Dioxin and Furan Emission Factors for Wood Waste Incinerators

Prepared for Environment Canada

by
Vic Uloth*, Tim Whitford** and Ron van Heek*,
*Paprican, Prince George, BC
** ET Consulting Ltd., Hinton, Alberta

December 23, 2002.

PULP AND PAPER RESEARCH INSTITUTE OF CANADA • 3800 WESBROOK MALL, VANCOUVER, BC, CANADA V6S 2L9

Dioxin and Furan Emission Factors for Wood Waste Incinerators

by
Vic Uloth*, Tim Whitford** and Ron van Heek*,
*Paprican, Prince George, BC
** ET Consulting Ltd., Hinton, Alberta

Executive Summary

The available literature on dioxin and furan formation during wood waste combustion is reviewed, together with the results of recent stack tests on power boilers at both Canadian and U.S. pulp and paper mills. The permit requirements for wood waste incinerators in both British Columbia and Alberta are also reviewed. Most of the permits for these incinerators, which are also referred to as teepee or silo burners, require an exit temperature in excess of 375 degrees C. The temperature drops quickly when gases exit the burner and the time that the gas is in the temperature zone for de novo synthesis (200 - 500 degrees C) is much less than that provided in a typical power boiler, or even in the chimney of a residential wood stove. In addition, the gases are more dilute, due to higher excess air and rapid dispersion once the gases exit the burner, so the chances of a hydrochloric acid or chlorine molecule colliding with a PAH precursor are reduced. De novo synthesis is, therefore, unlikely to occur. Emissions from a wood waste incinerator are, thus, likely to be substantially less than those from an interior power boiler.

There is a fairly large data bank from testing conducted on boilers, summarized in section 3 of this report, which indicates that dioxin emissions from power boilers burning clean wood waste are typically very low, with median emissions averaging only 38.5 ng TEQ/bone dry tonne of wood burned. There is similarly a fairly large data bank from the testing of ashes from power boilers burning clean wood waste, summarized in section 4 of this report. The flyash captured by the multiclones, electrostatic precipitators and wet scrubbers on power boilers has a mean dioxins concentration of only 0.46 pg TEQ/g of ash. If one uses the EPA recommended emission factor for particulate matter for a “satisfactorily operating wood waste conical burner without controls”, and an assumed dioxin concentration on flyash that is more than 10 times the mean concentration found in power boiler flyash, the estimated dioxin emission factor for a wood waste incinerator would be only 2.7 ng TEQ/AD t of wood waste burned. If one uses the highest dioxin concentrations found on power boiler flyash (29.4 pg TEQ/g) at a U. S. mill, which may have burned wood residues or wood wastes that were not clean, the maximum emission estimate for a wood waste incinerator is 14.7 ng TEQ/AD t of wood waste burned. Both of these calculated emission factors are very likely to overestimate the actual emissions from a wood waste burner burning clean wood waste only, for the reasons outlined in the paragraph above and in section 5.4 of this report. An emission factor of 5 ng TEQ/AD t of wood waste burned is nevertheless recommended to conservatively and safely estimate the maximum potential emissions from this source.

Dioxins and furans concentrations on the ash extracted from wood waste incinerators are expected to be similar to those for grate ash extracted from power boilers as the ash is extracted principally from the bottom of the incinerator and has not been exposed to temperatures in the range of 200 – 500 ^{o}C where de novo synthesis can occur. As little of the ash captured on the screening at the top of a teepee or silo burner is likely to fall back to the

bottom of the burner without burning, it can be assumed that essentially all of the ash from the burner corresponds to grate ash in a power boiler. Dioxin emissions with the ash can be estimated assuming an emission factor of 0.02 pg TEQ/g for the ash from wood waste incineration.

1. Introduction:

Dioxin and furan releases have now been added to the list of substances that have to be reported to the National Pollutant Release Inventory (NPRI). Dioxins and furans (D/F) are expensive to test and heavy reliance is placed on the use of emission factors such as those in USEPA AP-42. Various sectors in the forest products industry have reported difficulties in acquiring accurate emission factors. This problem has been compounded as no authority has compiled a dioxin-furan emission factor book. Heavy reliance is being placed on publications, such as the USEPA AP-42 book, but many of the factors are out of date and do not reflect recent test results.

PAPRICAN has, therefore, undertaken a contract with Environment Canada to prepare a set of emission factors, and supporting material to justify them, for use in inventory compilation by NPRI reporters in the pulp and paper (P&P) and forest products sectors. It is hoped that the resulting guidelines, once distributed to the industry, will improve the mandatory reporting of D/F to the NPRI program. Dioxin and Furan emissions from pulp mill sources were addressed in Part 1 of the contract and a separate report entitled “Dioxin and Furan Emission Factors for Combustion Operations in Pulp Mills” was recently sent to Environment Canada [Uloth, 2002].

The issue of estimating dioxin and furan emissions from wood waste burners at sawmills is particularly problematic as these operations are often semi-batch and practically impossible to test due to both safety-related and practical issues, such as the difficulty in estimating flue gas flow rates. For these reasons, Paprican was also commissioned to derive a best estimate emission factor for calculating dioxin and furan emissions from this source. This will involve the following tasks:

- Review existing scientific literature on D/F formation in various wood-waste incineration processes. (ie: power boilers, wood waste incinerators, teepee or beehive burners, silo burners, etc.).

- Search and list any existing D/F stack testing results performed on wood-waste incineration sources available in Canada and from other countries.

- Review and summarize typical burner operating conditions stated in environmental permits of Alberta and British Columbia.

- If possible, propose scientifically-defensible emission factors for burner wood-waste incineration processes.

1.1 Wood Waste Incineration in Silo, Teepee or Conical Burners:

In developing “best estimate” emission factors for this source, it is necessary to identify best practices related to maintenance and operation of wood residue incinerators, commonly referred to as beehive burners, teepee burners, conical wood waste combustors and wood residue silo burners. These burners are used to burn uncontaminated wood wastes, which have not been transported or stored in salt water. As no units have, to our knowledge, been tested for dioxin and furan emissions, the recommended emission factors for dioxin and furan will be developed based on a weight of evidence approach, utilizing recent EPA emission factors as well as data compiled by PAPRICAN and NCASI (the National Council of the U. S. Pulp and Paper Industry for Air and Stream Improvement) for boilers using uncontaminated wood fuels.

The forest products sector converts large volumes of roundwood into value added products that contribute significantly to Canada’s export trade balance. These exports were valued at $44.2 billion in 1999. There are many product lines involved. However, they share a common issue in that each process generates residuals when the prime commercial value product is extracted.

In many areas of the country, there are synergies between different products and their needs for feedstock and energy (ie. wood products and pulp and paper). The industry has been quite creative in maximizing value from the forest harvest. Regional public policy, particularly in regard to renewable energy, has been shown to foster balanced approaches where process residues are utilized to minimize consumption of purchased energy and fossil fuels. There are many situations where there are concentrations of wood products manufacturing facilities, remote from pulp and paper plants, where affordable infrastructure has been or could be constructed to convert large volumes of residues into energy.

It is not unusual to encounter situations where 30-50 % of the volume of wood processed at a wood products facility is designated as residue. These volumes add up quickly with 2-5 % breakage in log handling, 11-14 % loss in debarking, plus the generation of sawdust, planer dust and trim pieces, all additive through the process. Some species are also prone to breakage in handling while being processed.

As an alternative to landfilling these large volumes, facilities have invested in incineration technologies to reduce the volume to ash. The volume of ash is usually 2-4% of the initial waste volume. As the ash is the result of clean wood combustion, it is often sought after for use as a soil amendment with little concern for any contamination.

The literature review in section 2. of this report attempts to put air emissions from these devices in context primarily using a pair of studies performed several decades ago under the guidance of Oregon State University [Boudel, 1968, Boudel et al., 1958]. These studies were performed with rigorous quality control with consistent application of stipulated procedures performed by an experienced, common test crew. The studies were performed during a period when approximately 500 wood residue incinerators were operating in the State of Oregon. A large number of facilities participated in the test program. This enabled the utilization of custom test equipment and consistent procedures. Safety concerns in testing these operations mandates this type of approach.

2. Literature Review:

2.1 Power Boilers Burning Clean Wood-Waste (With or Without Wastewater Effluent Treatment Plant Sludges):

2.1.1 Rational for Reviewing the Current Emission Factor:

In developing their recommended emission factor for "industrial wood combustion", 0.82 ng TEQ/kg of wood burned [EPA/600/P-98/002Aa, April 1998], the U. S. Environmental Protection Agency relied heavily on a series of four tests conducted on five industrial wood waste boilers by the California Air Resources Board [CARB, 1990a – d]. Two of the tested boilers were characterized as "quad-cell wood-fired boilers"[CARB, 1990 a and d]. Both of these boilers burned only clean wood waste and sawdust and both had lower emissions (0.50 and 0.64 ng TEQ/kg of wood burned) than the average for the CARB tests, which was accepted by EPA as a reasonable emission factor [EPA/600/P-98/002Aa, April 1998]. Quad cells or fuel cells are now only rarely used in Canadian pulp mills for wood waste combustion as they are relatively inefficient in comparison to either a spreader-stoker grate fired boiler or a fluid bed boiler. Studies at one pulp mill on the British Columbia coast showed that dioxins production and emissions for two fuel cells firing salt laden hog fuel were approximately 8 times those for the larger spreader-stoker fired boiler at the same site. As fuel cells also operate with lower combustion air flow than wood waste incinerators, in order to increase the thermal efficiency of associated heat recovery and steam generation equipment, they might be expected to have higher emissions of carbon monoxide, polyaromatic hydrocarbons (PAH) and potentially dioxins.

