Kingdom that was equipped with an APCD consisting only of a grit arrestor. CRE (1994) reported results of testing at 13 commercial/ industrial coal-fired boilers in the United Kingdom. The I-TEQ_{DF} emission factors ranged from 0.04 to 4.8 ng I-TEQ_{DF}/kg coal combusted (mean value of 0.6 ng I-TEQ_{DF}/kg). CRE (1994) also reported testing results for one coal-fired power plant, 0.06 ng I-TEQ_{DF}/kg coal combusted.

Umweltbundesamt (1996) reported that the I-TEQ_{DF} content of stack gases from 16 coal-burning facilities in Germany ranged from 0.0001 to 0.04 ng I-TEQ_{DF}/m^3; the data provided in that report did not enable emission factors to be calculated.

The U.S. Department of Energy sponsored a project in 1993 to assess emissions of hazardous air pollutants at coal-fired power plants. As part of this project, CDD/CDF stack emissions were measured at seven U.S. coal-fired power plants. The preliminary results of this project (i.e., concentrations in stack emissions) were reported by Riggs et al. (1995) and are summarized in Table 4-17. The levels reported for individual 2,3,7,8-substituted congeners were typically very low (i.e., $\leq$0.033 ng/Nm^3) or not detected. In general, CDF levels were higher than CDD levels. OCDF and 2,3,7,8-TCDF were the most

frequently detected congeners (i.e., at four of the seven plants). Table 4-18 presents characteristics of the fuel used and APCD employed at each plant. Variation in emissions between plants could not be attributed by Riggs et al. (1995) to any specific fuel or operational characteristic.

During the early 1990s, EPRI also sponsored a project to gather information of consistent quality on power plant emissions. This project, the Field Chemical Emissions Measurement (FCEM) project, included testing of four cold-side ESP-equipped coal-fired power plants for CDD/CDF emissions. Two plants burned bituminous coal and two burned subbituminous coal. The final results of the DOE project discussed above (Riggs et al., 1995) were integrated with the results of the EPRI testing and published in 1994 (EPRI, 1994). The average congener and congener group emission factors derived from this 11 facility data set, as reported in EPRI (1994), are presented in Table 4-19. Congener and congener group profiles for the data set are presented in Figure 4-8. The average I-TEQ_{DF} and TEQ_{DF}-WHO_{98} emission factors, assuming nondetected values are zero, are 0.079 ng I-TEQ_{DF}/kg of coal combusted and 0.078 ng TEQ_{DF}-WHO_{98}/kg. A medium confidence rating is assigned to these emission factors derived from the DOE and EPRI studies because they are based on recent testing at U.S. utilities.

Because the EPRI and DOE data only characterized emissions from units with cold-side ESPs, there has been uncertainty regarding the applicability of the emission factors derived from these data to units with hot-side ESPs. In July 1999, EPA conducted testing of stack emissions at a coal-fired utility equipped with a hot-side ESP. The preliminary results of this testing indicate that the TEQ emission factor for hot-sided ESPs is of the same order of magnitude as the average TEQ emission factors derived above.

As stated above, consumption of coal by the U.S. utility sectors was 771 million metric tons in 1995 and 651 million metric tons in 1987. Applying the TEQ emission factors of 0.079 ng I-TEQ_{DF}/kg of coal combusted and 0.078 ng TEQ_{DF}-WHO_{98}/kg to these production factors yields estimated annual emissions of 60.9 g I-TEQ_{DF} and 60.1 g TEQ_{DF}-WHO_{98} in 1995 and 51.4 g I-TEQ_{DF} and 50.8 TEQ_{DF}-WHO_{98} in 1987 by the utility sector.

No testing of the CDD/CDF content of air emissions from commercial/industrial coal-fired combustion units in the United States could be located. However, as noted above, several studies have been performed in European countries (Bremmer et al., 1994; CRE, 1994). It is uncertain whether the data collected in these European studies

accurately represent U.S. sources, but the data suggest that emission factors for commercial/industrial sources can be higher than those reported above for U.S. coal-fired utilities. Therefore, no national emission estimate for this category is being derived at this time. However, a preliminary estimate of potential national TEQ emissions from this source category can be derived using the average emission factor reported in CRE (1994), 0.6 ng I-TEQ_{DF}/kg coal combusted. As noted above, 66 million metric tons of coal were consumed by the industrial sector (excluding 30 million metric tons consumed by coke plants). Applying the emission factor of CRE (1994) to this activity level estimate yields an estimated national emission of 39.6 g I-TEQ_{DF} in 1995. This estimate should be regarded as a preliminary indication of possible emissions from commercial/industrial coal-fired boilers; further testing is needed to confirm the true magnitude of these emission.

4.4.2. Residential/Commercial Coal Combustion

Coal is usually combusted in underfeed or hand-stoked furnaces in the residential sector. Other coal-fired heating units include hand-fed room heaters, metal stoves, and metal and masonry fireplaces. Stoker-fed units are the most common design for warm-air furnaces and for boilers used for steam or hot water production. Most coal combusted in these units are either bituminous or anthracite. These units operate at relatively low temperatures and do not efficiently combust the coal. Coal generally contains small quantities of chlorine and CDD/CDF; therefore, the potential for CDD/CDF formation exists. Typically, coal-fired residential furnaces are not equipped with particulate matter or gaseous pollutant control devices that may limit emissions of any CDD/CDFs formed (U.S. EPA, 1997b). No testing of the CDD/CDF content of air emissions from residential/commercial coal-fired combustion units in the United States could be located. However, several relevant studies have been performed in European countries.

Thub et al. (1995) measured flue gas concentrations of CDD/CDF from a household heating system in Germany, fired either with salt lignite coal (i.e., total chlorine content of 2,000 ppm) or normal lignite coal (i.e., total chlorine content of 300 ppm). CDD/CDFs were detected in the flue gases generated by combustion of both fuel types. (See Table 4-20.) The congener profiles and patterns were similar for both fuel types, with OCDD the dominant congener and TCDF the dominant congener group. However, the emissions were higher for the "salt" coal (0.109 ng I-TEQ_{DF}/m^3 or 2.74 ng I-TEQ_{DF}/kg of

coal) by a factor of eight than for the "normal" coal (0.015 ng I-TEQ_{DF}/m^3 or 0.34 ng I-TEQ_{DF}/kg of coal).

Eduljee and Dyke (1996) used the results of testing performed by the Coal Research Establishment in the United Kingdom to estimate emission factors for residential coal combustion units as follows:

- Anthracite coal: 2.1 ng I-TEQ_{DF}/kg of coal; and
- Bituminous coal: 5.7 to 9.3 ng I-TEQ_{DF}/kg of coal (midpoint of 7.5 ng I-TEQ_{DF}/kg).

CDD/CDF emission factors for coal-fired residential furnaces were estimated in U.S. EPA (1997b) based on average particulate CDD/CDF concentrations from chimney soot samples collected from seven coal ovens, and particulate matter emission factors specific to anthracite and bituminous coal combustion obtained from AP-42 (U.S. EPA, 1995b). The I-TEQ_{DF} emission factors estimated in U.S. EPA (1997b) (i.e., 60.0 and 98.5 ng I-TEQ_{DF}/kg of anthracite and bituminous coal, respectively) were derived using the calculated emission factors for 2,3,7,8-TCDD 2,3,7,8-TCDF, and the 10 congener groups. U.S. EPA (1997b) stated that the estimated factors should be considered to represent maximum emission factors, because soot may not be representative of the particulate matter actually emitted to the atmosphere. These emission factors are presented in Table 4-20, and congener group profiles are presented in Figure 4-9.

Although the congener group profiles of the Thub et al. (1995) measurements and the U.S. EPA (1997b) estimates are similar, the I-TEQ_{DF} emission factors differ by factors of 175 to 289 between the two studies. The emission factors used by Eduljee and Dyke (1996) to estimate national annual emissions of I-TEQ_{DF} from residential coal combustion in the United Kingdom fall in between those other two sets of estimates but are still about one to two orders of magnitude greater than the estimated emission factor for industrial/ utility coal combustors. (See Section 4.4.1.)

Because there are no direct measurements of CDD/CDF emissions from U.S. residential coal-fired combustors and because of uncertainties regarding the comparability of U.S. and German and British coal combustion units, no national emission estimate for this category is being derived at this time. However, a preliminary estimate of potential

national TEQ emissions from this source category can be derived using the emission factors of Eduljee and Dyke (1996). As noted above, 5.3 million metric tons of coal were consumed by the residential/commercial sector in 1995 (U.S. DOC, 1997). U.S. EPA (1997b) reports that 72.5 percent of the coal consumed by the residential sector in 1990 were bituminous and 27.5 percent were anthracite. Assuming that these relative proportions reflect the actual usage in 1995, then application of the emission factors from Eduljee and Dyke (1996) (i.e., 2.1 ng I-TEQ_{DF}/kg of anthracite coal and 7.5 ng I-TEQ_{DF}/kg of bituminous coal) to the consumption value of 5.3 million metric tons results in an estimated I-TEQ_{DF} emission of 32.0 g TEQ in 1995. This estimate should be regarded as a preliminary indication of possible emissions from this source category; further testing is needed to confirm the true magnitude of these emissions.

4.4.3. Solid Wastes from Coal Combustion

A limited amount of CDD/CDF concentration data have been developed for utility industry solid wastes (U.S.EPA, 1999b). These data are for utility industry solid wastes that are comanaged (i.e., combinations of fly ash, bottom ash, boiler slag, and flue gas desulfurization [FGD] wastes). Samples were taken from 11 disposal sites. A total of 15 samples were taken from the 11 sites. The average concentrations for each of the CDD and CDF congeners are presented in the second column of Table 4-21. It should be noted that most of the concentration values shown in Table 4-21 represent limits of detection. Consequently, the values overestimate the actual concentration.

Section 3.3 of U.S.EPA (1999c) indicates that there were approximately 63 million tons (assumed to be short tons, i.e., 2,000 pounds) of large-volume utility coal combustion solid wastes produced in 1995. Of this amount, about 67 percent was landfilled, and the balance was disposed of in surface impoundments. The concentration data presented in Table 4-21 is only for the 53 million tons that were comanaged (or about 84 percent of the total wastes). For purposes of this analysis it will be assumed that the CDD/CDF concentrations in the comanaged wastes are the same as for the entire waste quantity. Combining the concentration data with the 63 million tons of total waste yields the total quantities of each congener disposed of in 1995. These data are presented in the fourth column of Table 4-21. Section 4.4 of this document indicates that total consumption of coal for electric utility boilers in 1987 was 98.4 percent of 1995

consumption. Consequently, the quantities of CDD/CDF disposed of in 1987 is assumed to be 98.4 percent of the 1995 values. These values are presented in column 3 of Table 4-21.

The 1995 congener quantities are converted into I-TEQ_{DF} and TEQ_{DF}-WHO_{98} values in columns 5 and 6 of Table 4-21 respectively. The values for 1987 are assumed to be 98.4 percent of the 1995 values based on the assumptions stated in the above paragraph.

Table 4-1. Descriptions and Results of Vehicle Emission Testing Studies for CDDs and CDFs

Study	Country	Fuel Type	Scavenger[a]	Catalyst Equipped	Number of Test Vehicles	TEQ Emission Factor[g] (pg/km driven)	Driving Cycle; Sampling Location
CARB (1987a); Lew (1996)	United States	Diesel (truck)	No	NR	1	676-1,325[b] [597-1,307]	6-hr dynamometer test at 50 km/hr
Marklund et al. (1987)	Sweden	Unleaded Leaded	No Yes	Yes No	2 4	not detected (<13) approx. 20-220	A10 (2 cycles); muffler exhaust A10 (2 cycles); muffler exhaust
Bingham et al. (1989)	New Zealand	Unleaded Leaded	No Yes	NR NR	1 4	not detected (<20) 1-39	A10 (3 or 4 cycles); muffler exhaust A10 (3 or 4 cycles); muffler exhaust
Marklund et al. (1990)	Sweden	Unleaded Leaded Unleaded Leaded Diesel (truck)	No Yes No Yes No	No No Yes No NR	2 2 1 2 1	0.36-0.39 2.4-6.3 0.36 1.1-2.6[e] not detected (<18)[b]	FTP-73 test cycle; before muffler FTP-73 test cycle; before muffler FTP-73 test cycle; in tailpipe FTP-73 test cycle; in tailpipe U.S. Federal mode 13 cycle; before muffler
Hagenmaier et al. (1990)	Germany	Unleaded Unleaded Leaded Diesel (car)	No No Yes No	No Yes No NR	1 1 1 1	5.1[b] [6.0] 0.7[b] [0.8] 108[b] [129] 2.1[b] [2.5]	Comparable to FTP-73 test cycle; in tailpipe Comparable to FTP-73 test cycle; in tailpipe Comparable to FTP-73 test cycle; in tailpipe Comparable to FTP-73 test cycle; in tailpipe
Oehme et al. (1991) (tunnel study)	Norway	---	---	---	(c)	520[d] 38[d] avg = 280 9,500[d] 720[d] avg = 5,100	Cars moving uphill (3.5% incline) at 60 km/hr Cars moving downhill (3.5% decline) at 70 km/hr Car average Trucks moving uphill (3.5% incline) at 60 km/hr Trucks moving downhill (3.5% decline) at 70 km/hr Truck average
Schwind et al. (1991) Hutzinger et al. (1992)	Germany	Leaded Unleaded Unleaded Diesel (car) Diesel (truck)	Yes No No No No	No No Yes No No	1 1 1 1 1	5.2-118[b] [7.2-142] 9.6-17.7[b] [10.2-18.1] 1.0-2.6[b] [1.0-2.8] 1.0-13[b] [1.2-14] 13-15[b] [14-15]	Various test conditions (i.e., loads and speeds) Various test conditions (i.e., loads and speeds) Various test conditions (i.e., loads and speeds) Various test conditions (i.e., loads and speeds) Various test conditions (i.e., loads and speeds)
Gertler et al. (1996, 1998) (tunnel study)	United States	Diesel (truck)	---	---	(f)	mean = 172	Mean of seven 12-hour samples
Gullett and Ryan (1997)	United States	Diesel (truck)	No	---	1	mean - 29.0	Mean of five sample routes

[a] Dichloroethane and dibromoethane, except for Marklund et al. (1987), used as scavengers.