In addition, the other three boilers tested in the CARB studies fired mixed wastes. The two spreader stoker boilers tested at an electrical utility (emission factor = 0.82 ng TEQ/kg of wood burned) fired a 70:30 mixture of wood waste and "urban wood waste" [CARB, 1990b]. The fluid bed boiler tested in the CARB studies (emission factor = 1.32 ng TEQ/kg of wood burned) also fired wood wastes (the nature and source of which was not clarified, at least in the EPA summary [EPA, 1998]) and "agricultural wastes allowed by existing permits" [EPA, 1998, CARB, 1990c]. The results of these tests should be viewed with suspicion as several researchers have shown that the combustion of "urban wood wastes" and wood-based product residues, such as plywood, hardboard or treated wood, produces much higher dioxin emissions than the combustion of clean "natural" wood or bark (see Table 2.1.1 later in this report). Nakao et al. [2002] have shown that the amount of dioxins formed in open-air incineration of wood scrap are 10 to 230 times greater than those formed in burning natural wood in a forest fire. Schatowitz et al. [1994] also showed that the combustion of waste wood chips from building demolition produced dioxin emissions that were 82 to 216 times those produced by burning natural wood chips or even uncoated chipboard chips in a wood furnace. Kolenda et al. [1994] showed that the combustion of plywood (hardened with $(NH_4)_2SO_4$, with or without a PVC coating) or plywood and untreated wood mixtures in seven large (>1 MW) wood burning facilities produced dioxin emissions 5 to 70 times those from combustion of untreated pine wood alone. Oehme and Muller [1995] also showed that burning waste wood treated with pentachlorophenol produced dioxin concentrations on the baghouse filter ash that were 10 to 100 times those observed when burning "natural" wood waste alone.

As the CARB studies on which EPA based their emission factor estimate were conducted on old inefficient fuel cells or on boilers burning mixed wastes including demolition wastes, treated wood, or wet agricultural wastes, it is likely that this emission factor would significantly overestimate the emissions from a relatively modern spreader-stoker fired boiler, a fluid bed boiler, or even a wood waste incinerator firing only clean wood waste.

2.1.2 Emissions from Residential Wood Combustion:

Section 4.2 of EPA/600/P-98/002Aa [April 1998] provides an excellent summary of dioxin test results for both residential and industrial wood combustion up until 1996. A wide range of emissions and emission factors were noted in both sectors. For residential wood stoves, burning clean wood only, dioxin emissions ranged from 0.064 ng TEQ/dscm to 0.18 ng TEQ/dscm (dscm = dry standard cubic meters of gas; standard indicates that gas volumes and flows have been normalized to "standard conditions" of temperature (273 K) and pressure (101.325 kPA or 1 atmosphere)). The corresponding emission factors ranged from 0.77 ng TEQ/kg of dry wood to 1.9 ng TEQ/kg of dry wood. EPA subsequently recommended a rather conservative emission factor of 2 ng TEQ/kg of dry wood for residential wood combustion, based on the observation that a good percentage of the wood burned in homes is burned in fireplaces, rather than in more efficient wood stoves. More recent testing by Environment Canada [Report ERMD 2000-01, 2000] indicates that this emission factor is about 4 times too high for residential wood stoves and release estimates for this sector were subsequently substantially reduced using an emission factor of 0.5 ng TEQ/kg of wood.

2.1.3 Emissions from Industrial Wood Combustion:

For industrial wood combustion [EPA/600/P-98/002Aa, April 1998], the results of the four CARB studies (summarized earlier) and tests for 5 boilers burning bark and wood residues [NCASI, 1995] were reviewed. As the average emission factor for the boilers in the NCASI study (0.4 ng TEQ/kg of feed) was similar to that in the CARB studies, EPA again decided to use the more conservative emission factor estimate (0.82 ng TEQ/kg of wood). Since some of the units tested by NCASI were at wood products facilities, it is likely that their results may also have been skewed high due to the combustion of treated wood wastes.

The EPA report [1998] noted, based on tests by EPA on a three-cell dutch oven at lumber products plant where all the wood was stored in salt water, that their proposed emission factor would not be appropriate for facilities burning wood waste containing high levels of chloride (see section 2.1.4). They also noted that tests by Umweltbundesamt [1996] on 30 facilities of varying designs and using different types of wood fuel, indicated elevated dioxin and furan emissions when combustion conditions were poor, as indicated by elevated carbon monoxide emissions, and/or when the fuel contained elevated chlorine or chloride concentrations. Chipboard, preservative-treated wood and PVC-coated wood were found to contain up to 0.2, 1.2 and 0.3 % chloride by weight, respectively, versus the 0.001 to 0.01 % chloride by weight typical in untreated wood and bark [EPA, 1998]. Typical emission levels reported from studies on wood fired boilers are summarized in Table 2.1.1. The elevated concentrations of chloride in several of the waste wood sources at least partially explains the higher levels of dioxin emissions observed when burning demolition wastes or treated wood versus natural or clean wood waste [Nakao et al., 2002, Schatowitz et al.,1994, Kolenda et al., 1994, and Oehme and Muller, 1995].

Table 2.1: Dioxin Emissions from Wood Waste Combustion

Literature Reference	Type of Combustor	Nature of Fuel	Dioxin Emissions, pg TEQ/dscm @ 11 % O_2	Emissions Factor, ng TEQ/kg of dry wood
Schatowitz, 1994	Automatic chip furnace Automatic chip furnace Automatic chip furnace Household stove	Wood chips Uncoated chipboard Demolition waste Household waste	66 – 214 24 – 76 2 700 – 14 200 114 000	0.79 – 2.57 0.29 – 0.91 26 – 173.3 3 230 000
CARB, 1990 a-d	Quad cell Quad cell Spreader stoker Fluid bed boiler	Wood waste Wood waste Wood and urban wood waste Wood and agricultural wastes	116* 246* 246* 229*	0.50 0.64 0.82 1.32
NCASI,1995	Two coal burners and three spreader stokers	Wood wastes at various wood products facilities and pulp mills	0.4 – 281*	0.4
Kolenda, 1994	9.6 MW incinerator 9.6 MW incinerator 9.6 MW incinerator 39 MW grate incinerator	Pine wood Plywood residues Untreated wood and treated product residues Wood and coated plywood residues	3 – 5 2 – 210 25 110 – 150	
Zimmerman, 2001	1 MW pilot combustor	Wood waste - under good firing conditions Wood waste - under oxygen-deficient conditions	12 – 16 51 – 94	
Valttila, 1993	Fluid bed (65 – 84 MW) Stoker grate (47 MW) Circulating fluid bed (59 MW)	Bark and pulp mill sludge	140 – 390 1 090 710	
Maatila, 1992	60 MW district heating boiler	Bark and coal Bark, coal and chlorinated waste plastics	16.4 – 23 38 – 103	
Pandompatam, 1997	Batch type, three cell pilot incinerator	Aspen bark (0.007 % Cl) Aspen bark soaked in salt water (0.76 % Cl)	20 3 200	
EPA, 1998	Dutch oven boiler	Salt laden wood wastes		17.1

* at 12 % CO_2; see Appendix A

In contrast to many of the above studies, test burns on a power boiler at Northwood Pulp in Prince George, BC using a chlorophenol contaminated hog fuel indicated a high level of dioxin destruction [LC Engineering, April 1989]. The boiler was operated at a steam production rate of approximately 100 tonnes per hour or 60 % of the maximum rated capacity. Eight runs were completed in late September 1987. Two test runs were needed to develop the baseline (no chlorophenol injection), three for the condition where the fuel was spiked to a chlorophenol concentration of 57 ug/g of hog fuel and three for the condition where the chlorophenol concentration was 436 ug/g of hog fuel. All dioxins and furans were destroyed during the baseline and low chlorophenol spike conditions. While trace quantities of dioxins and furans were detected in the stack gases during the high spike condition trials, dioxin destruction efficiencies ranged from 99.9994 to 100 %. The need to assess destruction efficiencies when the boiler was operating closer to maximum rated capacity was, however, noted.

2.1.4 Effect of Chlorides and Chlorine on Dioxin and Furan Emissions:

Pandompatom et al. [1997] at the Alberta Environmental Centre used a batch-type three-chamber incinerator to fire hogged bark with and without salt addition. Clean aspen bark, untreated except for sizing, was used as the control sample. The test sample was similar bark soaked in NaCl brine and then air dried to a moisture level comparable to the control sample. The chloride contents of the two hog samples were 0.007 and 0.76 % by weight on dry hog, respectively. The resulting dioxin and furan emissions were 0.02 and 3.2 ng TEQ/dscm, demonstrating the feasibility of using simulated salt-laden hog to examine the effects of hog chloride content on dioxin and furan emissions. Vesterinen and Flyktman [1996], in co-combustion of refuse derived fuel and wood chips in a 4 MW bubbling fluid bed boiler, found a clear relationship between fuel chlorine content and dioxin and furan concentrations in the flue gas. Halonen et al. [1993 a, b] in pilot scale work also found that the chlorine content of the fuel correlated well with dioxin and furan concentrations at high gas temperatures, ie at the furnace exit, but the correlation disappeared as the gas temperature decreased. Maatila et al. [1992] similarly found that dioxin and furan emissions from a 60 MW district heating boiler increased by a factor of 2 to 5 when chlorinated waste plastics were co-fired with coal and bark. In this study, dioxin and furan concentrations correlated better with the measured HCl levels in the flue gas than with chlorine concentrations in the fuel.

2.1.5 Effect of Co-firing Wastewater Treatment Plant Sludges:

Studies on the No.5 power boiler at Fletcher Challenge Canada's Elk Falls Pulp and Paper mill [Bovar-Concord Environmental, May 1994] showed that the disposal of waste water treatment plant sludges through incineration in the hog fuel power boiler caused no significant increases in most stack emissions at either normal or catch-up disposal rates. This boiler burned salt-laden hog fuel and had much higher dioxin emissions than normally seen for power boilers burning clean wood waste [Luthe et al., 1996]. A decline in stack emissions of dioxins and furans with increasing sludge firing rates was later found to be due to sulphur introduced with the waste water treatment plant sludges and a resulting reduction of the chloride/sulphur ratio in the blended biomass fuel [Luthe et al., 1996, Luthe et al., 1998b]. NCASI [1995] similarly showed lower dioxin and furan emissions for one facility firing clean wood waste and biosludges (0.001 ng TEQ/kg of feed) than the

average emissions for the five boilers in the CARB [1990 a – d] study (0.82 ng TEQ/kg of feed).

Valttila [1993], on the other hand, found that when 5 – 14 % biosludge was burned with bark in three different types of pulp mill boilers, dioxin and furan emissions were higher than when bark alone was burned (see Table 2.1.1). He noted that burning up to 20 % sludge in the bubbling fluidized bed boiler did not result in any greater emissions than burning 5 - 14 % sludge, provided proper combustion conditions were maintained in the boiler. Valttila attributed the increases in dioxin and furan emissions for each boiler to the higher concentrations of chlorine or chloride in the sludges relative to bark.

The impact of sludges in general on boiler dioxin and furan emissions is likely to depend on the chloride, sulphur and moisture contents of the sludge relative to that of the wood waste. If the sludge chloride content is significantly higher than that in the wood waste, and the sludge sulphur content is not correspondingly high, it is likely to increase dioxin formation. Similarly, if the sludge is quite wet, it is likely to reduce the boiler combustion efficiency and increase the dioxin and furan formation potential.

2.1.6 Effect of Temperature:

Numerous studies have indicated that temperature profiles in a combustion process can dramatically influence dioxin and furan formation. Decomposition of dioxins and furans is generally favoured at temperatures in excess of 800 C. De novo synthesis, the main mechanism of dioxin and furan formation in most combustion systems, is a relatively low temperature process, generally thought to dominate D/F formation in a temperature range from 200 to 500 C. Luthe [1996] has shown that greater than 85 % of the dioxin formation in coastal power boilers burning salt-laden wood waste is by a de novo mechanism at temperatures of 180 to 500 C. Santoleri [1996] suggests that dioxin formation rates peak at temperatures in the 250 to 350 C range. Wunsch [1994] similarly reported a strong increase in the concentrations of PCDD/F in municipal incinerator boiler ash at temperatures in the 220 to 300 C range.

While simulating household waste incineration in a laboratory scale fluidized-bed reactor, Fangmark [1994] varied the residence time in the cooling section of the reactor from 0.9 to 2.9 seconds and the sample collection temperature from 260 to 510 C. The highest concentrations of PCDD/F were found at 340 C with a residence time of 2.9 seconds. The lowest concentrations were obtained under conditions of rapid quenching of the flue gas to temperatures of 260 C. Similarly, Stanmore [2000] reported that the amounts of PCDD/F formed in a pilot scale medical waste incinerator, when cooling from 900 C to ambient temperatures, were almost proportional to the residence time in the 400 to 200 C temperature zone.

Takeshita [1992] conducted experiments on a large incinerator in which the temperature into the electrostatic precipitator was varied by adjusting the amount of water sprayed into a gas cooling chamber above the furnace. Other variables were the concentrations of HCl and CO. At any combination of the other variables, both dioxins and furans increased as the precipitator inlet temperature was increased from 200 to 240 to 300 C, with only one exception. More recently, researchers in Belgium [Everaert and Baeyens, 2001] have

found that the major operating parameter affecting dioxin and furan emissions from 12 different municipal waste incinerators was the operating temperature in the electrostatic precipitator. High temperatures (> 200 C), which can enhance de novo synthesis, should be avoided to minimize TCDD/F emissions.

2.2 Power Boilers Burning a Combination of Clean Wood-Waste (With or Without Wastewater Effluent Treatment Plant Sludges) and De-inking Process Sludges:

Douglas et al. [1997] reviewed the results of field trials on the burning of paper de-inking sludges (PDS) in a Canadian Biomass Fluid Bed attached to the number 4 stoker grate boiler at Avenor's (now Bowater's) Thunder Bay pulp mill. The ABB patented fluidized bed process incorporated a refractory-lined furnace chamber. For the purpose of heat recovery, flue gases from the combustor were ducted to the number 4 boiler through the boiler ashpit. The authors noted that while mechanical dewatering can reduce the moisture content of PDS to 40 – 60 %, the high inert content of these materials make them difficult to burn on conventional stoker grates. Three sets of emission tests completed on the number 4 power boiler stack, while up to 4 tph of PDS were burned in the attached Biomass Fluid Bed, showed dioxin and furan emissions of 2.2, 70.3 and 2.7 pg TEQ/dscm at 11% O_2. Corresponding PAH emissions (total emissions of 25 PAH compounds analysed) in the three tests were 15.7, 24.1 and 5.0 ug/dscm at 11 % O_2. The high dioxin emissions in the second test were attributed to low fluid bed temperatures and combustor trips an hour before the test started and a half hour before the stack test was completed.

2.3 Wood Waste Incinerators:

Wood waste incinerators or conical burners are perceived to be significant sources of atmospheric contaminants, such as particulate matter. Part of this perception is due to the fact that they are virtually impossible to test using approved and commercially available methodologies. The only emission data readily available, including emission factors, is from two studies conducted by the University of Oregon in 1958 and 1968 [Boudel, 1968, Boudel et al., 1958]. These studies were used to develop emission factors which are available on the EPA website as part of Table 2.7-1 Emission Factors for Waste Incineration in Conical Burners Without Controls. The factors have not been updated by EPA as it is believed that there are no wood fired burners of this type operated in the United States (personal communication between T. Whitford of FPAC and J. Pinkerton of NCASI).

The EPA data provides three levels of assessment of operation to assist in assigning emission factors. Based on a sampling of operating and permit data for burners located in Alberta and British Columbia (discussed later in this report), only one category in the EPA table appears to be of relevance in these provinces. The conditions required to use these factors are that the burner be properly maintained with adjustable underfire air supply and adjustable, tangential overfire air inlets, operated at approximately 300-500% excess air, with a 370^{o}C (700^{o}F) or greater outlet temperature. The EPA emission factors are based on the as received wood fuel with a moisture content of approximately 50%.

The Boubel studies [1958, 1968] also identified operating and maintenance practices which contribute to attaining optimum operation and minimal emissions of contaminants.

The practices are still applicable today, as burner designs are basically unchanged. It is a reasonable conclusion to assume that silo burners that are operated at higher temperatures with lower opacities (or smoke concentrations) emit less pollutants than a beehive burner (see section 2.3.3 below).

Table 2.2 is derived from the EPA website. While it is somewhat dated, it is supported by the studies which were available for review [Boubel et al.,1958, Boubel, 1968]. Those studies had good quality control and represent the best available data for this application at this time.

Table 2.2: Emission Factors for Waste Incineration in Conical Burners Without Controls[a,e]

Type of waste	Particulate kg/AD t	Sulfur Oxides kg/AD t	CO kg/ADt	NMOC[i] kg/AD t	NO_x kg/ADt	Dioxin/ Furan gTEQ/t
Wood[e]	0.5[f]	0.05	65	5.5	0.5	
Wood[e]	3.5[g]					
Wood[e]	10[h]					

[a] Moisture content of as fired wood waste is approximately 50%. Blanks indicate no data available.
[e] Referenced sources of data include six studies, which include both of the R.W. Boubel studies [1958 and 1968] and numbered Bulletins 39 (June 1958) and 42 (August 1968) from Oregon State University.
[f] Satisfactory operation: properly maintained burner with adjustable underfire air supply and adjustable, tangential overfire air inlets, approximately 500% excess air, and 370^{o}C exit gas temperature.
[g] Unsatisfactory operation: Properly maintained burner with radial overfire near bottom of shell, approximately 1200% excess air, and 204^{o}C exit gas temperature.
[h] Very unsatisfactory operation: improperly maintained burner with radial overfire air supply near bottom of shell and many gaping holes in shell, approximately 1500% excess air and 204^{o}C exit gas temperature.
[i] NMOC = non methane organic compounds

2.3.1 Silo Burners :

Silo burners are somewhat more amenable to testing, based on access and personnel safety. It can, however, be challenging to confirm the required flow distribution for a valid stack test due to the tangential flow pattern in the burner and possible feed variability. The outlet throat configuration commonly used for these burners is too short to develop a uniform flow profile. Most of these burners are installed without fuel storage and may receive a blend of eight or more residue sources. If a section of the mill stops production or a conveyor plugs or stops the impact on burner operation due to the change in sizing and /or moisture in the fuel can be fairly significant.

It is, however, possible to install sample platforms and ports on silo burners. It may take a number of test runs to satisfy the qualitative requirements of the stack test code but some

successful tests have been conducted. Results from a three run test on one burner in 1993 follow. Fuel was collected in trucks and weighed during the tests. The average fuel flow to the burner was 14,096 pounds per hour.

Table 2.3: Particulate matter (PM) emissions from a silo burner.

Run	Flow Dscf/m	Gas Temp.	H_2O %	O_2 %	% fuel moisture	PM, grain/dscf	PM, grain/dscf @7 % O2
1	27,956	1061^oF	14.8	13.,9	41.3	0.0517	0.10
2	42,763	817^oF	10.8	15.7	36.0	0.0351	0.09
3	42,907	741^oF	13.3	14.1	32.8	0.0345	0.071
Avg.	37,875	873^oF	13.0	14.4		0.0406	0.087

The total particulate value expressed at 12 % O_2 is approximately 203 mg/m^3. This particular burner was located in Walden, Colorado and, at the time of testing, was being operated by Louisiana Pacific Corporation.

Data provided by one operator in Alberta indicates that they are able to maintain significantly higher outlet temperatures than shown in the above table and good combustion control down to 50% of design capacity. This particular burner has good airflow control to the different zones and operating data supplied for review confirmed that airflow to fuel flow ratio can be successfully controlled within the firing ranges indicated.

2.3.2 Study 1. Wood Waste Disposal and Utilization, 1958:

This study [Boubel et al., 1958] involved testing of eight wood residue burners. One of the burners was tested several times with differing operating parameters to predict the impact of operating and maintenance practices on emissions of concern. A note of interest is that the burner selected for assessing the impact of variables on the operation/emissions had to be of a configuration that included underfire air and tangential overfire air admission. The burner also had to be in good mechanical condition and accessible for periodic cleaning of the underfire air system.