[b] Results reported were in units of pg TEQ/liter of fuel. For purposes of this table, the fuel economy factor used by Marklund et al. (1990), 10 km/L or 24 miles/gal, was used to convert the emission rates into units of pg TEQ/km driven for the cars. For the diesel-fueled truck, the fuel economy factor reported in CARB (1987a) for a 1984 heavy-duty diesel truck, 5.5 km/L (or 13.2 miles/gal), was used.

[c] Tests were conducted over portions of 4 days, with traffic rates of 8,000-14,000 vehicles/day. Heavy duty vehicles (defined as vehicles over 7 meters in length) ranged from 4-15% of total.

[d] Emission factors are reported in units of pg Nordic TEQ/km driven; the values in units of I-TEQ_{DF}/km are expected to be about 3 to 6 percent higher.

[e] Table reflects the range of summary results reported in Marklund et al. (1990); however, the congener-specific results for the single run reported indicate an emission rate of about 7.3 pg I-TEQ_{DF}/km.

[f] Tests were conducted over 5 days with heavy-duty vehicle rates of 1,800-8,700 vehicles per 12-hour sampling event. Heavy-duty vehicles accounted for 21-28 percent of all vehicles.

[G] Values listed are in units of I-TEQ_{DF}. Values in brackets are in units of TEQ_{DF}-WHO_{98}.

NR = Not Reported

Table 4-2. Diesel-Fueled Automobile CDD/CDF Congener Emission Factors

Congener/Congener Group	Automobile Tailpipe Emission Study Results				Mean Emission Factors	
	63 km/hr (Ref. A) (pg/L)	Idling (test no. 25) (Ref. B) (pg/L)	57 km/hr (test no. 24) (Ref. B) (pg/L)	57 km/hr (full load) (test no. 28) (Ref. B) (pg/L)	Assuming ND = zero (pg/L)	Assuming ND = ½ det limit (pg/L)
2,3,7,8-TCDD	7.9	13.1	2.4	22	11.4	11.4
1,2,3,7,8-PeCDD	9.0	6.3	4.1	23	10.6	10.6
1,2,3,4,7,8-HxCDD	ND (5.1)	21.4	1.0	7.8	7.6	8.2
1,2,3,6,7,8-HxCDD	ND (5.1)	36	1.4	21	14.6	15.2
1,2,3,7,8,9-HxCDD	ND (5.1)	28	2.0	10	10.0	10.6
1,2,3,4,6,7,8-HpCDD	44.1	107	22.9	166	85.0	85.0
OCDD	440	635	525	560	540	540
2,3,7,8-TCDF	20.5	79	18.1	236	88.4	88.4
1,2,3,7,8-PeCDF	ND (5.1)	171	1.8	111	71.0	71.6
2,3,4,7,8-PeCDF	7.1	58.7	3.4	85	38.6	38.6
1,2,3,4,7,8-HxCDF	6.5	121	4.1	68	49.9	49.9
1,2,3,6,7,8-HxCDF	6.7	75	3.0	55	34.9	34.9
1,2,3,7,8,9-HxCDF	ND (5.1)	17.1	0.8	4.7	5.7	6.3
2,3,4,6,7,8-HxCDF	ND (5.1)	52	ND (0.4)	31	20.8	21.4
1,2,3,4,6,7,8-HpCDF	40.7	159	18.9	214	108.2	108.2
1,2,3,4,7,8,9-HpCDF	8.5	11.9	7.1	7.8	8.8	8.8
OCDF	94.4	214	101	305	178.6	178.6
Total 2,3,7,8-CDD	501.0	846.8	558.8	809.8	679.1	681.0
Total 2,3,7,8-CDF	184.4	958.7	158.2	1117.5	604.7	606.7
Total I-TEQ_{DF} (ND = zero)	20.8	100.7	10.4	129.6	65.4	
Total I-TEQ_{DF} (ND = ½ det limit)	22.2*	100.7	10.4	129.6		65.7
Total TEQ_{DF}-WHO_{98} (ND = zero)	24.8	103.1	11.9	140.4	70.0	
Total TEQ_{DF}-WHO_{98} (ND = ½ det limit)	26.2	103.1	1.9	140.4		70.4
Total TCDD	37.4	317	31	394	195	195
Total PeCDD	19.7	214	22	228	121	121
Total HxCDD	23.6	256	20	164	116	116
Total HpCDD	88.5	187	77	356	177	177
Total OCDD	440.5	635	525	560	540	540
Total TCDF	76.7	436	58	3093	916	916
Total PeCDF	39.3	821	36	1205	525	525
Total HxCDF	25.6	556	26	472	270	270
Total HpCDF	80.6	321	72	241	179	179
Total OCDF	94.4	214	101	305	179	179
Total CDD/CDF (ND = zero)	926.3	3,957	968	7,018	3,217	
Total CDD/CDF (ND = ½ det limit)	926.3	3,957	968	7,018		3,217

ND = Not detected; value in parentheses is the detection limit.

* = An I-TEQ_{DF} emission factor of 23.6 pg/L is reported in Ref. A; however, an I-TEQ_{DF} emission factor of 22.2 pg/L is calculated based on reported congener levels.

Ref. A: Hagenmaier et al. (1990)

Ref. B: Schwind et al. (1991); Hutzinger et al. (1992)

Table 4-3. Diesel-Fueled Truck CDD/CDF Congener Emission Factors

Congener/Congener Group	Truck Tailpipe Study Results			Mean Emission Factors	
	50 km/hr (test no. 40) (Ref. A) (pg/L)	90 km/hr (full load) (test no. 42) (Ref. A) (pg/L)	50 km/hr (Ref. B) (pg/L)	Assuming ND = zero (pg/L)	Assuming ND = ½ det lim (pg/L)
2,3,7,8-TCDD	25	16	ND (560)	13.7	107
1,2,3,7,8-PeCDD	5	18	ND (1,340)	7.7	231
1,2,3,4,7,8-HxCDD	14.0	5.7	ND (2,160)	6.6	367
1,2,3,6,7,8-HxCDD	28	6	ND (1,770)	11.3	307
1,2,3,7,8,9-HxCDD	14	6	ND (2,640)	6.7	446
1,2,3,4,6,7,8-HpCDD	119	74	116,000	38,731	38,731
OCDD	1,355	353	344,400	115,369	115,369
2,3,7,8-TCDF	87	53	ND (605)	46.7	148
1,2,3,7,8-PeCDF	45	34	ND (4,750)	26.3	819
2,3,4,7,8-PeCDF	18	51	ND (5,190)	23.0	887
1,2,3,4,7,8-HxCDF	56	29	ND (8,210)	28.3	1,397
1,2,3,6,7,8-HxCDF	84	31	ND (6,480)	38.3	1,119
1,2,3,7,8,9-HxCDF	4.7	5.1	13,400	4,469	4,469
2,3,4,6,7,8-HxCDF	63	23	ND (7,780)	28.7	1,325
1,2,3,4,6,7,8-HpCDF	375	71	73,460	24,636	24,636
1,2,3,4,7,8,9-HpCDF	40	5.4	ND (11,700)	15.1	1,960
OCDF	397	104	140,400	46,981	46,981
Total 2,3,7,8-CDD	1,560	478.7	460,400	154,146	155,558
Total 2,3,7,8-CDF	1,170	406.5	227,300	76,292	83,739
Total I-TEQ_{DF} (ND = zero)	81	70	3,720	1,290	
Total I-TEQ_{DF} (ND = ½ det limit)	81	70	7,290		2,480
Total TEQ_{DF}-WHO_{98} (ND = zero)	82	79	3,280	1,150	
Total TEQ_{DF}-WHO_{98} (ND = ½ det limit)	82	79	7,190		2,450
Total TCDD	200	208	ND (3,760)	136	762
Total PeCDD	32	117	ND (3,020)	49.7	553
Total HxCDD	130	67	ND (45,300)	65.7	7,620
Total HpCDD	200	155	203,300	67,892	67,892
Total OCDD	1355	353	344,000	115,252	115,252
Total TCDF	763	694	25,000	8,831	8,831
Total PeCDF	230	736	47,900	16,294	16,294
Total HxCDF	524	268	169,200	56,670	56,670
Total HpCDF	509	76	150,700	50,414	50,414
Total OCDF	397	104	140,300	46,932	46,932
Total CDD/CDF (ND = zero)	4,340	2,778	1,080,500	362,538	
Total CDD/CDF (ND = ½ det limit)	4,340	2,778	1,104,700		370,596

ND = Not detected; value in parentheses is the detection limit.

Ref. A: Schwind et al. (1991); Hutzinger et al. (1992)
Ref. B: Lew (1993, 1996)

Table 4-4. Leaded Gasoline-Fueled Automobile CDD/CDF Congener Emission Factors

Congener/Congener Group	Automotive Tailpipe Emission Study Results							Mean Emission Factors	
	FTP cycle (Ref. A) (pg/L)	63 km/hr (Ref. B) (pg/L)	Idling (test no. 12) (Ref. C) (pg/L)	Full load (test no. 13) (Ref. C) (pg/L)	64 km/hr (test no. 14) (Ref. C) (pg/L)	Rated power (test no. 15) (Ref. C) (pg/L)	FTP cycle (test no. 22) (Ref. C) (pg/L)	Assuming ND = zero (pg/L)	Assuming ND = ½ det limit (pg/L)
2,3,7,8-TCDD	ND	128	NR	60	141	NR	5	67	68
1,2,3,7,8-PeCDD	(14.4)	425	43	106	468	40	73	165	168
1,2,3,4,7,8-HxCDD	ND (36)	188	17	15	206	16	41	69	73
1,2,3,6,7,8-HxCDD	ND (54)	207	32	35	228	30	62	85	89
1,2,3,7,8,9-HxCDD	ND (54)	188	NR	NR	206	NR	35	107	114
1,2,3,4,6,7,8-HpCDD	ND (54)	503	119	136	554	111	518	277	281
OCDD	ND (54) ND (90)	498	380	513	549	1166	1,581	670	676
2,3,7,8-TCDF	432	1,542	NR	678	1,697	78	214	774	774
1,2,3,7,8-PeCDF	21.6	1,081	49	367	1,190	45	218	425	425
2,3,4,7,8-PeCDF	43.2	447	26	156	492	24	225	202	202
1,2,3,4,7,8-HxCDF	ND (54)	856	33	70	942	31	381	330	334
1,2,3,6,7,8-HxCDF	ND (54)	856	22	60	942	20	375	325	329
1,2,3,7,8,9-HxCDF	ND (54)	ND (76)	NR	NR	NR	NR	85	28	50
2,3,4,6,7,8-HxCDF	ND (54)	273	NR	25	301	NR	1,033	326	332
1,2,3,4,6,7,8-HpCDF	ND (54)	4,051	170	NR	4,460	158	2,301	1857	1861
1,2,3,4,7,8,9-HpCDF	ND (54)	ND (76)	NR	NR	NR	NR	109	36	58
OCDF	ND (90)	230	1115	NR	253	447	1,128	529	536
Total 2,3,7,8-CDD	ND	2,137	≥ 591	≥ 865	2,352	≥ 1,363	2,315	1,440	1,469
Total 2,3,7,8-CDF	496.8	9,336	≥ 1,415	≥ 1,356	≥ 10,277	≥ 803	6,069	4,832	4,900
Total I-TEQ_{DF} (ND = zero)	65.9	1,075	≥ 52	≥ 300	≥ 1,184	≥ 56	419	≥ 450	
Total I-TEQ_{DF} (ND = ½ det limit)	102	1,080	≥ 52	≥ 300	≥ 1,184	≥ 56	419		≥ 456
Total TEQ_{DF}-WHO_{98} (ND = zero)	65.9	1,287	≥ 72	≥ 352	≥ 1,417	≥ 75	454	≥ 532	
Total TEQ_{DF}-WHO_{98} (ND = ½ det limit)	111	1,291	≥ 72	≥ 352	≥ 1,417	≥ 75	454		≥ 539
Total TCDD	5,220	4,555	517	8,134	5,012	4,558	921	4,131	4,131
Total PeCDD	ND (360)	3,338	658	2,161	3,675	6,389	359	2,369	2,394
Total HxCDD	ND (540)	1,868	354	623	2,056	1,973	996	1,124	1,163
Total HpCDD	ND (90)	1,164	194	297	1,281	2,374	988	900	906
Total OCDD	ND (90)	498	380	513	549	1,166	1,581	670	676
Total TCDF	15,300	50,743	2,167	20,513	55,857	29,353	4,290	25,460	25,460
Total PeCDF	2,430	11,591	452	3,608	12,757	10,580	3,165	6,369	6,369
Total HxCDF	ND (540)	6,308	192	477	6,947	12,553	3,132	4,230	4,268
Total HpCDF	ND (270)	5,642	170	NR	6,210	4,767	2,920	3,285	3,307
Total OCDF	ND (90)	230	1,115	NR	253	447	1,128	529	536
Total CDD/CDF (ND = zero)	22,950	85,937	6,199	≥ 36,326	94,597	74,160	19,480	≥ 49,066	
Total CDD/CDF (ND = ½ det limit)	23,940	85,937	6,199	≥ 36,326	94,597	74,160	19,480		≥ 49,212

NR = Not reported.
ND = Not detected; value in parentheses is the reported detection limit.