Some key conclusions of this study include the following:

1. Burners must be maintained in a condition that allows proper introduction of underfire air, and a shell and support integrity that allows a minimum of tramp air entrainment. This is addressed through cleaning schedules and regular inspections that include items like skirt to ground or foundation sealing, and an assessment of the condition of access doors, air nozzles and shell seals.
2. Tangential inlets for overfire air are necessary to ensure that complete burnout of pyrolized compounds or entrained materials occurs before gases exit the burner.
3. Smoking burners are emitting more particulate than ones with a white plume. This particulate may be partially burned or even unburned. The size of the

particulate is related to the intensity of the smoke and all measures that reduced smoke reduced particulate emissions.

4. Burners smoke during the startup and shutdown cycles. Any measure that shortened these smoking periods reduced the amount of particulate emitted. Use of auxiliary burners to get the residue burner up to temperature before fuel was introduced, or to maintain temperature until the fuel bed is reduced after stopping the feed, reduces overall emissions.
5. Underfire air systems must be kept clean and nozzles maintained for effective supply of air to the fuel bed. Each burner will have its own requirement for cleaning based on the mass of fuel processed and the ash content of the fuel. The underfire air system should be capable of control on volume and of supplying no less than 30% of the total air requirement with a good distribution profile.
6. Burners have to be sized properly to produce optimum operating conditions and to minimize emissions. If a burner is too small, it may suffer mechanical damage when operated at the minimum temperature required to maintain an acceptable emission level. If a burner is too large, it may not be possible for it to achieve an exit temperature that satisfies the required emission profile. An obvious conclusion is that burners that have some turndown capability on both the air and fuel systems, and that have adequate capacity to allow cleanout and repair scheduling, will have the capability to minimize overall emissions.

For the purposes of this document, the recommendations above constitute best practices as applied to wood residue combustors. Demonstration of compliance with temperature requirements(i.e. >90% of operating time exceeding permit value) is the key requirement. Permits may also require demonstration of compliance related to opacity limits (normally less than 20% opacity except for very brief periods).

2.3.3 Study 2. Particulate Emission From Sawmill Waste Burners:

A study, published by the University of Oregon in 1968 [Boubel, 1968] included data on emission testing on 19 wood residue burners. A total of 100 tests were conducted over a period of 42 days. All tests were conducted by the same personnel using standardized procedures and the same equipment.

No changes to operating practices were made at any of these sites. The objective of the testing was to assemble a database of “typical” operating data. The mills were not identified except by number.

The tests included long range photographs, close range photographs, assignment of a smoke index, as well as the emission testing. The burners were all ranked based on mechanical condition as well as ranking based on actual versus theoretical draft attained. The draft ratio co-related very well with the amount of smoke generated, the mass of total particulate emission measured, and the exit temperature that was attained.

The sample train was arranged so that very large particulate would settle out ahead of the filter. These large particles were examined for weight mean, count mean and geometric deviation.

Particulate captured on the filter was examined in the laboratory for size distribution and % ash. The average size for all samples was 3.28 microns with significant variability from burner to burner. The per cent ash in the particulate varied significantly as well, with the burners which ranked “poor” emitting considerable unburned particulate. This was attributed to the poor airflow patterns in these burners, often due to tramp air introduced due to leakage around buckled plates and open or poorly sealed doors.

A computer correlation with a matrix of variables was run to determine if there was any significant correlation between variables measured during the study. Three specific study conclusions were:

1. Particulate emission correlated inversely with the emission temperature. The higher the temperature, the lower the PM emissions.
2. The draft ratio (actual/theoretical) correlated directly with the emission temperature. Higher exit temperatures, and hence lower emissions, were achieved with tighter burner control (better maintenance and access doors closed).
3. The per cent ash in the PM emissions correlated directly with temperature. Higher emission temperatures indicated more complete combustion.

The size of the particulate did not correlate significantly with the temperature which would indicate that it was more a function of the material being fed to the burner than how the burner was operated.

2.3.4 Local issues:

Wood residue burners tend to focus local interest groups when operated inconsistently, at low outlet temperatures and when cooling down and starting up. At the very least, they are not an aesthetic asset in a community during these operational periods. In communities where the wood products industry is the main employer tolerance tends to be at a higher level than in more diversified communities where the majority of employment is not linked to the mills.

During these periods of poor operation, there is a visible opacity related to the emissions which may result in low level smoke during inversion conditions. It is also a reasonable assumption that emissions are at their highest when visible smoke is present (see sections 2.2.2 and 2.2.3 above). Poor combustion conditions are generally reflected in higher PAH levels, CO concentrations, and higher particulate emissions. Poor mixing and low combustion temperatures may also foster formation of dioxins and furans.

2.3.5 Ambient Impacts:

Operators can minimize the fallout of unburned particles by adhering to recommended operating practices. High emissions of unburned particles have specifically been linked with poor air flow patterns in the burners. These poor flow patterns are generally due to tramp air infiltration through leaking setting and doors and dirty, poorly maintained or obstructed airflow nozzles. The unburned particles, in particular, have a tendency to be carried significant distances due to their irregular shape and low density.

Typical ambient impacts around burners will be some discernable particulate fallout, related largely to transients in operation. If the burner receives a shot of fine dry fuel, in particular, there is a tendency for it to flash with a resultant puff of smoke and particulate. As the majority of installed wood waste burners have no emission control equipment, this is unavoidable but the fallout is normally very local to the burner. These variations can often be minimized through minor changes in mill operation or to the fuel feed conveying system.

Burners have a tendency to smoke during warmup and cooldown cycles. This is related to the lack of (or low) temperature in the unit with resultant poor combustion. In many urban areas, this becomes a major community issue and results in pressure on the regulator to have the burner eliminated. Odour is a related issue when the burners are below optimum operating temperatures. Best practices in some regions have required the use of auxiliary fuel burners to shorten these cycles.

3. Review of Stack Test Results and Development of Emission Factors:

Both the United States and Canada have regulatory programs with requirements for annual reporting by industrial facilities of the emissions of certain substances to the environment. The U.S. program is commonly known as TRI (Toxic Release Inventory) while the Canadian program is the National Pollutant Release Inventory (NPRI). The two programs have many similar features, due in part to environmental provisions contained in the North American Free Trade Agreement (NAFTA). However, there are some important differences. In the area of dioxin and furan emissions, NPRI releases are to be reported in toxic equivalents using the International Toxicity Equivalency Factors (ITEQ), which range from 0.001 to 1 for the 17 congeners that must be measured under both NPRI and TRI guidelines (see Table 3.1). Environment Canada has specified a level of quantification (LOQ) of 32 pg TEQ/dscm for gaseous streams. When measurements are below this value, a facility has the option of reporting the measured value or that the measured release is less than the LOQ. In addition, if a facility has no information at all, it may indicate this on the reporting form and not provide release or transfer estimates.

In the TRI program, the reporting threshold is 0.1 g/y, based on the total of the 17 analysed congeners, not in TEQs. Because NPRI releases are reported in ITEQ units, and TRI releases are reported as the total of the 17 congeners, reported emissions will be much lower for Canadian mills. Using emission data for 11 kraft recovery boilers, the National Council for Air and Stream Improvement (NCASI) in the U. S. has estimated [Pinkerton, 2001] that the emissions expressed in ITEQ units are less than 3 % of the total for the 17 congeners. Because much of the data on dioxin and furan emissions from pulp and paper sources, that is available, was compiled by NCASI, we have appended the raw data to this report, allowing readers to check the emissions of any given congener or to covert emissions using other toxicity equivalency guidelines, such as those from the World Health Organization (WHO).

The data compiled in the appendices attached to this report were collected by independent certified, stack testing contractors working at each facility. Stack testing was done in

accordance with EPA Method 23 or Environment Canada "Reference Method for Source Testing: Measurement of Releases of Selected Semi-Volatile Organic Compounds from Stationary Sources", EPS 1/RM/2, June 1989. Each sampling run was typically 3 or 4 hours long. Quality assurance and quality control (QA/QC) evaluation of the PCDD/F data was based on three sets of analyses: (1) recoveries from pre-spike standards prior to sampling; (2) analysis of laboratory control samples for the 17 PCDD/F isomers listed in EPA Method 23; and (3) analysis of field and trip blank samples for PCDD/Fs. All samples and tests met the pre-test QA/QC criteria. In all cases, the concentrations for non-detect congeners were set equal to zero as currently recommended by EPA for sources with very low emissions. In determining averages and medians for a given unit operation, the averages for each series of tests on a given boiler were used. If more than one boiler was tested at a given mill, the results for each boiler were included in the determination of average and median emissions. The averages for a boiler with 8 stack tests were, however, given no more weighting than those for a boiler with only one or two tests.

Table 3.1: Dioxin and Furan Congeners Included in the NPRI Dioxins/Furans Group.

Compound	*TEF*
2,3,7,8-tetrachlorodibenzo-*p*-dioxin	1.0
1,2,3,7,8-pentachlorodibenzo-*p*-dioxin	0.5
1,2,3,4,7,8-hexachlorodibenzo-*p*-dioxin	0.1
1,2,3,6,7,8-hexachlorodibenzo-*p*-dioxin	0.1
1,2,3,7,8,9-hexachlorodibenzo-*p*-dioxin	0.1
1,2,3,4,6,7,8-heptachlorodibenzo-*p*-dioxin	0.01
Octachlorodibenzo-*p*-dioxin	0.001
2,3,7,8-tetrachlorodibenzofuran	0.1
1,2,3,7,8-pentachlorodibenzofuran	0.05
2,3,4,7,8-pentachlorodibenzofuran	0.5
1,2,3,4,7,8-hexachlorodibenzofuran	0.1
1,2,3,6,7,8-hexachlorodibenzofuran	0.1
1,2,3,7,8,9-hexachlorodibenzofuran	0.1
2,3,4,6,7,8-hexachlorodibenzofuran	0.1
1,2,3,4,6,7,8-heptachlorodibenzofuran	0.01
1,2,3,4,7,8,9-heptachlorodibenzofuran	0.01
Octachlorodibenzofuran	0.001

3.1 Power Boilers Burning Clean Wood-Waste (With or Without Wastewater Effluent Treatment Plant Sludges) :

As dioxin and furan emissions from power boilers burning clean wood waste can vary dramatically due to co-firing of wood product residues, plywood or even agricultural wastes (see Table 2.1), only emission data for wood waste power boilers at pulp and paper facilities will be used to estimate a suitable emission factor for these boilers. Appendix A contains dioxin and furan emission data, compiled by NCASI for the four non-pulp and

paper boilers in the CARB studies [1990a – d] and for 21 tests on 10 pulp and paper industry boilers in the U. S. As NCASI did not have data on the boiler firing rates, but did have accurate flue gas flow rate data, they have estimated the hog firing rate by assuming a wood heating value and a flue gas flow per million BTU of input heat, corrected to 12 % CO_2. All 10 boilers were equipped with multiclones for particulate emission control. Three of the boilers were also equipped with dry electrostatic precipitators (ESP), four with wet scrubbers and one with a wet scrubber followed by a wet ESP. Two had only multiclones for PM control. While the four boilers with wet scrubbers generally had lower dioxin and furan emissions, NCASI researchers found it difficult to conclude that the final PM control device had any effect on the total PCDD/F emissions, because of the wide range of emissions for a given boiler and between boilers.

Appendix B contains dioxin and furan emission data, compiled by Paprican, for 16 tests on 5 additional Canadian pulp and paper industry boilers. The mills in this data set provided Paprican with estimates of the hog firing rates based on the amount of steam produced from hog fuel during each stack test or average hog firing rates for each boiler. As most of these tests were done during permit compliance testing, and the boilers are required to operate at 85 % or better of their typical loading during compliance testing, the average hog firing rates should reasonably approximate the firing rates during the stack tests. The data compiled by Paprican is normalized to 8 % O_2 as this is the standard in many provincial permits for combustion sources. We have assumed that emissions at 12 % CO_2 in NCASI's data base are comparable to those at 8 % O_2 in Paprican's data base. In both data sets, the concentrations of non-detect congeners were set equal to zero as currently recommended by EPA. Both sets of data are summarized in Table 3.2.

Only four of the 10 boilers in NCASI's data set (see page A–17), and only one of the five boilers in Paprican's data set (see page B-7), had average dioxin and furan emissions exceeding Environment Canada's LOQ of 32 pg TEQ/dscm. In addition, the second test on wood fired boiler G (WFBG) in NCASI's data set gave dioxin and furan emissions that were a factor of 10 lower than those observed in test 1, suggesting that either very poor combustion conditions existed during the first test or that treated wood or processed wood residues (plywood, chipboard, fibreboard, etc.) may have been burned during the first test. Only 2 of the 16 stack tests on the five boilers at Canadian mills in Paprican's data set showed dioxin emissions that were marginally greater than the average emission (81.5 pg TEQ/dscm) for the power boilers in the NCASI data set. This strongly suggests that treated wood or wood product wastes were likely burned in many of the wood waste boilers in NCASI's data set.

Table 3.2: Dioxin and Furan Emission Data for Pulp and Paper Industry Wood Waste Boilers.

	In NCASI's Data Set	In Paprican's Data Set	For the Combined Data Set
Number of Boilers Tested	10	5	15
Total Number of Stack Tests	21	16	37
Stack Emissions, pg TEQ/dscm*			
Range	0.4 – 339.2	0.8 – 86.5	0.4 – 339.2
Average	81.5	20.2	58.5
Median	3.7	5.7	4.7
Estimated Emission Factor, ng TEQ/BDt of hog			
Range	3.3 – 2799	10.2 – 247.3	3.3 – 2799
Average	672	84.2	451.6
Median	30.4	46.6	38.5

* at 12 % CO_2 for the NCASI data set and at 8 % O_2 for the Paprican data set

It should be noted that one high or low test result can significantly skew the average of a small data set, as evidenced by the large differences between the average and median test results in both data sets. If the results for boiler G in NCASI's data set are disregarded, the average stack emission drops by 35 %, from 81.5 to 52.9 pg TEQ/dscm, and the average emission factor for the NCASI data set drops from 672 to 435.7 ng TEQ/BDt of hog. Similarly, if the single highest test result (test 2 at Mill D) is excluded from Paprican's data set, the average emission factor for the five boilers in Paprican's data set drops by 13 %, from 84.2 to 73.3 ng TEQ/BDt of hog fuel. Since the median stack emissions and emission factors are much closer than the averages in the two data sets, use of an emission factor close to the median emission factor of 38.5 ng/BD tonne of hog fuel burned has been recommended [Uloth, 2002] to estimate dioxin and furan emissions from this source.

3.2 Power Boilers Burning a Combination of Clean Wood-Waste (With or Without Wastewater Effluent Treatment Plant Sludges) and De-inking Process Sludges:

Appendix C contains dioxin and furan emission data, compiled by Paprican, for 21 tests on all 5 of the Canadian pulp and paper industry boilers that burn de-inking sludge. The coding for the boilers in Appendices B and C are identical, allowing the reader to compare boiler emissions with and without the co-firing of de-inking sludges. The mills in this data set again provided Paprican with estimates of the hog firing rates based on the amount of steam produced from hog fuel during each stack test or average hog firing rates for each boiler. As most of these tests were done during permit compliance testing and the boilers are required to operate at 85 % or better of their typical loading during compliance testing, the average hog firing rates should reasonably approximate the firing rates during the stack tests.

Mill O (see page C-10) has been excluded from the summary table and data set because we could not find a reasonable way to appropriate the dioxin emissions measured for the power boiler stack. The mill has four power boilers discharging through one common

stack. One (30,000 lbs/hr maximum steam production capacity) burns wood waste. Two (each producing up to 60,000 lbs/hr of steam) burn only coal. The fourth and largest (165,000 lbs/hr maximum steam production) burns coal and sludge from both the de-inking process and the waste water treatment plant. The mill conducted one stack test when there was no de-inking sludge fired (5.6 pg TEQ/dscm) and two tests when firing deinking sludge (average emission- 22.3 pg TEQ/dscm). The mill burnt 3.9 to 10 BDMT per day of bark, 31.1 to 33.3 BDMT per day of wastewater treatment plant sludges, 1.8 to 28.5 BDMT per day of de-inking plant sludge and 44.4 to 120.4 ADMT per day of coal during the three stack tests. The better than 3 fold increase in dioxin emissions when firing deinking sludge is consistent with the data for the other mills (compare test results for mills C and E on pages B-7 and C-9 or in Table 3.3 below). Since the amount of hog fired in the four boilers at Mill O was relatively small, however, and we could not reasonably allocate the proportion of dioxins produced from hog, sludges and coal, we decided to drop the mill from the averaging exercise.

Stack dioxin emissions increased significantly in power boilers burning de-inking sludge (compare test results for mills C and E in Table 3.3 and for Mill O on page C-10). This is consistent with reports that while mechanical dewatering can reduce the moisture content of de-inking sludge to 40 – 60 %, the high inert content of these materials make them difficult to burn on conventional stoker grates [Douglas, 1997]. De-inking sludges have also been found to contain a number of metals and chlorine compounds [Douglas, 1997] that can catalyse dioxin and furan formation during combustion. When co-firing de-inking sludge, average stack dioxin emissions at the 4 mills ranged from 15.9 to 182 pg TEQ/dscm at 8 % O_2 in the 20 stack tests. Average and median stack emissions for the 5 boilers were 87.9 and 76.9 pg TEQ/dscm at 8 % O_2. When co-firing de-inking sludges, average emission factors for the four boilers ranged from 118 to 1576 ng TEQ/BD tonne of hog fuel. Average and median emissions for the four boilers tested were 791 and 735 ng TEQ/BD tonne of hog fuel, respectively. Use of the median emission factor of 735 ng TEQ/BD tonne of hog fuel has been recommended [Uloth, 2002] to estimate dioxin and furan emissions from this source.

4. Review of Power Boiler Ash Analyses and Development of Emission Factors:

As dioxin and furan emissions from power boilers burning clean wood waste can vary dramatically due to co-firing of wood product residues, plywood or even agricultural wastes (see Table 2.1), only emission data for wood waste power boilers at pulp and paper facilities should be used to estimate a suitable emission factor for these boilers. Appendix D contains dioxin and furan analyses, compiled by NCASI, for 63 ash samples taken from 27 different wood waste incinerators. Unfortunately, several of these incinerators were at wood processing plants, such as plywood mills, and may have burned wood residues in addition to clean wood (see section 3.1 above).