Ref. A: Marklund et al. (1990); values in the table were calculated from the reported units of pg/km to pg/L using a fuel economy of 9 km/L for leaded gas as reported in Marklund et al. (1990).
Ref. B: Hagenmaier et al. (1990)

Table 4-5. Unleaded Gasoline-Fueled (Without Catalytic Converters) Automobile CDD/CDF Congener Emission Factors

Congener/Congener Group	Automotive Tailpipe Emission Study Results						Mean Emission Factors	
	FTP cycle (Ref. A) (pg/L)	63 km/hr (Ref. B) (pg/L)	FTP cycle (test no. 21) (Ref. C) (pg/L)	64 km/hr (test no. 17) (Ref. C) (pg/L)	64 km/hr (test no. 20) (Ref. C) (pg/L)	64 km/hr (test no. 31/2) (Ref. C) (pg/L)	Assuming ND = zero (pg/L)	Assuming ND = ½ det limit (pg/L)
2,3,7,8-TCDD	ND (5)	2.6	24	44	7	8.9	14.4	14.8
1,2,3,7,8-PeCDD	ND (3)	19.1	14	31	11	14.1	14.9	15.1
1,2,3,4,7,8-HxCDD	ND (40)	16.6	24	26	25	16.3	18.0	21.3
1,2,3,6,7,8-HxCDD	ND (40)	17.1	84	28	42	60.1	38.5	41.9
1,2,3,7,8,9-HxCDD	ND (40)	17.6	15	29	23	17.1	17.0	20.3
1,2,3,4,6,7,8-HpCDD	ND (40)	40.4	192	66	121	197.8	103	106
OCDD	ND (50)	176	868	280	685	2,634	774	778
2,3,7,8-TCDF	64	44.0	70	71	77	295.2	104	104
1,2,3,7,8-PeCDF	ND (7)	44.5	40	72	69	161.8	64.6	65.1
2,3,4,7,8-PeCDF	ND (7)	20.7	30	34	184	135.2	67.3	67.9
1,2,3,4,7,8-HxCDF	ND (40)	41.9	68	68	88	129.1	65.8	69.2
1,2,3,6,7,8-HxCDF	ND (40)	21.2	62	34	35	113.2	44.2	47.6
1,2,3,7,8,9-HxCDF	ND (40)	37.8	47	61	ND (1)	36.9	30.5	33.9
2,3,4,6,7,8-HxCDF	ND (40)	54.3	55	88	42	82.1	53.6	56.9
1,2,3,4,6,7,8-HpCDF	ND (40)	27.9	278	45	22	418.0	132	135
1,2,3,4,7,8,9-HpCDF	ND (40)	16.6	ND (1)	27	24	54.5	20.4	23.8
OCDF	ND (70)	119	374	194	288	991	328	334
Total 2,3,7,8-CDD	ND	289.4	1,221	504	914	2,948	979	998
Total 2,3,7,8-CDF	64	427.9	1,024	694	829	2,417	909	936
Total I-TEQ_{DF} (ND = zero)	6.4	50.9	96.4	122	144	177	99.5	
Total I-TEQ_{DF} (ND = ½ det limit)	26.2	50.9	96.4	122	144	177		103
Total TEQ_{DF}-WHO_{98} (ND = zero)	6.4	60.2	102	138	148	181	106	
Total TEQ_{DF}-WHO_{98} (ND = ½ det limit)	26.9	60.2	102	138	148	181		109
Total TCDD	13	435	429	706	500	304	398	398
Total PeCDD	ND (3)	481	837	784	542	170	469	469
Total HxCDD	ND (40)	305	484	496	563	114	327	330
Total HpCDD	ND (10)	93	392	147	225	301	193	194
Total OCDD	ND (5)	176	868	280	685	2,634	774	774
Total TCDF	170	569	718	923	478	6,379	1540	1540
Total PeCDF	ND (7)	931	531	1,513	437	1,969	897	897
Total HxCDF	ND (40)	378	165	615	258	1,226	440	444
Total HpCDF	ND (20)	476	278	773	445	1,088	510	512
Total OCDF	ND (7)	119	374	194	288	991	328	328
Total CDD/CDF (ND = zero)	183	3,963	5,076	6,431	4,421	15,176	5875	
Total CDD/CDF (ND = ½ det limit)	249	3,963	5,076	6,431	4,421	15,176		5886

ND = Not detected; value in parentheses is the reported detection limit.

Ref. A: Marklund et al. (1990); the pg/L values in the table were calculated from the reported units of pg/km assuming a fuel economy of 10 km/L for unleaded gas.

Table 4-6. Unleaded Gasoline-Fueled (With Catalytic Converters) Automobile CDD/CDF Congener Emission Factors

Congener/Congener Group	Automotive Tailpipe Emission Study Test Results				Mean Emission Factors	
	63 km/hr (Ref. A) (pg/L)	64 km/hr (test no. 29I) (Ref. B) (pg/L)	64 km/hr (test no. 30/2) (Ref. B) (pg/L)	64 km/hr (test no. 18) (Ref. B) (pg/L)	Assuming ND = zero (pg/L)	Assuming ND = ½ det limit (pg/L)
2,3,7,8-TCDD	1.6	3.0	ND (7.9)	14	4.7	5.6
1,2,3,7,8-PeCDD	1.6	2.6	ND (7.9)	4	2.1	3.0
1,2,3,4,7,8-HxCDD	2.4	5.3	ND (7.9)	1	2.2	3.2
1,2,3,6,7,8-HxCDD	3.5	6.0	6.4	2	4.5	4.5
1,2,3,7,8,9-HxCDD	3.1	6.0	ND (7.9)	2	2.8	3.8
1,2,3,4,6,7,8-HpCDD	15.3	27.8	78.1	14	33.8	33.8
OCDD	170	275	427	197	267	267
2,3,7,8-TCDF	4.3	10.6	12.7	35	15.7	15.7
1,2,3,7,8-PeCDF	3.3	8.7	5.1	13	7.5	7.5
2,3,4,7,8-PeCDF	2.4	7.2	6.2	6	5.5	5.5
1,2,3,4,7,8-HxCDF	4.8	10.6	4.5	5	6.2	6.2
1,2,3,6,7,8-HxCDF	6.3	9.1	3.9	7	6.6	6.6
1,2,3,7,8,9-HxCDF	0.2	ND (3.8)	2.1	5	1.8	2.3
2,3,4,6,7,8-HxCDF	4.6	18.1	8.2	ND (1)	7.7	7.9
1,2,3,4,6,7,8-HpCDF	16.3	54.3	154.2	51	69.0	69.0
1,2,3,4,7,8,9-HpCDF	ND (0.2)	ND (3.8)	7.9	1	2.2	2.7
OCDF	27.9	38	106	140	78.0	78.0
Total 2,3,7,8-CDD	197.5	325.7	511.5	234	317	321
Total 2,3,7,8-CDF	70.1	156.6	310.8	263	200	201
Total I-TEQ_{DF} (ND = zero)	7.2	16.0	10.1	26.3	14.9	
Total I-TEQ_{DF} (ND = ½ det limit)	7.2	16.2	16.8	26.4		16.6
Total TEQ_{DF}-WHO_{98} (ND = zero)	7.8	17.1	9.6	28.0	15.6	
Total TEQ_{DF}-WHO_{98} (ND = ½ det limit)	7.8	17.3	18.3	28.1		17.9
Total TCDD	28.6	51	13	82	43.7	43.7
Total PeCDD	25.5	51	ND (15)	101	44.4	46.3
Total HxCDD	26.3	56	36	50	42.1	42.1
Total HpCDD	38.7	50	163	25	69.2	69.2
Total OCDD	170	275	427	197	267.3	267.3
Total TCDF	52.6	152	79	332	153.9	153.9
Total PeCDF	53.4	122	29	84	72.1	72.1
Total HxCDF	33.3	71	60	39	50.8	50.8
Total HpCDF	27.1	62	174	83	86.5	86.5
Total OCDF	27.9	38	106	140	78.0	78.0
Total CDD/CDF (ND = zero)	483.4	928	1,095	1,133	910	
Total CDD/CDF (ND = ½ det limit)	483.4	928	1,087	1,133		945

ND = Not detected; value in parentheses is the reported detection limit.

Ref. A: Hagenmaier et al. (1990)

Ref. B: Schwind et al. (1991); Hutzinger et al. (1992)

Table 4-7. European Tunnel Study Test Results

Congener/Congener Group	Tunnel Air Germany (Ref. A) (pg/m3)	Tunnel Air Germany (Ref. A) (pg/m3)	Tunnel Air Belgium (Ref. B) (pg/m3)	Tunnel Air Norway (workdays)[a] (Ref. C) (pg/m3)	Tunnel Air Norway (weekend)[a] (Ref. C) (pg/m3)
2,3,7,8-TCDD	ND (0.01)	0.06	0.002	0.02	0.02
1,2,3,7,8-PeCDD	0.31	0.28	0.025	0.18	0.04
1,2,3,4,7,8-HxCDD	0.37	ND (0.17)	0.025	0.06	0.03
1,2,3,6,7,8-HxCDD	1.19	0.66	0.042	0.29	0.03
1,2,3,7,8,9-HxCDD	0.44	ND (0.17)	0.030	0.25	0.06
1,2,3,4,6,7,8-HpCDD	1.9	2.0	0.468	1.41	0.16
OCDD	6.3	6.4	2.190	0.10	0.50
2,3,7,8-TCDF	0.17	0.72	0.013	0.58	0.07
1,2,3,7,8-PeCDF	0.40	0.36	0.143	0.83	0.75
2,3,4,7,8-PeCDF	0.19	NR	0.039	0.78	0.58
1,2,3,4,7,8-HxCDF	0.26	0.13	0.073	0.79	0.34
1,2,3,6,7,8-HxCDF	0.16	0.15	0.093	0.62	0.31
1,2,3,7,8,9-HxCDF	ND (0.04)	ND (0.05)	0.143	0.04	0.03
2,3,4,6,7,8-HxCDF	0.12	ND (0.05)	0.004	0.74	0.13
1,2,3,4,6,7,8-HpCDF	1.2	0.98	0.499	1.78	0.93
1,2,3,4,7,8,9-HpCDF	ND (0.16)	ND (0.17)	0.074	0.22	0.14
OCDF	ND (1.3)	ND (1.0)	0.250	1.62	2.54
Total 2,3,7,8-CDD	10.51	9.40	2.782	2.31	0.84
Total 2,3,7,8-CDF	2.50	2.34	1.330	7.98	5.82
Total I-TEQ_{DF} (ND = zero)	0.58	0.42	0.096	0.91	0.48
Total I-TEQ_{DF} (ND = 1/2 det limit)	0.59	0.44	0.096	0.91	0.48
Total TEQ_{DF}-WHO_{98} (ND = zero)	0.73	0.55	0.106	1.00	0.49
Total TEQ_{DF}-WHO_{98} (ND = 1/2 det limit)	0.74	0.58	0.106	1.00	0.49
Total TCDD	0.23	0.22	NR	0.26	0.16
Total PeCDD	2.5	1.3	NR	1.78	0.41
Total HxCDD	7.8	2.7	NR	1.32	0.12
Total HpCDD	3.4	3.4	NR	1.31	0.23
Total OCDD	6.3	6.4	NR	0.10	0.50
Total TCDF	3.5	6.2	NR	13.20	1.70
Total PeCDF	3.6	4.1	NR	10.17	7.91
Total HxCDF	2.0	1.1	NR	6.42	2.08
Total HpCDF	1.9	1.2	NR	2.62	1.41
Total OCDF	ND (1.3)	ND (1.0)	NR	1.62	2.54
Total CDD/CDF (ND = zero)	31.2	26.6	NR	38.80	17.06
Total CDD/CDF (ND = 1/2 det limit)	31.9	27.1	NR	38.80	17.06

ND = Not detected; value in parentheses is the detection limit.

Ref. A: Rappe et al. (1988)
Ref. B: Wevers et al. (1992)
Ref. C: Oehme et al. (1991)

[a] Listed values are the differences between the concentrations at the inlet and outlet of the northbound tunnel lanes.

Table 4-8. Baltimore Harbor Tunnel Study: Estimated Emission Factors for Heavy-Duty (HD) Diesel Vehicles

Congener/Congener Group	Run-Specific Emission Factors							Mean Emission Factors (pg/km)
	Run No. 2 (pg/km)	Run No. 3 (pg/km)	Run No. 5 (pg/km)	Run No. 6 (pg/km)	Run No. 8 (pg/km)	Run No. 9 (pg/km)	Run No. 10 (pg/km)	
2,3,7,8-TCDD	24.5	61.6	0.0	21.2	37.8	40.1	54.9	34.3
1,2,3,7,8-PeCDD	40.2	20.6	15.4	5.6	38.4	0.0	83.0	29.0
1,2,3,4,7,8-HxCDD	18.2	25.2	46.5	8.3	64.5	0.0	123	40.8
1,2,3,6,7,8-HxCDD	37.5	28.2	64.3	19.6	153	71.1	186	80.0
1,2,3,7,8,9-HxCDD	53.6	56.5	91.6	48.4	280	126	370	147
1,2,3,4,6,7,8-HpCDD	0	401	729	111	2,438	963	2,080	960
OCDD	0	3,361	3,382	1,120	9,730	5,829	7,620	4,435
2,3,7,8-TCDF	0	94.3	67.6	152.8	155.8	73.4	61.7	86.5
1,2,3,7,8-PeCDF	0	48.9	72.6	23.6	53.3	0.0	43.3	34.5
2,3,4,7,8-PeCDF	24.5	75.7	131	46.6	85.0	63.9	108	76.4
1,2,3,4,7,8-HxCDF	15.4	139	204	93.8	124	164	166	129
1,2,3,6,7,8-HxCDF	0.3	75.1	73.7	51.0	61.3	54.4	95.5	58.8
1,2,3,7,8,9-HxCDF	27.7	14.8	75.6	0	20.6	37.2	63.5	34.2
2,3,4,6,7,8-HxCDF	15.2	82.5	152	55.7	93.0	86.8	111	85.2
1,2,3,4,6,7,8-HpCDF	12.6	280	445	154	313	354	308	267
1,2,3,4,7,8,9-HpCDF	0	58.5	60.8	31.1	25.0	2.3	34.9	30.4
OCDF	0	239	401	175	416	534	370	305
Total 2,3,7,8-CDD	174	3,954	4,328	1,335	12,743	7,028	10,515	5,725
Total 2,3,7,8-CDF	95.7	1,108	1,684	784	1,347	1,371	1,362	1,107
Total I-TEQ_{DF}	73.8	175	170	96	235	153	303	172
Total TEQ_{DF}-WHO_{98}	93.8	182	175	97	245	147	337	182
Total TCDD	245	0	140	165	311	109	97.3	152
Total PeCDD	110	21.9	83.3	35.6	174	0.0	165	84.2
Total HxCDD	677	0	753	54.5	2,009	1,666	2,971	1,162
Total HpCDD	0	802	1,498	142	5,696	1,933	4,377	2,064
Total OCDD	0	3361	3,382	1,120	9,730	5,829	7,620	4,435
Total TCDF	0	901	1,314	656	2,416	1,007	687	997
Total PeCDF	124	119	1,152	78.4	1,055	282	626	491
Total HxCDF	136	319	852	67.6	444	719	619	451
Total HpCDF	0	223	814	144	513	354	637	384
Total OCDF	0	239	401	175	416	534	370	305
Total CDD/CDF	1,291	5,987	10,390	2,638	22,766	12,434	18,168	10,525
HD vehicles as % of total vehicles	21.2	22.0	22.6	34.0	28.8	24.2	27.4	25.7

Source: Gertler et al. (1996, 1998)

Notes:
1) Listed values are based on the difference between the calculated chemical mass entering the tunnel and the mass exiting the tunnel.
2) All calculated negative emission factors were set equal to zero.
3) All CDD/CDF emissions were assumed to result from heavy-duty diesel fueled vehicles. The table presents in the last row the percent of total traffic that was heavy-duty vehicles.