The first column under each sample (<ppt) shows the detection limit for each congener while the second column shows the concentrations of only those congeners which

Table 3.3: Stack Dioxin and Furan Emissions Tests on Power Boilers With and Without Burning of De-inking Process Sludges

Mill	Type of Furnace	Fuel Mix	Particulate Control System	Number of Tests	Range of Stack Particulate Emissions (Average) mg/Rm^3 @ 11% O_2	Range of Stack Dioxins Emissions (Average) pg TEQ/Rm^3 @ 8% O_2	Emission Factor ng TEQ/BDt of hog (ng TEQ/t wet hog) low/high/avg	Emission Factor Ng TEQ/BDt hog & sludge (ng/wet tonne) low/high/avg.	Fuel Firing Rates BDtph (moisture content)
C – does not normally burn deinking sludge	Riley Stoker travelling grate	Hog & gas (1996) Hog, primary, secondary and deink sludge & gas	ESP	5 (on 2 boilers) 3 (on 1 boilers)	3.1 – 47.9 (averages for each boiler) 1.4 - 21.0	4.9 – 6.5 (5.7) (averages for each boiler) 10.8 – 19.1 (15.9)	40.0 / 53.1 / 46.6 (19.2 / 30.2 / 24.4) 79.9 / 141.4 / 117.7 (38.3 / 80.6 / 67.1)	40.0 / 53.1 / 46.6 (19.2 / 30.2 / 24.4) 73.8 / 132.2/ 110.0 (34.9 / 72.9 / 61.1)	10.4 – 10.8 hog (43 - 52 %) 10.2 – 10.5 hog (43 – 52%) 0.75 deink (35%)
E – no longer burns deinking sludge	Stoker (PB #1) Stoker (PB #2)	Hog & deink sludge (1997) Hog & effluent sludge (1999)	Venturi scrubber 2-stage multiclone plus an ESP	3 3	44.8 – 89.3 (74.0) 3.2 – 7.1 (4.7)	47.2 – 280.2 (182.1) 2.2 – 9.2 (6.5)	408.5 / 2 425.0 / 1 576.0 (183.8 / 1 091.3 / 709.2) 35.7 / 149.3 / 105.5 (16.1 / 74.7 / 50.2)	389.6 / 2 312.8 / 1 503.1 (177.2 / 1 053.3 / 684.6) 30.7 / 128.3 / 90.7 (13.1 / 60.5 / 40.7)	18.6 hog (55%), 0.9 deink (41%) 31.25 Bark (50%) 3.8 Primary sludge (65%) 1.3 Secondary sludge (65%)
F	Stoker boiler with vibrating grate	Bark/hog , Primary, secondary and deinking sludges	ESP	5	27 – 41 (32)	23.4 – 266.4 (108.2)	204.2 / 2 325 / 944.4 (102.1 / 1 162.6 / 472.2)	139.8 / 1 589.2 / 646.5 (63.4 / 724.2 / 293.2)	13.5 Bark (50%) 3.75 Deink (58.1%) 2.5 P&S Sludge (66.1%)
G	3 KMW combustors into three Renteck boilers (1999) 3 Fuel Cells (1997) – now burn only gas	Hog ,primary, secondary and deink sludges Hog, primary, secondary and deinking sludges & gas	Cyclones on each boiler to common ESP Multiclones	3 6	(7.6) 717 – 942	2.3 – 111.4 (40.4) 7.2 – 142.8 (50.8)	26.5 / 1 281.1 / 464.7 (13.0 / 630.4 / 228.7) 82.9 / 1 643.6 / 584.7 (39.7 / 639.6 / 227.5)	21.0 / 1 015.1 / 368.2 (9.8 / 474.3 / 172.0) 65.8 / 1 345.0 / 471.4 (28.1 / 495.0 / 90.5)	12.4 Hog (50.8%) 3.25 Sludge (60.2%) 29 % deinking sludge 5.2 – 8.3 Hog (51.9 – 61.1%) 1.4 – 1.9 Sludge (70.4%) – 33 % deink

- Average emission factor for mills burning deinking sludges (20 tests on 5 boiler stacks) = 790.7 ng TEQ/BD tonne of hog fuel burned.
  Median emission factor for mills burning deinking sludges (20 tests on 5 boiler stacks) = 734.5 ng TEQ/BD tonne of hog fuel burned.

exceeded the detection limit in each ash sample. The toxic equivalents for all of the detected congers in each ash sample, as calculated using both the International Toxic Equivalency Factors (I-TEF) and the World Health Organization (WHO) Toxicity Equivalency Factors (TEF) are shown on the bottom two lines for each ash sample.

Two primary types of ash samples were collected at the different facilities:

Flyash – comprised of lightweight wood ash, salt, fine sand and partially burned residues, which are carried up with the combustion air, emitted from the furnace cavity and captured on heat transfer surfaces or by particulate emission control equipment. Flyash was broken down according to the type of particulate control device used to remove it from the flue gas – an electrostatic precipitator (ESP), a wet scrubber, or a multiclone (cyclone). In some cases, the collection system did not permit sampling of the particulate removed by each device and only a combined flyash sample was available for analysis.

Bottom or grate ash – composed of coarse material, such as gravel and rocks from the incoming wood waste or hog fuel, and the ash residue from combustion, collected from the bottom of the boiler.

The NCASI data set contains grate ash analyses for 7 different wood waste burners, multiclone ash analyses for 22 different wood waste incinerators, and ESP, scrubber or combined flyash analyses for 16 different wood waste incinerators. As illustrated in Table 4.1, both the mean and median dioxin concentrations in the ash increased as the gas flowed through the boiler. Median concentrations increased from 0.02 pg TEQ/g for grate ash to 0.10 pg TEQ/g for multiclone ash to 1.47 pg/g for ESP, scrubber or combined flyash. A similar pattern was reported for power boilers burning salt-laden hog fuel [Luthe et al., 1996]. Unfortunately, several of the incinerators in the NCASI data set were at wood processing plants, such as plywood mills, and may have burned wood residues in addition to clean wood, which would result in higher dioxin and furan formation than that resulting from burning clean wood waste alone (see Table 2.1 and section 3.1 above).

Appendix E contains dioxin and furan analyses for 23 ash samples from 9 wood waste incinerators at Canadian forest product plants and pulp and paper mills, as compiled by Paprican, FPAC, AIFQ and AFPA. Only clean, raw wood waste, and no processed wood waste, was burnt in these facilities. The Canadian data set contains no data for grate ash and data for multicyclone ash from only one power boiler. While the median and mean concentrations of dioxins on flyash are much lower than the corresponding medians and means for the NCASI data set, the average for the multicyclone ash is much higher in the Canadian data set because multiclone ash from only one boiler was analysed.

Both sets of data are summarized in Appendix F and Table 4.1 below. Because of the lack of multiclone and grate ash samples in the Canadian data set, it is necessary to use the combined data set to obtain reasonable estimates of the emission factors for each type of ash. Again, these estimates are likely to be very conservative and safe as several of the incinerators in the NCASI data set were at wood processing plants, such as plywood mills, and may have burned wood residues in addition to clean wood. The median concentrations for the combined data set are, therefore, recommended for use in estimating dioxin and furan concentrations in landfilled boiler ashes.

Table 4.1: Summary of Power Boiler and Wood Waste Boiler Ash Dioxin and Furan Analysis

Data Source	Type of Ash	Number of Samples	Number of Facilities Tested	Minimum pg TEQ/g	Maximum pg TEQ/g	Mean pg TEQ/g	Median pg TEQ/g
NCASI	ESP/WS or combined MC/ESP - Scrubber Ash	24	16	0.0	29.4	7.72	1.47
	Multiclone Ash	29	22	0.0	11.2	1.04	0.10
	Grate (Bottom) Ash	10	7	0.0	0.17	0.05	0.02
Paprican, FPAC, AIFQ and AFPA	ESP/WS or combined MC/ESP - Scrubber Ash	19	8	0.0	3.65	0.62	0.20
	Multiclone Ash	4	1	0.0	3.93	1.84	1.72
Both data sets	ESP/WS or combined MC/ESP - Scrubber Ash	43	24	0.0	29.4	5.35	0.46
	Multiclone Ash	33	23	0.0	11.2	1.07	0.10
	Grate (Bottom) Ash	10	7	0.0	0.17	0.05	0.02

Review of Typical Wood Waste Incinerator Permits and Operating Conditions:

5.1 Alberta:

The regulatory program for wood waste burners in Alberta is a little less specific than that in BC. Shutdown requirements may be specified in individual permits but there is provision to meet with the regulator if the schedule becomes unrealistic or unachievable for economic reasons. Consultation is taking place at different levels including through the provincial forest products association. The association has undertaken to maintain an inventory of wood residues and periodically update the province on the industry's progress in reducing the number of urban burners.

A recent communication from the association to the province indicated that two burners were shutdown in 2001 and that a third one is now operated only about 5% of the time. Two larger burners will be phased out of operation on completion of the district heating and power generation project in Grande Prairie. There is no formal program at this time to reduce the number of rural burners (ie. those that are more than 8 km from a subdivision), unless they are a source of complaints.

The 19 permits for wood waste incinerators in Alberta all have minimum operating temperatures specified. 15 burners are required to exceed 375 C greater than 90 % of the operating time, 2 to excedd 400 C, and1 each to exceed 425 C and 540 C. A survey of actual operating temperatures indicated that all operations exceed temperatures by a comfortable margin with one silo burner reporting an average exit temperature of 1320 C.

Operating practice is to balance exit temperatures against maintenance requirements. Each burner will have an operating range of exit temperature that comfortably exceeds the permit requirement with the upper limit being set to minimize mechanical damage from overheating. As a general statement, the refractory silo burners can handle a higher exit temperature than teepee or conical burners before temperature-induced damage occurs.

5.2 British Columbia:

Some sample operating approvals were made available by the British Columbia Ministry of Water, Air and Land Protection (BCMWALP). These were for a conical burner and a silo burner. BC has a formal phase out program for Tier I burners (urban) but no timeline developed for shutting down the Tier II burners (rural). Permit temperature requirements are more tailored to individual burners in BC than in Alberta. These requirements are determined by running tests to determine or correlate generation of excessive smoke to exit temperature. A margin of safety is added and a compliance temperature determined. Permitted compliance temperatures ranged from 287 degrees C to 432 degrees C.

Based on data supplied by industry for about 10 installations, the actual operating temperatures tended to be 75 to 180 degrees C above the compliance temperatures. The lowest operating temperature reported in this sample was 370 degrees C with the range for the units going up to about 500 degrees C. Operating exit temperatures in the 10 units averaged ~ 482 ^{o}C, just below the upper temperature limit for de novo formation of dioxins and furans. Each unit reported its compliance temperature and measured operating range.

5.3 Other Jurisdictions:

Information supplied from the province of Quebec indicates that they have not required the best practices approach and, consequently, apply the second level EPA emission factor to estimate particulate emissions from this source. The value stated was a particulate emission of 7 lbs. TPM per oven dry tonne of wood burned. Quebec also indicated that their intent is to curtail the operation of any device unable to demonstrate compliance with their new clean air act. This act is expected to be proclaimed in 2002 and six months would be allowed for demonstration of compliance.