Table 4-9. CDD/CDF Emission Factors for Industrial Wood Combustors

Congener	Four Facilities Tested by CARB Mean Emission Factors (ng/kg wood)		Five Facilities Tested by NCASI Mean Emission Factors (ng/kg wood)		Nine Facilities Tested by CARB and NCASI Mean Emission Factors (ng/kg wood)	
	Nondetects Set to Zero	Nondetects Set to ½ Det. Limit	Nondetects Set to Zero	Nondetects Set to ½ Det. Limit	Nondetects Set to Zero	Nondetects Set to ½ Det. Limit
2,3,7,8-TCDD	0.007	0.016	0.066	0.068	0.040	0.046
1,2,3,7,8-PeCDD	0.044	0.054	0.110	0.112	0.079	0.084
1,2,3,4,7,8-HxCDD	0.042	0.055	0.179	0.183	0.115	0.123
1,2,3,6,7,8-HxCDD	0.086	0.096	0.191	0.193	0.138	0.143
1,2,3,7,8,9-HxCDD	0.079	0.132	0.522	0.524	0.321	0.342
1,2,3,4,6,7,8-HpCDD	0.902	0.905	0.635	0.637	0.745	0.748
OCDD	6.026	6.026	1.317	1.317	3.329	0.329
2,3,7,8-TCDF	0.673	0.673	0.707	0.719	0.684	0.690
1,2,3,7,8-PeCDF	0.790	0.790	0.145	0.149	0.406	0.409
2,3,4,7,8-PeCDF	0.741	0.741	0.159	0.164	0.389	0.392
1,2,3,4,7,8-HxCDF	0.761	0.768	0.108	0.111	0.375	0.379
1,2,3,6,7,8-HxCDF	0.941	0.941	0.071	0.073	0.418	0.419
1,2,3,7,8,9-HxCDF	0.343	0.350	0.064	0.067	0.178	0.183
2,3,4,6,7,8-HxCDF	0.450	0.491	0.015	0.017	0.192	0.209
1,2,3,4,6,7,8-HpCDF	2.508	2.749	0.072	0.074	1.062	1.155
1,2,3,4,7,8,9-HpCDF	0.260	0.344	0.017	0.020	0.113	0.152
OCDF	1.587	1.590	0.049	0.060	0.674	0.681
Total TCDD	0.151	0.154	1.628	1.629	0.969	0.970
Total PeCDD	1.039	1.039	1.958	1.980	1.521	1.533
Total HxCDD	1.748	1.748	1.792	1.796	1.663	1.665
Total HpCDD	2.936	2.936	1.120	1.132	1.821	1.823
Total OCDD	6.026	6.026	1.317	1.317	3.329	0.329
Total TCDF	4.275	4.275	4.532	4.552	4.353	4.364
Total PeCDF	9.750	9.750	1.548	1.549	4.930	4.930
Total HxCDF	7.428	7.428	0.536	0.543	3.316	3.320
Total HpCDF	3.747	3.988	0.111	0.116	1.580	1.674
Total OCDF	1.588	1.590	0.049	0.060	0.674	0.681
Total I-TEQ_{DF}	0.82	0.85	0.40	0.41	0.56	0.58
Total TEQ_{DF}-WHO_{98}	0.84	0.87	0.46	0.46	0.60	0.62
Total CDD/CDF	38.69	38.93	14.593	14.674	24.155	24.294

Sources: CARB (1990b); CARB (1990e); CARB (1990f); CARB (1990g); NCASI (1995)

Table 4-10. CDD/CDF Concentrations in Residential Chimney Soot from Wood Stoves and Fireplaces

Congener/Congener Group	U.S. East Region (Ref. A) (ng/kg)	U.S. West Region (Ref. A) (ng/kg)	U.S. Central Region (Ref. A) (ng/kg)	German Farmhouse (Ref. B) (ng/kg)	Canadian Wood Stove (Ref. C) (ng/kg)	Canadian Fireplace (Ref. C) (ng/kg)	Canadian Wood Stove (Ref. D) (ng/kg)
2,3,7,8-TCDD	66	13.3	66	150	NR	NR	ND (12)
1,2,3,7,8-PeCDD	NR	NR	NR	70	NR	NR	70
1,2,3,4,7,8-HxCDD	250*	522*	1,831*	35	NR	NR	ND (10)
1,2,3,6,7,8-HxCDD	250*	522*	1,831*	60	NR	NR	625
1,2,3,7,8,9-HxCDD	208	282	1,450	30	NR	NR	281
1,2,3,4,6,7,8-HpCDD	1,143	1,653	6,160	90	NR	NR	948
OCDD	2,033	2,227	13,761	90	NR	NR	530
2,3,7,8-TCDF	NR	NR	NR	930	NR	NR	235
1,2,3,7,8-PeCDF	NR	NR	NR	560	NR	NR	58
2,3,4,7,8-PeCDF	NR	NR	NR	590	NR	NR	68
1,2,3,4,7,8-HxCDF	NR	NR	NR	330	NR	NR	51
1,2,3,6,7,8-HxCDF	NR	NR	NR	400	NR	NR	57
1,2,3,7,8,9-HxCDF	NR	NR	NR	70	NR	NR	8
2,3,4,6,7,8-HxCDF	NR	NR	NR	200	NR	NR	24
1,2,3,4,6,7,8-HpCDF	NR	NR	NR	490	NR	NR	97
1,2,3,4,7,8,9-HpCDF	NR	NR	NR	40	NR	NR	20
OCDF	NR	NR	NR	70	NR	NR	41
Total 2,3,7,8-CDD	3,450	4,175	21,437	525	NR	NR	2,454
Total 2,3,7,8-CDF	NR	NR	NR	3,680	NR	NR	659
Total I-TEQ_{Df}	≥125	≥112	≥479	720	NR	NR	211
Total TEQ_{DF}-WHO_{98}	≥123	≥110	≥467	755	NR	NR	246
Total TCDD	1,987	269	1,511	3,900	ND (10)	ND (10)	11
Total PeCDD	NR	NR	NR	880	ND (10)	500	608
Total HxCDD	2,183	4,273	14,243	600	ND (50)	1,700	3,450
Total HpCDD	2,104	3,243	12,603	200	100	500	1,550
Total OCDD	2,033	2,227	13,761	90	200	400	530
Total TCDF	NR	NR	NR	13,400	ND (10)	300	1,010
Total PeCDF	NR	NR	NR	6,100	ND (10)	1,400	948
Total HxCDF	NR	NR	NR	3,200	ND (50)	1,700	482
Total HpCDF	NR	NR	NR	720	ND (50)	400	154
Total OCDF	NR	NR	NR	70	ND (50)	100	41
Total CDD/CDF	8,307	10,012	42,118	29,160	300	7,000	8,783

NR = Not reported.
* = Analytical method could not distinguish between congeners; listed value is the sum of both congeners.

Ref. A: Nestrick and Lamparski (1982, 1983); mean values listed - six samples collected in each Region.
Ref. B: Bacher et al. (1992)
Ref. C: Clement et al. (1985b)
Ref. D: Van Oostdam and Ward (1995); mean of two samples - nondetected values assumed to be zero.

Table 4-11. CDD/CDF Concentrations in Residential Bottom Ash from Wood Stoves and a Fireplace

Congener/Congener Group	Canadian Wood Stove Ash (ng/kg)	Canadian Wood Stove Ash (ng/kg)	Canadian Wood Stove Ash (ng/kg)	Canadian Fireplace Ash (ng/kg)
2,3,7,8-TCDD	NR	NR	NR	NR
1,2,3,7,8-PeCDD	NR	NR	NR	NR
1,2,3,4,7,8-HxCDD	NR	NR	NR	NR
1,2,3,6,7,8-HxCDD	NR	NR	NR	NR
1,2,3,7,8,9-HxCDD	NR	NR	NR	NR
1,2,3,4,6,7,8-HpCDD	NR	NR	NR	NR
OCDD	NR	NR	NR	NR
2,3,7,8-TCDF	NR	NR	NR	NR
1,2,3,7,8-PeCDF	NR	NR	NR	NR
2,3,4,7,8-PeCDF	NR	NR	NR	NR
1,2,3,4,7,8-HxCDF	NR	NR	NR	NR
1,2,3,6,7,8-HxCDF	NR	NR	NR	NR
1,2,3,7,8,9-HxCDF	NR	NR	NR	NR
2,3,4,6,7,8-HxCDF	NR	NR	NR	NR
1,2,3,4,6,7,8-HpCDF	NR	NR	NR	NR
1,2,3,4,7,8,9-HpCDF	NR	NR	NR	NR
OCDF	NR	NR	NR	NR
Total 2,3,7,8-CDD	NR	NR	NR	NR
Total 2,3,7,8-CDF	NR	NR	NR	NR
Total TEQ	NR	NR	NR	NR
Total TCDD	ND (10)	100	100	ND (10)
Total PeCDD	ND (10)	3,000	200	ND (10)
Total HxCDD	ND (50)	10,000	700	300
Total HpCDD	300	1,200	500	2,000
Total OCDD	2,600	900	100	3,100
Total TCDF	9,100	400	100	ND (10)
Total PeCDF	2,200	4,600	200	ND (10)
Total HxCDF	1,000	9,300	500	100
Total HpCDF	700	1,000	300	400
Total OCDF	ND (50)	100	ND (50)	100
Total CDD/CDF	15,900	30,600	2,700	6,000

NR = Not reported.
Source: Clement et al. (1985b)

Table 4-12. CDD/CDF Concentrations in Chimney Soot (Bavaria, Germany)

Unit Type	Fuel Type	Number of Samples	CDD/CDF Concentrations in Soot (ng I-TEQ$_{DF}$/kg)		
			Minimum	Mean	Maximum
Oven	Wood	33	10.4	2,015	15,849
Tiled Stove	Wood	39	4.0	3,453	42,048
Heating System	Wood	9	16.9	1,438	20,450
Oven	Wood/coal	27	77.3	2,772	10,065
Tiled Stove	Wood/coal	5	53.1	549	4,911
Oven	Wood, wood/coal, waste	5	116.3	6,587	10,652

Source: Dumler-Gradl et al. (1995a).

Table 4-13 Fly Ash from Wood Working Industry
(Concentrations in ng/kg)

Congener	Concentration	I-TEQ_{DF}	TEQ_{DF}-WHO_{98}
2,3,7,8-TCDD	<15	<15	<15
Total TCDD	1,730	-	-
1,2,3,7,8-PeCDD	100	50	100
Total PeCDD	1,250	-	-
1,2,3,4,7,8-HxCDD	130	13	13
1,2,3,6,7,8-HxCDD	150	15	15
1,2,3,7,8,9-HxCDD	140	14	14
Total HxCDD	750	-	-
1,2,3,4,6,7,8-HpCDD	280	3	3
Total HpCDD	470	-	-
Total OCCD	300	0.3	0.03
TOTAL TCDD TEQs		**95-110**	**145-160**
2,3,7,8-TCDF	130	13	13
Total TCDF	1,300	-	-
1,2,3,7,8-PeCDF	100	5	5
2,3,4,7,8-PeCDF	120	60	60
Total PeCDF	790	-	-
1,2,3,4,7,8-HxCDF	40	4	4
1,2,3,7,8,9-HxCDF	40	4	4
1,2,3,6,7,8-HxCDF	<10	<1	<1
Total HxCDF	150	-	-
1,2,3,4,6,7,8-HpCDF	320	3	3
1,2,3,4,7,8,9-HpCDF	<10	<0.1	<0.1
Total HpCDF	570	-	-
Total OCDF	60	0.06	0.006
TOTAL CDF TEQs		**89-90**	**89-90**

Table 4-14. Electrostatic Precipitator Waste Ash from Wood-Fired Industrial Boiler

	Average[a] Concentration (ng/kg)	I-TEQ_{DF} Concentration (ng/kg)	TEQ_{DF}-WHO_{98} Concentration (ng/kg)
2,3,7,8-TCDD	17.85	17.85	17.85
Total TCDD	239.00	-	-
1,2,3,7,8-PeCDD	30.67	15.33	30.67
Total PeCDD	226.83	-	-
1,2,3,4,7,8-HxCDD	20.33	2.03	2.03
1,2,3,6,7,8-HxCDD	26.33	2.63	2.63
1,2,3,7,8,9-HxCDD	23.33	2.33	2.33
Total HxCDD	300.00	-	-
1,2,3,4,6,7,8-HpCDD	325.00	3.25	3.25
Total HpCDD	706.67	-	-
Total OCDD	786.67	0.79	0.08
Total CDD	2,439.17	44.22	58.85
2,3,7,8-TCDF	285.00	28.50	28.50
Total TCDF	2,713.33	-	-
1,2,3,7,8-PeCDF	154.50	7.73	7.73
2,3,4,7,8-PeCDF	641.67	320.83	320.83
Total PeCDF	2,666.67	-	-
1,2,3,4,7,8-HxCDF	244.83	24.48	24.48
1,2,3,6,7,8-HxCDF	179.67	17.97	17.97
2,3,4,6,7,8-HxCDF	296.67	29.67	29.67
1,2,3,7,8,9-HxCDF	7.28	0.73	0.73
Total HxCDF	1,520.00	-	-
1,2,3,4,6,7,8-HpCDF	147.67	1.48	1.48
1,2,3,4,7,8,9-HpCDF	21.33	0.21	0.21
Total HpCDF	248.33	-	-
Total OCDF	48.33	0.05	0.00
Total CDF	7,196.67	431.64	431.60
Total Dioxins/Furans		475.86	490.44

a Calculated from data in Table 30 of CARB 1990e).

Table 4-15. Estimated CDD/CDF Emission Factors for Oil-Fired Residential Furnaces

Congener/Congener Group	Mean Facility Emission Factor (pg/L oil)
2,3,7,8-TCDD	56
1,2,3,7,8-PeCDD	NR
1,2,3,4,7,8-HxCDD	NR
1,2,3,6,7,8-HxCDD	NR
1,2,3,7,8,9-HxCDD	NR
1,2,3,4,6,7,8-HpCDD	NR
OCDD	66
2,3,7,8-TCDF	53
1,2,3,7,8-PeCDF	NR
2,3,4,7,8-PeCDF	NR
1,2,3,4,7,8-HxCDF	NR
1,2,3,6,7,8-HxCDF	NR
1,2,3,7,8,9-HxCDF	NR
2,3,4,6,7,8-HxCDF	NR
1,2,3,4,6,7,8-HpCDF	NR
1,2,3,4,7,8,9-HpCDF	NR
OCDF	30
Total 2,3,7,8-CDD	NR
Total 2,3,7,8-CDF	NR
Total I-TEQ_{DF}	150
Total TCDD	139
Total PeCDD	82
Total HxCDD	66
Total HpCDD	63
Total OCDD	66
Total TCDF	663
Total PeCDF	420
Total HxCDF	170
Total HpCDF	73
Total OCDF	30
Total CDD/CDF	1,772

NR = Not reported.

Source: U.S. EPA (1997b)

Table 4-16. CDD/CDF Emission Factors for Oil-Fired Utility/Industrial Boilers

Congener/Congener Group	U.S. EPA (1997b) Median Emission Factor (pg/L oil)	EPRI (1994) Mean Emission Factor	
		ND = zero (pg/L oil)	ND = ½ DL (pg/L oil)
2,3,7,8-TCDD	117	0	26.6
1,2,3,7,8-PeCDD	104	24.7	43.1
1,2,3,4,7,8-HxCDD	215	63.3	108
1,2,3,6,7,8-HxCDD	97	65.8	79.3
1,2,3,7,8,9-HxCDD	149	79.7	102
1,2,3,4,6,7,8-HpCDD	359	477	546
OCDD	413	2055	2141
2,3,7,8-TCDF	83	0	35.7
1,2,3,7,8-PeCDF	77	64.1	73.9
2,3,4,7,8-PeCDF	86	49.3	59.6
1,2,3,4,7,8-HxCDF	109	76.5	94.9
1,2,3,6,7,8-HxCDF	68	35.4	45.2
1,2,3,7,8,9-HxCDF	104	0	37.7
2,3,4,6,7,8-HxCDF	86	23.8	42.2
1,2,3,4,6,7,8-HpCDF	169	164	218
1,2,3,4,7,8,9-HpCDF	179	0	137
OCDF	179	0	139
Total 2,3,7,8-CDD	1,453	2,766	3,047
Total 2,3,7,8-CDF	1,141	414	883
Total I-TEQ_{DF}	314	83.1	147
Total TEQ_{DF}-WHO_{98}	366	93.6	167
Total TCDD	102	NR	NR
Total PeCDD	104	NR	NR
Total HxCDD	145	NR	NR
Total HpCDD	359	NR	NR
Total OCDD	413	NR	NR
Total TCDF	90	NR	NR
Total PeCDF	131	NR	NR
Total HxCDF	172	NR	NR
Total HpCDF	27	NR	NR
Total OCDF	179	NR	NR
Total CDD/CDF	1,722	3,179	3,931

Sources:

U.S. EPA (1997b) - number of facilities not reported.
EPRI (1994) - based on two cold side ESP-equipped power plants.

Note: Assumes a density for residual fuel oil of 0.87 kg/L.

Table 4-17. CDD/CDF Concentrations in Stack Emissions from U.S. Coal-Fired Power Plants

Congener/Congener Group	Plant 1 (pg/Nm^3)	Plant 2 (pg/Nm^3)	Plant 3 (pg/Nm^3)	Plant 4 (pg/Nm^3)	Plant 5 (pg/Nm^3)	Plant 6 (pg/Nm^3)	Plant 7 (pg/Nm^3)
2,3,7,8-TCDD	ND (3.5)	ND (3.5)	1.0	ND (2.0)	ND (3.3)	ND (2.6)	ND (1.7)
1,2,3,7,8-PeCDD	ND (0.56)	ND (4.8)	ND (1.8)	ND (10)	ND (4.7)	ND (3.2)	ND (1.8)
1,2,3,4,7,8-HxCDD	ND (0.56)	ND (5.7)	ND (3.6)	ND (10)	ND (15.4)	ND (2.7)	ND (2.0)
1,2,3,6,7,8-HxCDD	ND (0.44)	5.0	ND (1.8)	ND (10)	ND (9.9)	ND (4.2)	ND (1.4)
1,2,3,7,8,9-HxCDD	ND (0.56)	4.9	ND (1.8)	ND (10)	ND (12.1)	ND (4.3)	ND (1.2)
1,2,3,4,6,7,8-HpCDD	ND (1.7)	29	ND (1.8)	ND (10)	ND (26.4)	4.3	2.4
OCDD	ND (12)	32	ND (14)	ND (20)	ND (131)	20	21.6
2,3,7,8-TCDF	ND (1.7)	8.1	7.8	ND (2.0)	ND (3.3)	13	0.7
1,2,3,7,8-PeCDF	ND (1.0)	ND (5.7)	7.2	ND (10)	ND (3.2)	ND (5.7)	ND (1.1)
2,3,4,7,8-PeCDF	2.4	ND (19)	6.6	ND (10)	ND (3.2)	ND (4.8)	ND (1.4)
1,2,3,4,7,8-HxCDF	3.3	16	8.4	ND (10)	ND (16.4)	ND (5.1)	ND (1.8)
1,2,3,6,7,8-HxCDF	1.1	ND (5.0)	2.9	ND (10)	ND (5.8)	ND (4.0)	ND (1.3)
1,2,3,7,8,9-HxCDF	ND (0.44)	11	ND (1.8)	ND (10)	ND (8.8)	ND (6.9)	ND (1.5)
2,3,4,6,7,8-HxCDF	ND (2.0)	ND (4.2)	3.0	ND (10)	ND (16.4)	ND (2.5)	ND (2.0)
1,2,3,4,6,7,8-HpCDF	2.0	29	6.0	ND (10)	ND (23)	ND (30)	ND (2.2)
1,2,3,4,7,8,9-HpCDF	ND (0.63)	ND (6.1)	ND (3.6)	ND (10)	ND (15.4)	ND (5.0)	ND (2.1)
OCDF	5.6	33	2.4	ND (20)	ND (131)	ND (19)	11.4
Total 2,3,7,8-CDD	0	71	1	0	0	24.3	24
Total 2,3,7,8-CDF	14	97	44.3	0	0	13	12.1
Total TCDD	1.8	12	12	NR	6.7	ND (2.6)	ND (55)
Total PeCDD	ND (1.0)	4.4	6.0	ND (10)	ND (4.7)	ND (3.2)	ND (32)
Total HxCDD	1.3	18	2.7	ND (10)	ND (26.3)	ND (4.0)	ND (24)
Total HpCDD	3.4	45	ND (2.4)	ND (10)	ND (26.4)	ND (14)	ND (8.1)
Total OCDD	ND (12)	32	ND (14)	ND (20)	ND (131)	20	21.6
Total TCDF	ND (5.2)	29	78	ND (2)	ND (3.3)	88	ND (37)
Total PeCDF	5.4	33	61	ND (10)	ND (6.6)	14	3.0
Total HxCDF	7.6	39	29	ND (10)	ND (16.4)	ND (5.0)	ND (27)
Total HpCDF	4.3	34	9.0	ND (10)	ND (29.5)	ND (20)	2.9
Total OCDF	5.6	33	2.4	ND (20)	ND (131)	ND (19)	11.4
Total CDD/CDF	29	279	200.1	0	6.7	122	38.9

ND = Not detected; value in parentheses is the detection limit.
NR = Not reported; suspected contamination problem.
Source: Riggs et al. (1995)

Table 4-18. Characteristics of U.S. Coal-Fired Power Plants Tested by DOE

Plant No.	Coal Type	Coal Chlorine Content (mg/kg)	Temperature (°C) at:			
			Pollution Control Device[a]			Stack
			ESP	Bag	FGD	
1	Bituminous	800	160	--	--	160
2	Bituminous	1,400	130	--	--	130
3	Subbituminous	300	--	150	--	150
4	Subbituminous	390	--	70	130	75
5	Bituminous	1,400	130	--	120	40
6	Lignite	400	170	--	170	110
7	Bituminous	1,000	150	--	--	150

[a] ESP = Electrostatic precipitator, Bag = Baghouse, FGD = Flue gas desulfurization system.

Source: Riggs et al. (1995).

Table 4-19. CDD/CDF Emission Factors for Coal-Fired Utility/Industrial Power Plants

Congener/Congener Group	Mean Emission Factor	
	ND = zero (ng/kg coal)	ND = ½ DL (ng/kg coal)
2,3,7,8-TCDD	0.005	0.018
1,2,3,7,8-PeCDD	0	0.016
1,2,3,4,7,8-HxCDD	0	0.034
1,2,3,6,7,8-HxCDD	0.004	0.028
1,2,3,7,8,9-HxCDD	0.004	0.035
1,2,3,4,6,7,8-HpCDD	0.216	0.241
OCDD	0.513	0.644
2,3,7,8-TCDF	0.109	0.117
1,2,3,7,8-PeCDF	0.007	0.021
2,3,4,7,8-PeCDF	0.074	0.084
1,2,3,4,7,8-HxCDF	0.098	0.120
1,2,3,6,7,8-HxCDF	0.014	0.030
1,2,3,7,8,9-HxCDF	0.013	0.038
2,3,4,6,7,8-HxCDF	0.043	0.060
1,2,3,4,6,7,8-HpCDF	0.354	0.385
1,2,3,4,7,8,9-HpCDF	0.087	0.112
OCDF	0.158	0.281
Total I-TEQ_{DF}	0.079	0.124
Total TEQ_{DF}-WHO_{98}	0.078	0.131
Total TCDD	0.051	0.052
Total PeCDD	0.014	0.015
Total HxCDD	0.030	0.030
Total HpCDD	0.063	0.074
Total OCDD	0.513	0.644
Total TCDF	0.154	0.158
Total PeCDF	0.180	0.180
Total HxCDF	0.104	0.104
Total HpCDF	0.064	0.064
Total OCDF	0.158	0.281
Total CDD/CDF	1.331	1.602

Source: EPRI (1994) - 11 facility data set.

Table 4-20. CDD/CDF Emission Factors from Residential Coal Combustors

Congener/Congener Group	"Salt" Lignite Ref. A (ng/kg coal)	"Normal" Lignite Ref. A (ng/kg coal)	Anthracite Ref. B (ng/kg coal)	Bituminous Ref. B (ng/kg coal)
2,3,7,8-TCDD	0.58	0.06	1.60	2.40
1,2,3,7,8-PeCDD	0.73	0.08	NR	NR
1,2,3,4,7,8-HxCDD	0.63	0.06	NR	NR
1,2,3,6,7,8-HxCDD	0.60	0.09	NR	NR
1,2,3,7,8,9-HxCDD	0.40	0.06	NR	NR
1,2,3,4,6,7,8-HpCDD	3.24	0.59	NR	NR
OCDD	16.19	2.42	77	120
2,3,7,8-TCDF	2.49	0.50	42.0	63.0
1,2,3,7,8-PeCDF	2.24	0.43	NR	NR
2,3,4,7,8-PeCDF	2.09	0.31	NR	NR
1,2,3,4,7,8-HxCDF	0.38	0.13	NR	NR
1,2,3,6,7,8-HxCDF	1.86	0.36	NR	NR
1,2,3,7,8,9-HxCDF	0.07	0.02	NR	NR
2,3,4,6,7,8-HxCDF	1.01	0.12	NR	NR
1,2,3,4,6,7,8-HpCDF	2.59	0.95	NR	NR
1,2,3,4,7,8,9-HpCDF	0.25	0.06	NR	NR
OCDF	0.63	0.30	4.2	6.3
Total 2,3,7,8-CDD*	22.37	3.38	NR	NR
Total 2,3,7,8-CDF*	13.60	3.20	NR	NR
Total I-TEQ_{DF}*	2.74	0.34	60.0	98.5
Total TCDD	14.23	9.00	61.6	92.4
Total PeCDD	14.15	2.22	31	46
Total HxCDD	11.14	1.81	60	90
Total HpCDD	7.06	0.82	57	86
Total OCDD	16.19	2.42	77	120
Total TCDF	80.34	20.33	412	613
Total PeCDF	29.21	8.98	340	550
Total HxCDF	12.72	3.78	130	190
Total HpCDF	3.87	1.27	32	47
Total OCDF	0.63	0.30	4.2	6.3
Total CDD/CDF	189.5	50.9	1,205	1,841

NR = not reported.
* Values as reported in References A and B.

Sources: Ref A: Thub et al. (1995); listed results represent means of three flue gas samples.
Ref B: U.S. EPA (1997b); based on average particulate CDD/CDF concentrations from chimney soot samples collected from seven coal ovens and particulate emission factors for anthracite and bituminous coal combustion.

Table 4-21. Coal-Fired Utility Solid Wastes

	Mean Concentration(1) (ng/kg)	Grams/Year Disposed of in Solid Waste(3) 1987	Grams/Year Disposed of in Solid Waste(2) 1995	I-TEQ_{DF}/Yr (grams) 1995	TEQ_{DF}-WHO_{98}/Yr (grams) 1995
CDDs					
2,3,7,8-TCDD (4)	0.17	10	10	9.72	9.72
1,2,3,7,8-PeCDD (4)	0.25	14	14	7.15	14.30
1,2,3,4,7,8-HxCDD (4)	0.35	20	20	2.00	2.00
1,2,3,6,7,8-HxCDD (4)	0.28	16	16	1.60	1.60
1,2,3,7,8,9-HxCDD (5)	0.30	17	17	1.72	1.72
1,2,3,4,6,7,8-HpCDD (6)	0.59	33	34	0.34	0.34
OCDD (7)	10.54	593	603	0.60	0.06
CDFs					
2,3,7,8-TCDF (8)	0.19	11	11	1.09	1.09
1,2,3,7,8-PeCDF (4)	0.17	10	10	0.49	0.49
2,3,4,7,8-PeCDF (4)	0.17	10	10	4.86	4.86
1,2,3,4,7,8-HxCDF (5)	0.25	14	14	1.43	1.43
1,2,3,6,7,8-HxCDF (4)	0.18	10	10	1.03	1.03
2,3,4,6,7,8-HxCDF (4)	0.28	16	16	1.60	1.60
1,2,3,7,8,9-HxCDF (4)	0.24	14	14	1.37	1.37
1,2,3,4,6,7,8-HpCDF (5)	0.29	16	17	0.17	0.17
1,2,3,4,7,8,9-HpCDF (4)	0.35	20	20	0.20	0.20
OCDF (9)	0.59	33	34	0.03	<0.01
Total Quantities:				**35.41**	**41.98**

(1) From Table 2-9, Data for Co-managed Wastes of U.S. EPA (1999b).
(2) Based on EPRI estimate of 63 million tons/yr of large-volume utility coal combustion solid wastes. From Section 3.3 of U.S. EPA (1999c). Assumes all waste characteristics are same as for Comanaged Wastes.
(3) Assumes that solid waste quantity for 1987 is 98.4% of 1995, based on total utility coal use in those years (see Section 4.4).
(4) All 17 analyses were non-detects.
(5) 16 of the 17 analyses were non-detects.
(6) 11 of the 17 analyses were non-detects.
(7) 5 of the 17 analyses were non-detects.
(8) 14 of the 17 analyses were non-detects.
(9) 15 of the 17 analyses were non-detects.