In regions where dispersion models have been run with assumed values (permit or maximum) entered for the burner(s), the contribution of particulate attributed to the burners ranges from 3 to 5% of the ambient concentrations. In at least one community (Prince George), where a number of burners have been removed from service over a period of years, there has been no statistically significant change in ambient particulate concentrations which can be related to the schedule of burner shutdowns.

5.4 Comparison With Other Wood Combustion Processes:

FUEL – As a general statement, the residue burners will see the premium or best fuel. Particularly in plants where the product is dried, trimmed, and planed, the fuel tends to be much cleaner and dryer than fuel used in, for example, pulp mill boilers in non-integrated mills. The sawmill residues tend to be of lower moisture content, especially if compared to a pulp mill where the sludge from primary effluent treatment or water treatment may be burned with the hogged fuel.

One of the attractions of using clean chemical free wood residues for fuel is the very low chloride content. Test values from several BC and Alberta harvesting operations range from 20-60 ppm. As this is likely below the precision of the test, it might be more appropriate to say that the fuel has <100 ppm Cl content. This contrasts with the >500 ppm values common in salt-laden coastal hog fuels. Therefore, the potential to form dioxins and furans is inherently low.

AIR SUPPLY – there is a significant difference in the amount of air supplied for combustion. Residue burners tend to run with approximately 500% excess air compared to that theoretically required for combustion. There are a couple of reasons for this. One is to limit the maximum temperatures to which the burner structure is exposed. The other is to promote smoke free pile burning with a fairly simple air delivery system. A boiler (or even a fuel cell), on the other hand, will be operated with the lowest excess air level consistent with good combustion to maximize thermal efficiency and minimize the flue gas volume that has to be handled and cleaned.

EXIT TEMPERATURE – The exit temperatures in industrial wood waste boilers and thermal fluid systems tend to be significantly lower than those from wood residue (teepee or silo) burners. A typical value would be 200 degrees C. The main limitation is the prevention of gas side corrosion in economizers and precipitators. Note too, that silo and conical burner exit temperatures (287 to 540 C) are typically higher than those seen in the dioxin emission tests on residential wood stoves (249 to 359 C) [Environment Canada, 2000].

OPERATING CYCLE – another difference between boilers and burners is the operating cycle. Boilers tend to be installed in continuous operations; ash removal occurs either automatically or manually, and a boiler may, thus, see only one or two startup cycles a year. Burners tend to follow the operating week of the facility, often a five day cycle, and are usually shut down for cleanout on the non-operating days. This is reflected in their permits in that time at operating temperature must exceed 90% of the operating time and many approvals have maximum opacities stated with time limits to manage these conditions.

6. Recommendation:

The factors of significance that have been implicated in the generation of dioxin and furan (see sections 2 and 3 of this report) are:

- Poor and incomplete combustion, with low temperature zones in the combustor.
- The presence of elevated levels of chloride.
- The co-firing of de-inking sludges which contain more chloride, moisture, ash and dioxins than other sludges. The dioxins contained in deinking sludges are likely due to airborne contamination of papers during periods of initial use and collection, with some plastic contamination possible as well.

The factors common in operation that are significant in avoiding the generation of dioxin and furan are:

- Controlled combustion with good turbulence and some residence time at temperatures above 500 C.
- The presence of sulfur above certain concentrations when fuels containing high concentrations of chloride are being combusted.
- Very low chloride levels; the fuel should not contain either chloride salts or chlorine in the form of plastics, nor should it be contaminated with other waste streams.
- Short time duration in the temperature range where de novo synthesis is most probable (generally 200 to 500 C).

As clean wood fuel contains very little sulfur (only that present from growth of the tree), the combination of the other factors are the most relevant in assessing the likelihood of dioxin formation in wood waste burners. In developing the recommendation that follows, it is important to consider the assumptions made:

1. Only clean uncontaminated low chloride wood waste is burned.

2. The burner operates consistently above a specified outlet temperature of 370^{o}C (normally specified >90% of operating hours). A review of operating data for a number of burners with these permit requirements indicates that normal operating practice is to exceed the minimum operating requirement by 80 to 100 C.

3. The burner operates consistently with opacities below 20% as an indication that good mixing and complete combustion are occurring.

4. The expectation that de novo synthesis may occur is diminished by elevated outlet temperatures. The higher the outlet temperature, the lower the probability, with a likely near zero probability at temperatures above 500 C.

This weight of evidence approach is predicated on the burners being less likely to emit dioxin and furan than boilers and energy systems which are burning similar or worse fuels, worse in this case being higher moisture content and inorganics. Based on the information itemized above, there is a high probability that burners operating with exit temperatures >500 C would be non-detect (at least less than the LOQ) for dioxin and furan if they could be tested. Similarly, burners operating consistently with an exit temperature above 370 C, and with opacities <20 %, would also be expected to have dioxin and furan levels below those measured for the low chloride power boilers tested and the LOQ. Power boilers with outlet temperatures in the 200 C range would have a higher probability of de novo synthesis occurring than the wood waste burners. The gases exiting from a burner will cool extremely quickly through the de novo range of 200 – 500 C. The low test results from power boilers suggests that emissions from wood waste burners are, therefore, likely to be below the LOQ and to be very low. Based on the median emissions measured for power boilers burning clean wood waste (with no de-inking sludge), and the higher excess air use in a wood waste burner, emissions are likely to be in the range of 1.5 to 3.0 pg TEQ/dscm, 10 to 20 times lower than the LOQ.

The only reason to consider a higher emission factor than that for a boiler burning the same fuel, is the weekly startup and cooldown period. In considering the above data, one would expect the boiler to be more prone to producing dioxins and furans by de novo synthesis than the burner as there is no heat recovery in a beehive burner and the de novo mechanism for dioxins formation should, therefore, not occur. As summarized above, most of the permits for wood waste incinerators require an exit temperature in excess of 375 degrees C. The temperature drops quickly when gases exit the burner and the time that the gas is in the temperature zone for de novo synthesis (200 - 500 degrees C) is much less than that provided in a typical power boiler or even in the chimney of a residential wood stove. In addition, the gases are more dilute (due to higher excess air and rapid dispersion once the gases exit the burner) so the chances of an HCl or chlorine molecule colliding with a PAH precursor are reduced. De novo synthesis is, therefore, unlikely to occur. Emissions from a wood residue burner are, thus, likely to be less than those from an interior power boiler.

There is a fairly large data bank from testing conducted on boilers, summarized in section 3 above, which indicates that dioxin emissions from power boilers burning clean wood waste are typically very low, with median emissions averaging only 38.5 ng TEQ/bone dry tonne of wood burned. Using the emission factor for a power boiler to estimate emissions from a wood waste incinerator will substantially over-estimate the potential dioxins emissions from this source because the generally high incinerator exit temperatures preclude dioxin formation by de novo synthesis (at temperatures of 200 to 500 C), which is the dominant mechanism for dioxin and furan formation during wood waste and hog fuel incineration.

To further illustrate that a dioxin emission factor for wood waste incinerators that is lower than that used for power boilers would still be very conservative, data on the concentrations of dioxins and furans in the fly ash captured in wood waste boilers at both pulp and paper and wood products facility boilers burning clean "interior" (chloride free) wood waste is compiled in Table 4.1. These ashes would have passed through the de novo temperature zone and would thus be expected to have much higher dioxin concentrations than ash exiting a wood waste incinerator. Analyses of the 43 fly ash samples from 24 different boilers, nevertheless, show mean and median dioxin and furan concentrations of only 5.35 and 0.46 pg TEQ/g respectively. This is a thousand times lower than the concentrations seen on ash from

coastal power boilers burning salt laden hog fuel [Luthe et al., 1996 and 1998]. The maximum dioxin concentration on fly ash in the Canadian data set was 3.65 pg TEQ/g, less than the mean for the combined data set, suggesting that some of the boilers in the NCASI data set may have burnt other wood wastes that increased dioxin formation substantially (see Table 2.1 and section 3.1 and 4 of this report).

EPA has recommended a particulate matter (PM) emission factor for a "satisfactorily operating, wood waste conical burner without controls" of 0.5 kg/AD t of wood burned (see Table 2.2). The pre-requisites for using this emission factor are that the incinerator is in good mechanical condition, with both underfire and overfire air systems, and operating with specified and monitored exit temperatures. These are the same conditions prescribed for use of the dioxin emission factor which we will propose for wood waste incinerators.

Assuming 5.35 pg of dioxin TEQ/g of fly ash (the mean concentration on flyash in the combined data set in Table 4.1, which is over 10 times the median concentration which is recommended as the emission factor, and almost 1.5 times the maximum concentration for flyash in the Canadian data set), this would correspond to a dioxin emission factor of:

0.5 kg fly ash/ADt on wood burned X 1000 g/kg X 5.35 pg TEQ/g of fly ash =
2675 pg TEQ/AD t of wood burned or 2.7 ng TEQ/AD t of wood waste burned.

This is only 7 % of the proposed emission factor of 40 ng TEQ/BD t (36 ng TEQ/AD t) of wood waste burned for power boilers burning clean wood waste. An emission factor of 5 ng TEQ/BD t of wood waste would, therefore, very conservatively and safely estimate the potential emissions from this source. The non-operating hours are not an issue due to the low amount of fuel consumed during these times.

The following volumes of wood residues are projected as the maximum that would be disposed of in wood waste incinerators. An annual emission estimate can be calculated from this data together with the above (“best estimate”) emission factor.