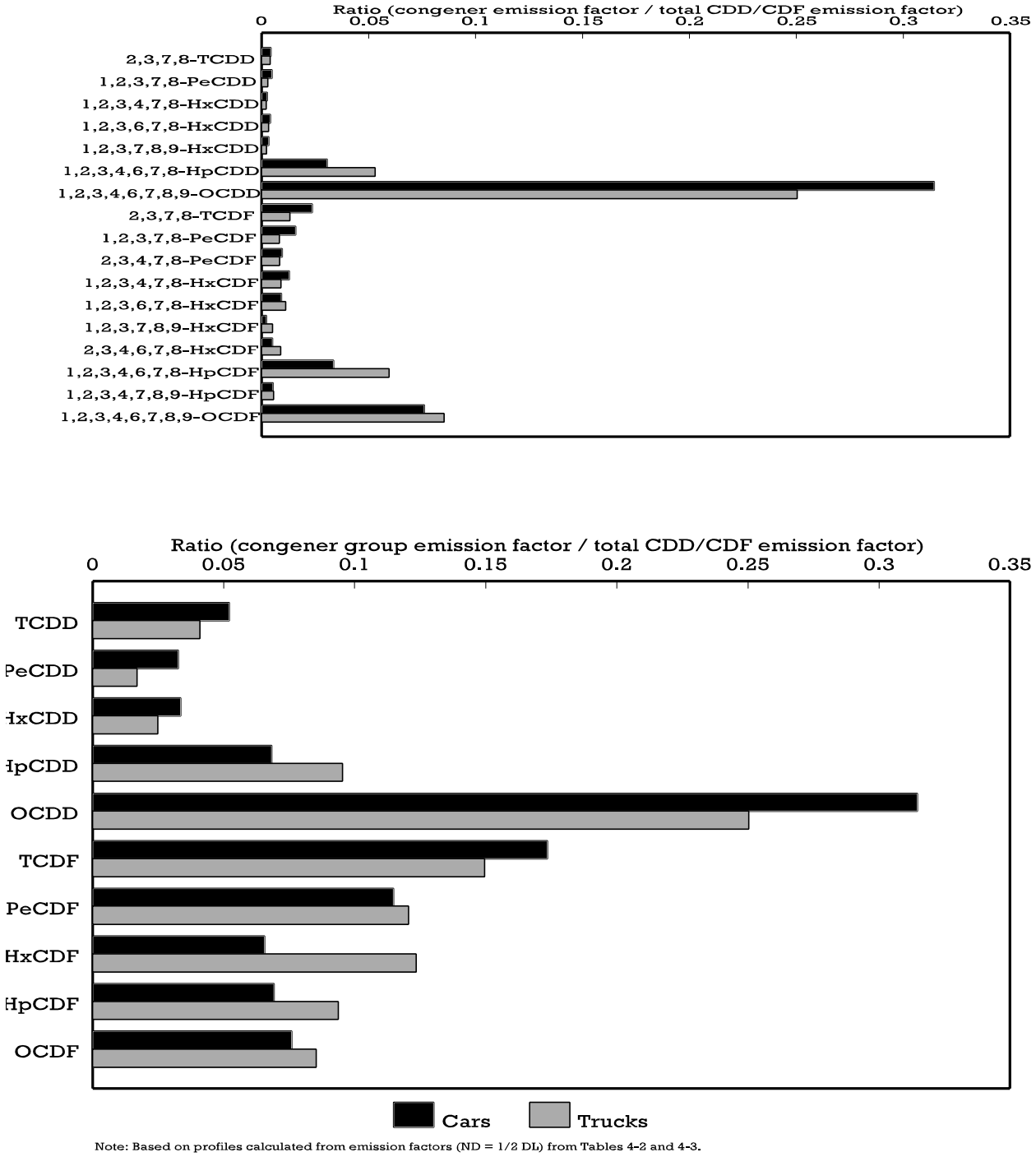


Figure 4-1. Congener and Congener Group Profiles for Air Emissions from Diesel-fueled Vehicles

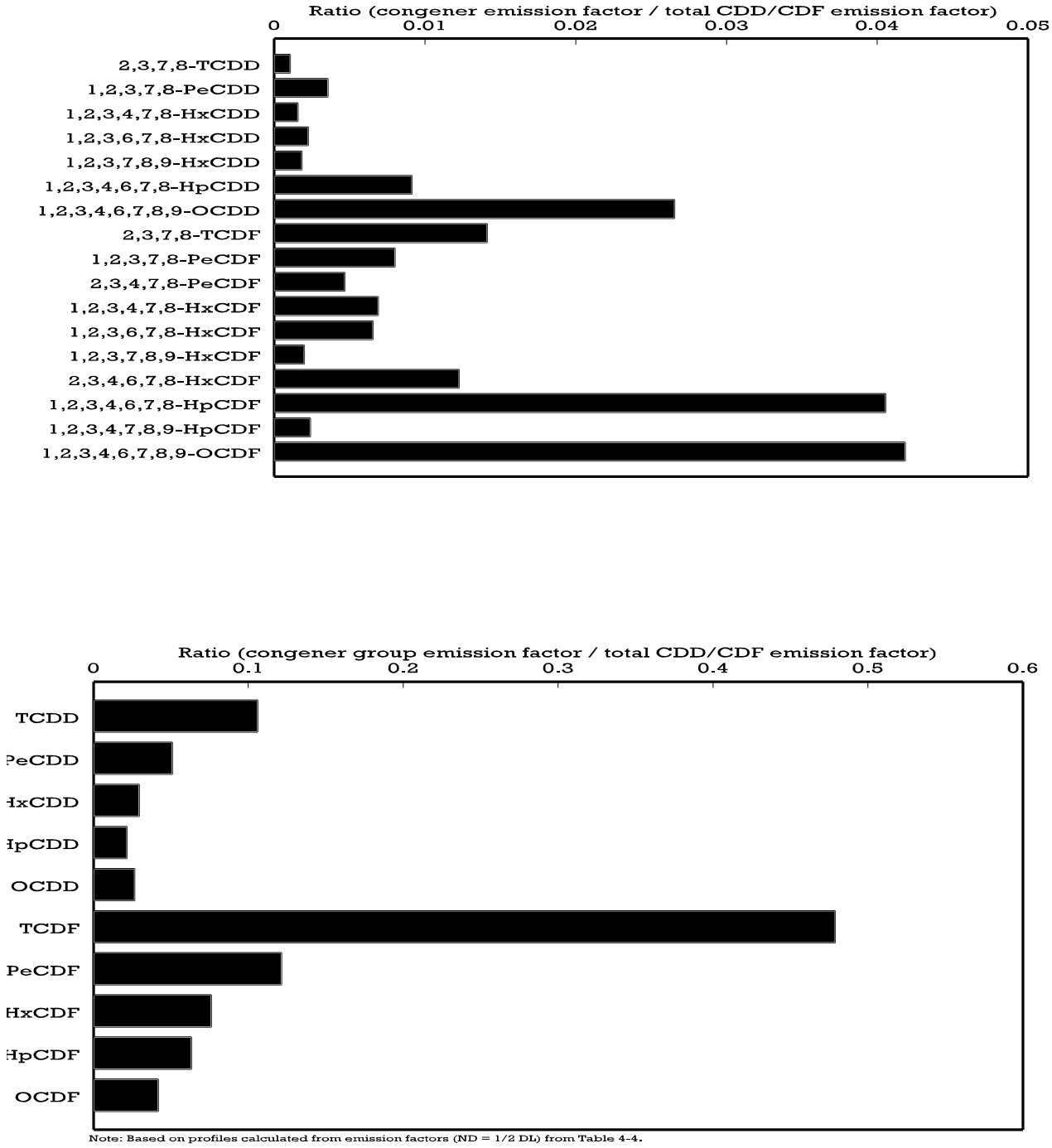


Figure 4-2. Congener and Congener Group Profiles for Air Emissions from Leaded Gas-fueled Vehicles

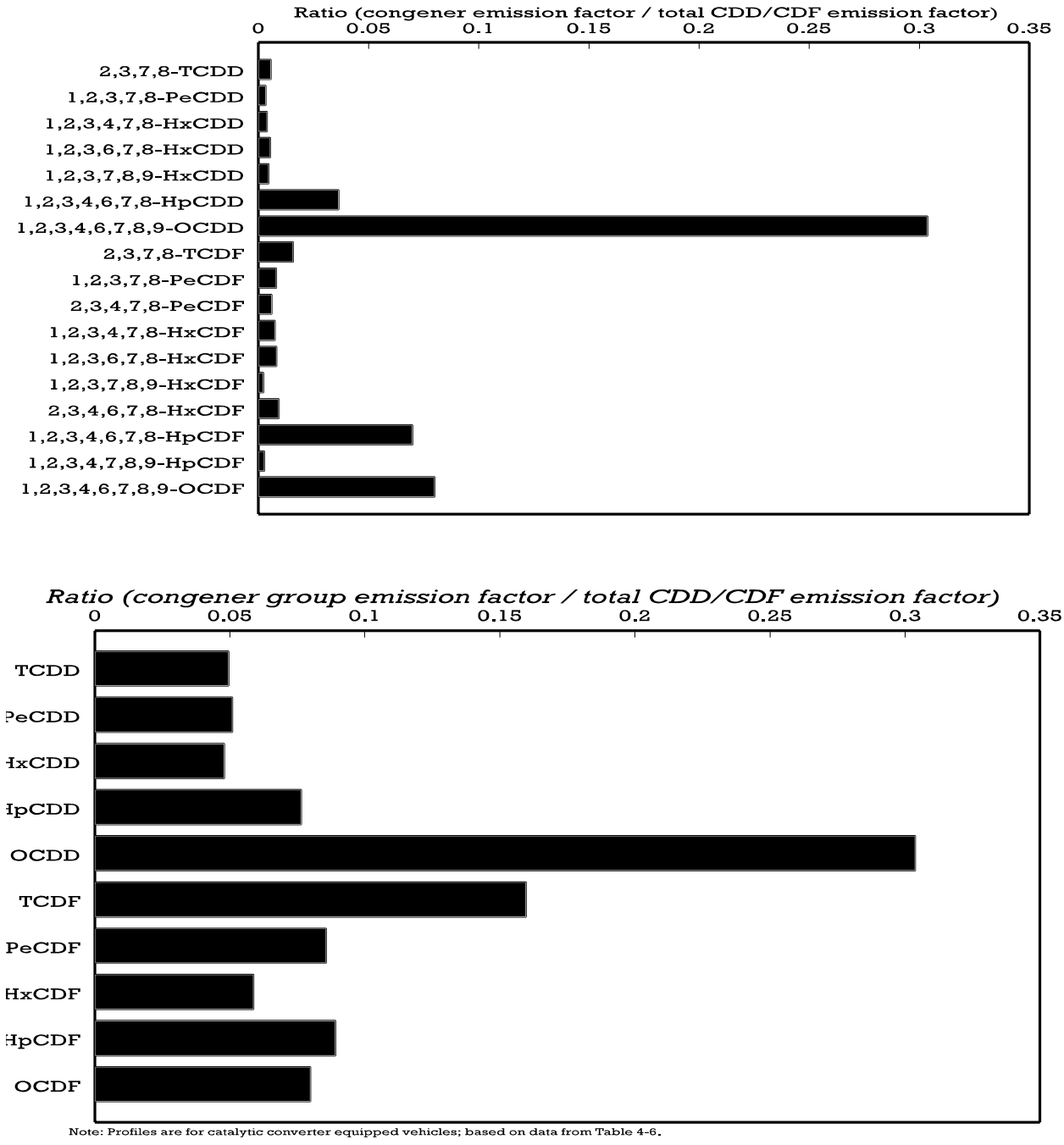


Figure 4-3. Congener and Congener Group Profiles for Air Emissions from Unleaded Gas-fueled Vehicles

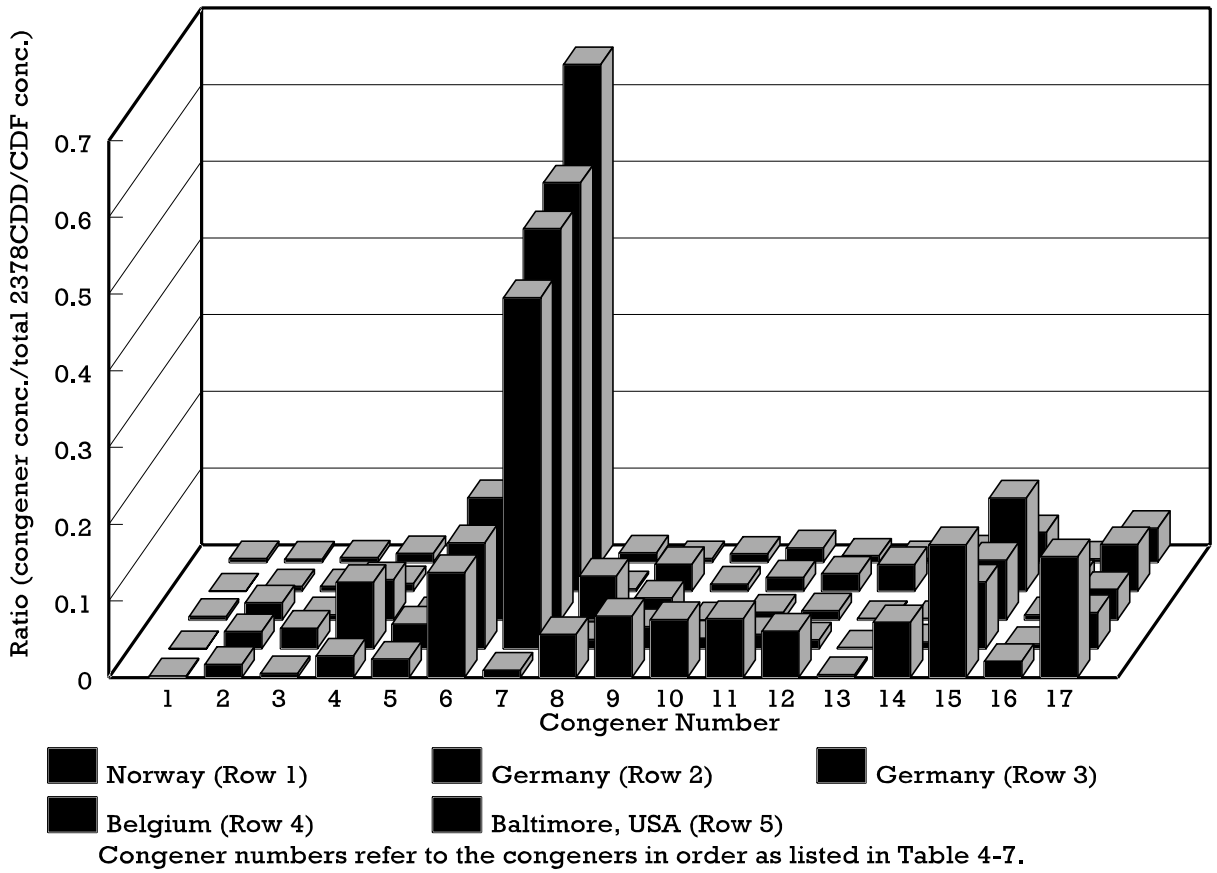
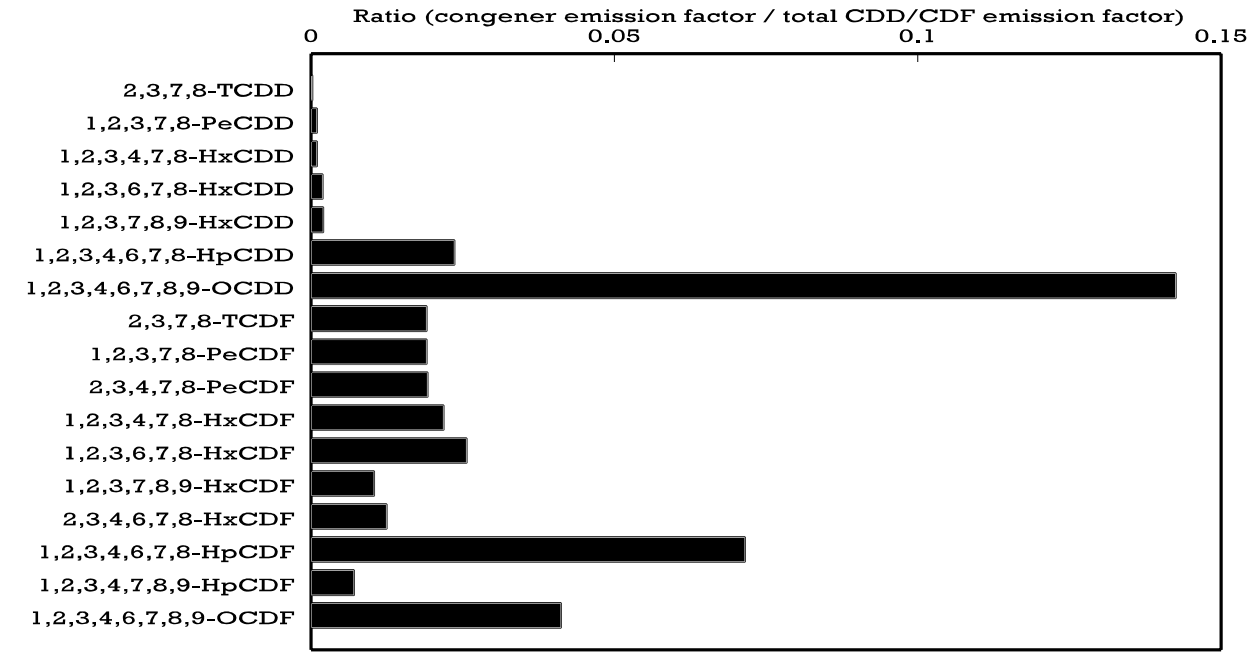


Figure 4-4. Tunnel Air Concentrations



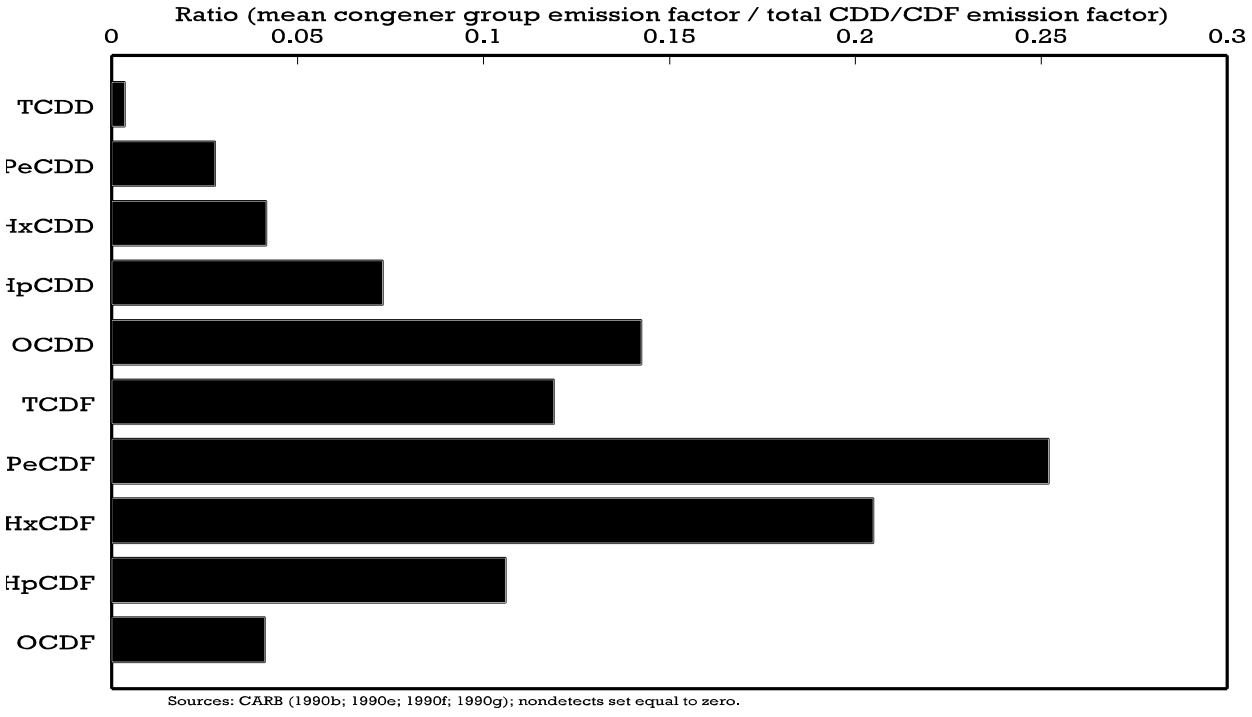
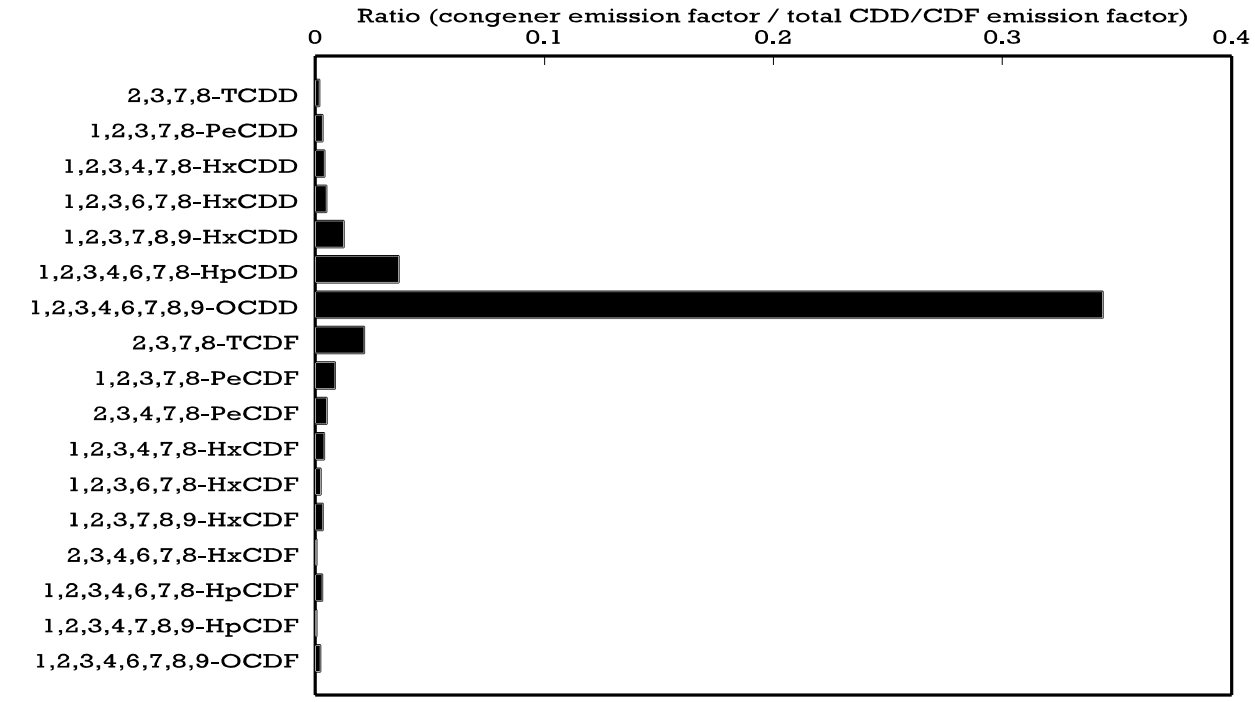
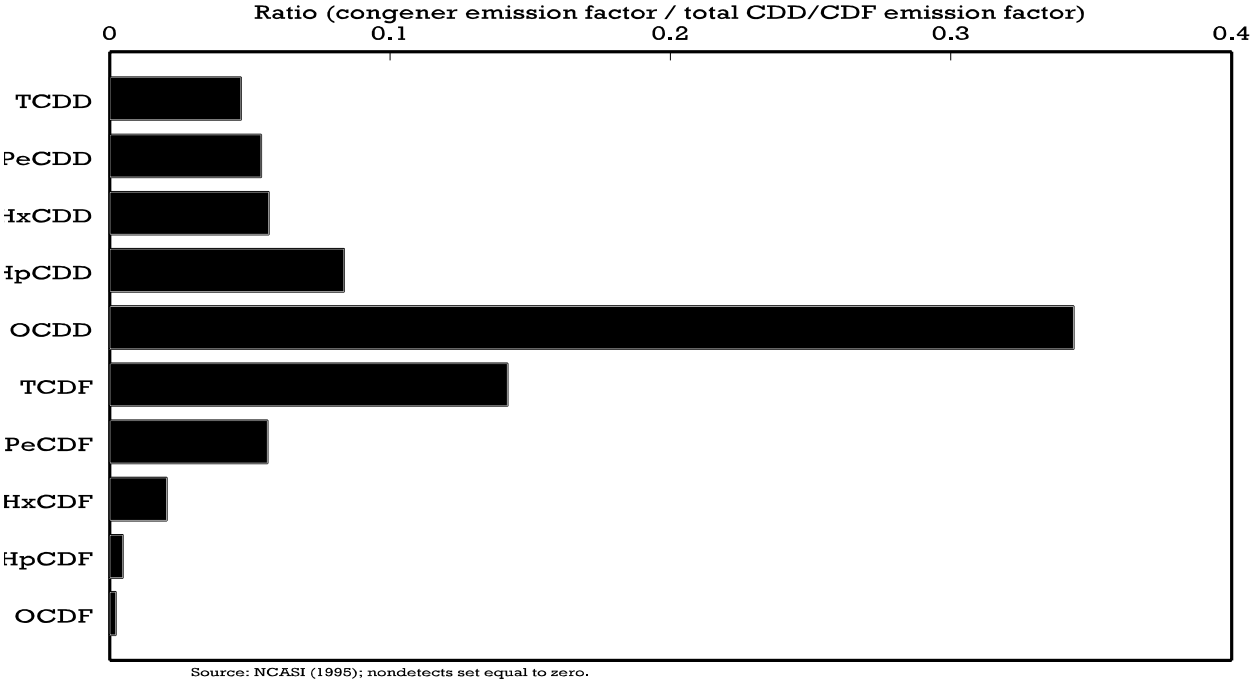


Figure 4-5a. Congener and Congener Group Profiles for Air Emissions from Industrial Wood Combustors





Source: NCASI (1995); nondetects set equal to zero.