Province	***Residue Volume Green***	***Estimated # Burners***
British Columbia	3.500,000 tonnes	76
Alberta	800,000 tonnes	15
Ontario	100,000 tonnes	4(unconfirmed)
Quebec	500,000 tonnes	10-12(23 in 1998)

Dioxins and furans concentrations on the ash extracted from wood waste incinerators are expected to be similar to those for grate ash extracted from power boilers as the ash is extracted principally from the bottom of the incinerator and has not been exposed to temperatures in the range of 200 – 500 ^{o}C where de novo synthesis can occur. As little of the ash captured on the screening at the top of a teepee or silo burner is likely to fall back to the bottom of the burner without burning, it can be assumed that essentially all of the ash from the burner corresponds to grate ash in a power boiler. Dioxin emissions with the ash can be estimated assuming an emission factor of 0.02 pg TEQ/g for the ash from wood waste incineration.

7. Acknowledgements:

The authors would like to thank all of the mills that generously provided both emission test data, ash analyses and operating data for their power boiler tests. Thanks also to Tim Whitford of ET Consulting, Louis Desilets of AIFQ, and Lucie Veilleux of FPAC who helped track down all of the Canadian mills that had dioxin emission test data or ash analyses. Thanks to Arun Someshwar and John Pinkerton at NCASI who agreed to share the emission data compiled by NCASI for emission tests on power boilers at pulp mills in the United States. Thanks finally to Environment Canada who provided funding which allowed us to compile and review all of the emission data and literature and to recommend scientifically-defensible emission factors for wood waste incinerators burning clean wood waste.

8. Literature References:

Boubel, R. W., Northcraft, M., Van Vliet, A., and Popovich, M., “Wood Waste Disposal and Utilization”, Oregon State University, 1958.

Boubel, R. W., “Particulate Emissions From Sawmill Waste Burners”, Oregon State University, Aug. 1968.

Bovar-Concord Environmental, “Evaluation of Stack Emissions and Waste Streams from the Combined Burning of Pulp Mill Waste Residues and Hog Fuel in a Power Boiler”, prepared for Fletcher Challenge Canada Ltd. and Environment Canada (May 1994).

CARB (California Air Resources Board), Evaluation of a woodwaste fired incinerator at Koopers Company, Oroville, California. Test Report No. C-88-065. Engineering Evaluation Branch, Monitoring and Laboratory Division. (May 29, 1990a).

CARB (California Air Resources Board), Evaluation of a wood waste fired incinerator at Pacific Oroville Power Inc. Test Report No. C-88-050. Engineering Evaluation Branch, Monitoring and Laboratory Division. (May 29, 1990b).

CARB (California Air Resources Board), Evaluation test on twin fluidized bed wood waste fuelled combustors located in Central California. Test Report No. C-87-042. Engineering Evaluation Branch, Monitoring and Laboratory Division. (February 7, 1990c).

CARB (California Air Resources Board), Evaluation of a wood waste fired incinerator at Louisiana Pacific Hardboard Plant, Oroville, CA. Test Report No. C-88-066. Engineering Evaluation Branch, Monitoring and Laboratory Division. (May 29, 1990d) - as reported in NCASI, 1995.

Douglas, M., Friedrich, F., Mortzavi, R., and Razbin, V., “Field Trials and Emission Testing of Paper De-Inking Solids (PDS)”. Proceedings of the 83rd Annual Meeting of the Technical Section of the Canadian Pulp and Paper Asssociation. pp. B393 – 400. (January 1997).

Everaert, K. and Baeyens, J., “Correlation of PCDD/F Emissions with Operating Parameters of Municipal Solids Waste Incinerators”, Journal of the Air and Waste Management Association, 55: 718 – 724 (May 2001).

Environment Canada, “Characterization of Organic Compounds from Selected Residential Wood Stoves and Fuels”, Environment Canada Emissions Research and Measurement Division, Report No. ERMD 2000-01 (December 2000).

EPA/600/P-98/002Aa, “The Inventory of Sources of Dioxin in the United States”, External Review Draft, April 1998.

Fangmark, I., Stromberg, B., Berge, N., and Rappe, C., “Influence of Postcombustion Temperature Profiles on the Formation of PCDDs, PCDFs, PCBzs, and PCBs in a Pilot Incinerator”, Environmental Science and Technology, 28(4): 624 – 629 (1994).

Halonen, I., Tarhanen, J., Kopsa, T. Palonen, J., Vilokki, H., and Ruuskanen, J., “Formation of Polychlorinated Dioxins and Dibenzofurans in Incineration of Refuse Derived Fuel and Biosludge”, Chemosphere, 26(10) : 1869 – 1880 (1993a).

Halonen, I., Tarhanen, J., Oksanen, J., Vilokki, H., Vartiainen, T. and Ruuskanen, J., “Formation of Organic Chlorinated Compounds in Incineration of Pulp and Paper Mill Biosludges”, Chemosphere, 27(7) : 1253 – 1268 (1993b).

Kolenda, J., Gass, H., Jager, J., and Zeschmar-Lahr, B., “Determination of PCDD/F Emissions From Wood Burning Facilities”, Chemosphere 29(9-11): 1927 – 1938 (1994).

LC Engineering. “Detailed Report for Test Burns of Chlorophenol Contaminated Wood Wastes at Northwood Pulp Mill, Prince George, B.C.”, prepared for Environment Canada and the Ministry of Environment, Province of British Columbia (April 1989).

Lindbauer, R., Wurst, F., Prey, T., “Combustion dioxin suppression in municipal solid waste incineration with sulphur additives”, Chemosphere, 25 (7 – 10): 1409 - 1414 (1992).

Luthe, C.E., Karidio, I., and Uloth, V.C., "Controlling Dioxin Emissions in Coastal Power Boilers: A Status Report", Pulp and Paper Canada, 97(9) : T320-T326 (1996).

Luthe, C.E., Karidio, I., and Uloth, V.C., "Dioxins Formation in Salt-laden Power Boilers: a Mass Balance", Chemosphere, 36(2): 231-250 (1998).

Luthe, C.E., Strang, A., Uloth, V.C., Karidio, I., Prescott, B. and Wearing, J., "Sulphur Addition to Control Dioxins Formation in Salt-Laden Power Boilers", Pulp and Paper Canada, 99(11): T391-T395 (1998b).

Maatila, H. Virtanen, T., Vartiainen, T., and Ruuskanen, J., “Emissions of Polychlorinated Dibenzo-P-Dioxins and Dibenzifurans in Flue Gas from Co-Combustion of Mixed Plastics with Coal and Bark”, Chemosphere, 25(11): 1599 – 1609 (1992).

Nakao, T., Aozasa, O., Ohta, S., and Miyata, H., “Formation of dioxin analogs by open-air incineration of waste wood and by fire of buildings and houses concerning Hanshin Great earthquake in Japan”, Chemosphere, 46:429 – 437 (2002).

NCASI (National Council of the Paper Industry for Air and Stream Improvement), “NCASI summary of PCDD/F emission from wood residue and black liquor combustion. Attachment 2 to comments submitted on January 13, 1995, to EPA’s Office of Health and Environmental Assessment concerning the draft document entitled “Estimating Exposure to Dioxin-Like Compounds”.

Oehme, M. and Mueller, M., “Levels and Congener Patterns of Polychlorinated Dibenzo-P-Dioxins and Dibenzofurans in Solid Residues from Wood-fired Boilers. Influence of Combustion Conditions and Fuel Type”, Chemosphere, 30 (8) : 1527 – 1539 (1995).

Pandompatam, B., Kumar, Y., Guo, I., and Liem, A. J., “Comparison of PCDD and PCDF Emissions from Hog Fuel Boilers and Hospital waste Incinerators”, Chemosphere, 34(5 – 7): 1065 – 1073 (1997).

Pinkerton, J. “Differences in the Reporting of Persistent Bioaccumulative Toxics Under the TRI and NPRI Programs”, NCASI National Meeting, Charlotte, NC (2001).

Santoleri, J., “Chlorine vs. Dioxins – Control Methods to Minimize Emissions”, Proceedings of the 17th Biennial Waste Processing Conference, ASME (1996).

Schatowitz, B., Brandt, G., Gafner, F., Schlumpf, E., Buhler, R., Hasler, P., and Nussbaumer, T., “Dioxin Emissions from Wood Combustion”, Chemosphere, 29 (9-11): 2005 – 2013 (1994).

Stanmore, B. R. and Clunies-Ross, C., “An Empirical Model for the De Novo Formation of PCDD/F in Medical Waste Incinerators”, Environmental Science and Technology, 34(21): 4538 – 4544 (2000).

Takeshita, R., Akimoto, Y., and Nito, S., “Relationship Between the Formation of Polychlorinated-P-Dioxins and Dibenzofurans and the Control of Combustion, Hydrogen Chloride Level in Flue Gas and Gas Temperature in a Municipal Waste Incinerator”, Chemosphere, 24(5) ; 589 – 598 (1992).

Uloth, V., “Dioxin and Furan Emission Factors for Combustion Operations in Pulp Mills”, prepared for Environment Canada, (March 2002).

Umweltbundesamt, “Determination of requirements to limit emissions of dioxins and furans”. Report from the Working Group of the Subcommittee on Air/Technology of the Federal Government/Federal States Immision Control Committee. Berlin, Germany (1996).

Valttila, O., “Combustion of Biosludge” in the Leikki Combustion research Program Technoical Review, 1988 – 1992. Abo Akademi. (1993).

Vesterinen, R. and Flyktman, M., “organic Emissions from Co-Combustion of RDF with Wood Chips and Milled Peat in a Bubbling Fluid Bed Boiler”, Chemosphere, 32(4): 681 – 689 (1996).

Wunsch, p., Leichsenring, S., Schramm, K-W., and Kettrup, A., “Temperature Dependence of PCDD/F Fformation in Boiler Ash”, Chemospher, 29(6) ; 1235 – 1243 (1994).

Zimmerman, R., Blumenstock, M., Heger, H., Schramm, K., and Kettrup, A., “Emission of Nonchlorinated and Chlorinated Aromatics in the Flue Gas of Incineration Plants During and After Disturbances of Combustion Conditions: Delayed Emission Effects”, Environmental Science and Technology, 35: 1019 – 1030 (2001).

To obtain Appendices A - F, contact your nearest NPRI Regional Office.