Figure 4-5b Congener and Congener Group Profiles for Air Emissions from Bleached Kraft Mill Bark Combustors

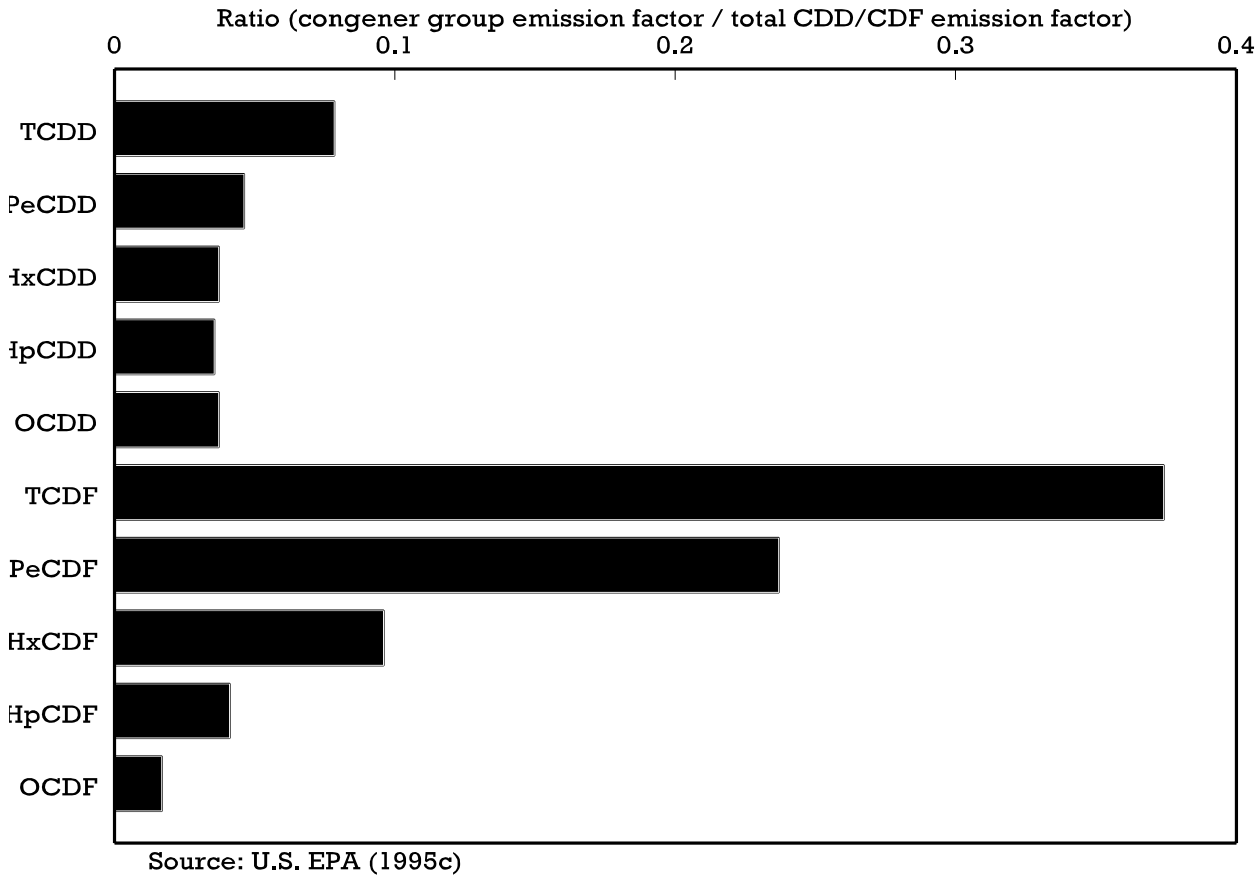


Figure 4-6. Congener Group Profile for Air Emissions from Residential Oil-fueled Furnaces

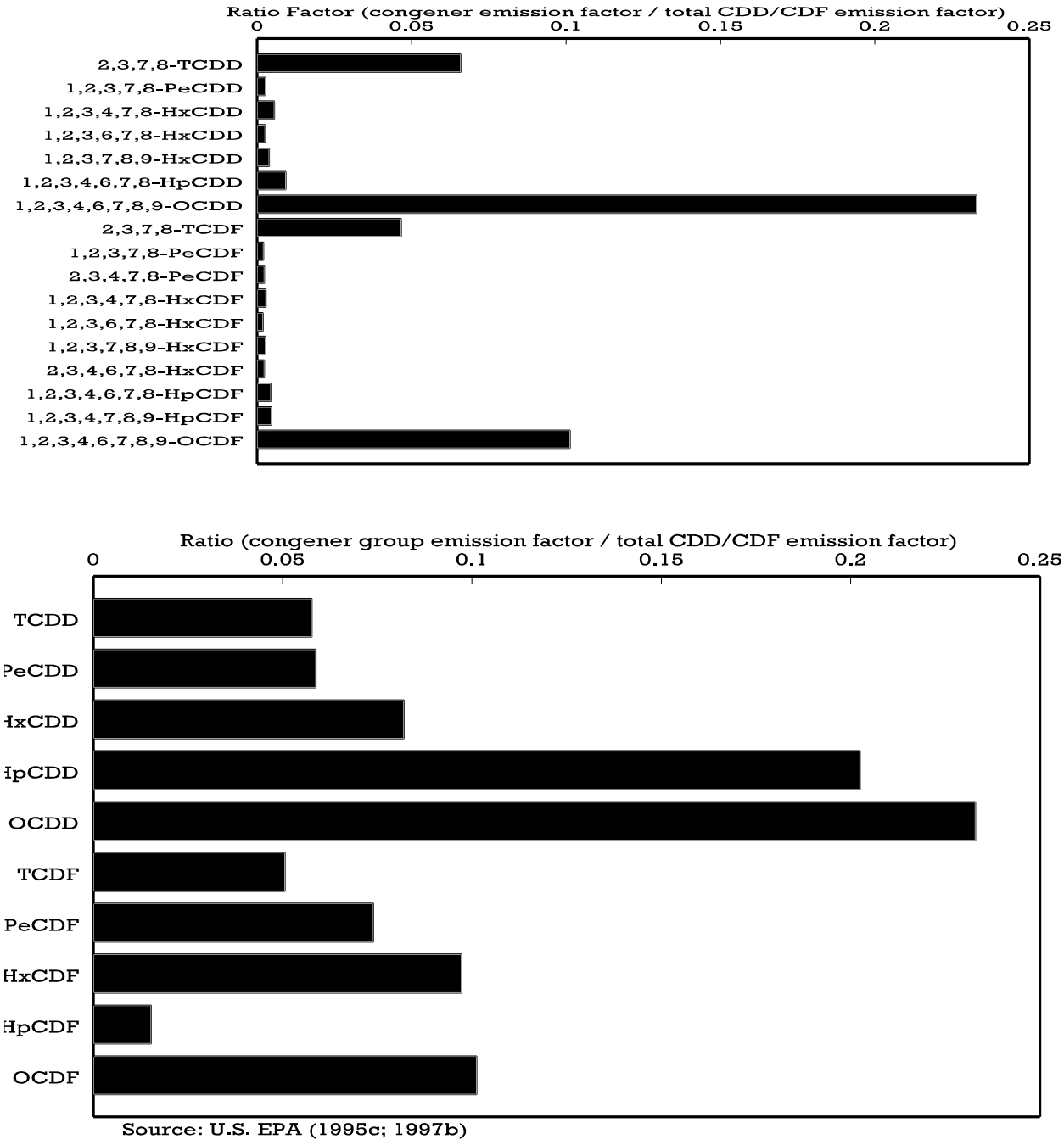


Figure 4-7. Congener and Congener Group Profiles for Air Emissions from Industrial Oil-fueled Boilers

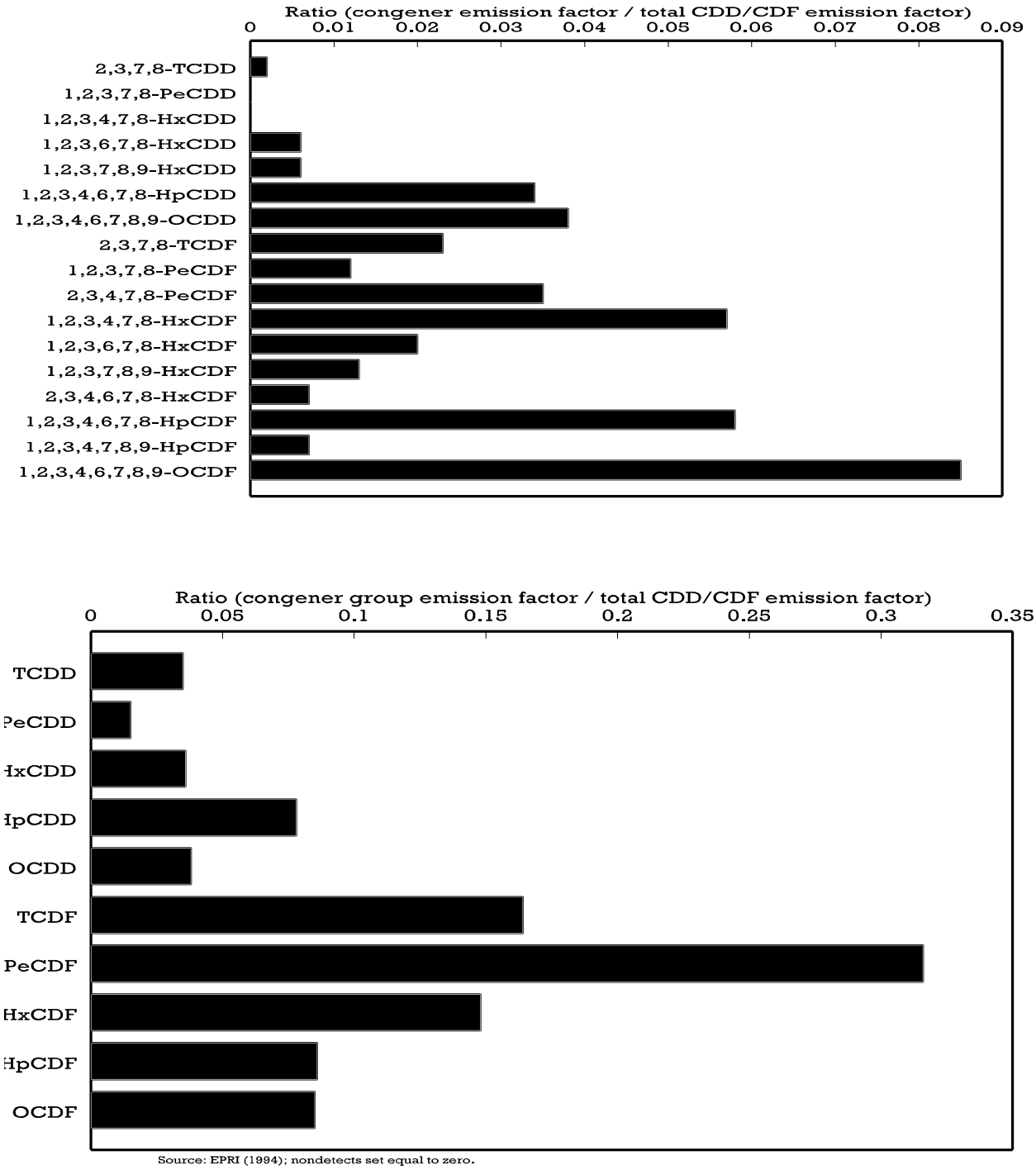


Figure 4-8. Congener and Congener Group Profiles for Air Emissions from Industrial/Utility Coal-fueled Combustors

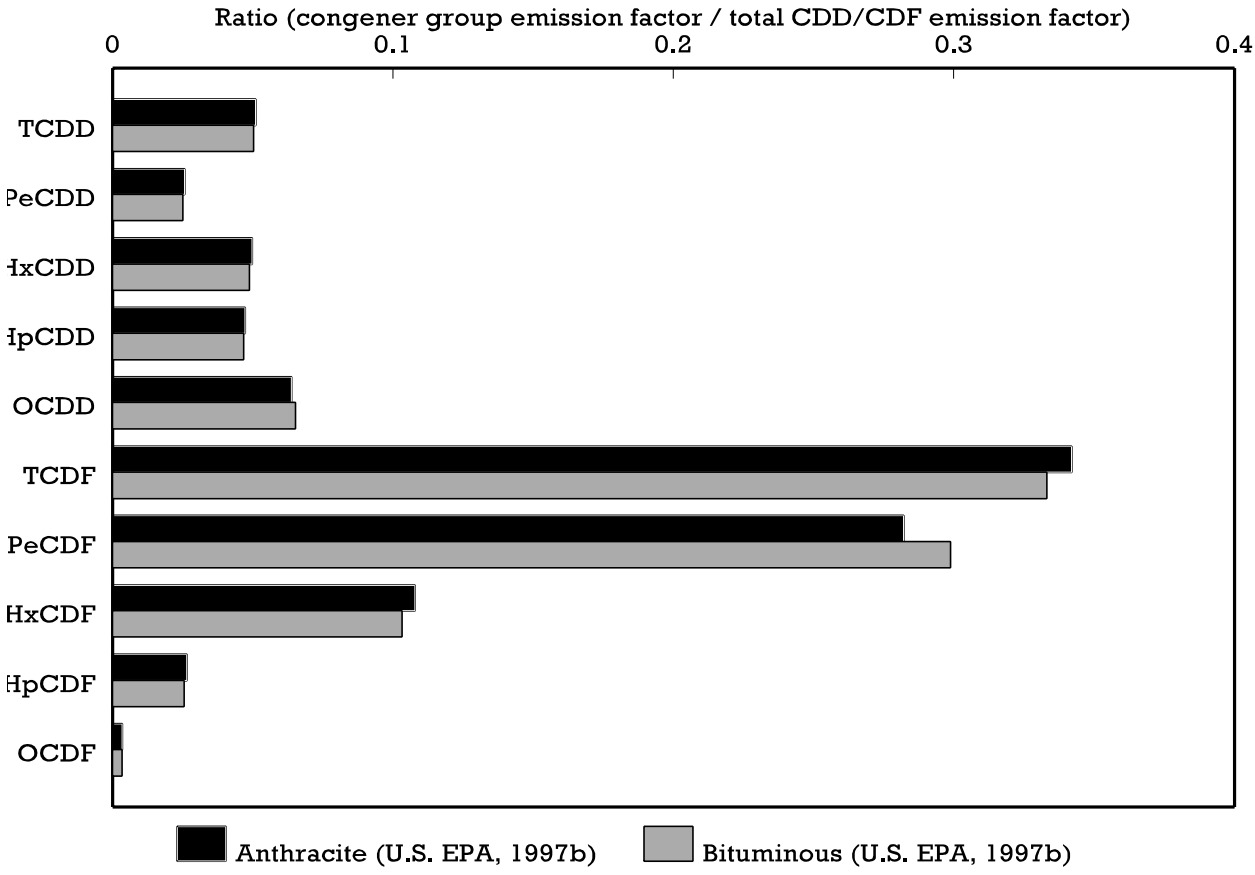


Figure 4-9. Congener Group Profile for Air Emissions from Residential Coal-fueled Combustors