



## **Hog Fuel Boiler RACT Determination**

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# Hog Fuel Boiler RACT Determination

## Summary

The purpose of this project was to determine the reasonably available control technology (RACT) for wood and combination-wood (also known as hog fuel) fired boilers that are typically used in the pulp and paper industry in order to meet their steam and heat needs. This report sets forth procedures for RACT development, and provides technical information that will assist state and local air pollution control agencies in developing guidelines for RACT for certain criteria pollutants from existing stationary sources on a case-by-case basis.

Furthermore, this RACT review evaluates costs for effective removal of “pollutants of concern” (POCs) and air quality benefits for different size boilers: (1) small, (2) medium, and (3) large. For small size boilers (<3,500 lb/hr steam), multi-cyclone (MC) alone is capable of removing particulate matter (PM) at a reasonable cost (\$180 per ton), while meeting air quality standards for other criteria pollutants. On the other hand, PM control cost for small size boiler would be far greater using either electrostatic precipitator (ESP) (\$594/ton) or fabric filter (FF) (\$958/ton). This analysis, therefore, indicates that MC is RACT for PM for small size boiler. Similarly, the cost analysis indicates that both ESP and FF are RACT for PM for medium size boilers (15,000-45,000 lb/hr steam), while venturi scrubber (VS) represents RACT for acid gases. For large size boilers (200,000-700,000 lb/hr steam), all three control options (FF, ESP, and VS), based on their cost effectiveness, represent RACT for POCs.

This report is divided into three chapters and five Appendices. The first chapter describes the steps of selecting POC from the wood-fired boiler. The first step in the POC selection process involved a wide search of sources of emission data including but not limited to:

- (1) Washington State Emission Inventory;
- (2) Title V Air Operating Permit;
- (3) National Council of the Industry for Air and Stream Improvement (NCASI) Technical Bulletins;
- (4) Air Chief Version 6.0 CD ROM;
- (5) Toxic Release Inventory (TRI);
- (6) Literature Search Database developed by Ecology’s Air Quality Program Staff.

By consolidating all the candidate pollutants of concern, pollutants were selected that are most-representative as far the criteria and toxic pollutants emission from wood-fired boilers were concerned.

The second chapter summarizes a qualitative analysis of all reasonably available control technologies for each of the categories of POC. This chapter is divided into the following sections: particulate-related controls, carbon monoxide related controls, acid gases and sulfur compounds controls, and nitrogen oxide controls. For each POC category, control technologies are described and evaluated using the Source Category RACT Guidelines.

The third chapter describes the energy, environmental, and economic impacts of each control option and the selection of the final level of control for hogged fuel boilers as RACT. The final RACT for each category POC was determined based on cost per ton of pollutant removal and air quality impacts relative to ambient standards. Appendix A shows the detailed calculations on how total annualized costs were estimated for air pollutant control devices, including mechanical collectors, venturi scrubbers, electrostatic precipitators, fabric filters, and gas absorbers for acid gas control. Appendix B shows calculations of pollutant removal in tons per year, and dollars per ton of pollutant removal. Appendix C presents a summary of all ash production, handling, and landfill disposal costs at facilities with wood fired boilers in Washington. And Appendix D presents values of maximum ambient concentration of pollutant of concern and its corresponding distances where these maximum concentrations may occur. These values were obtained by using the SCREEN 3 model for three different size boilers: small, medium, and large.

The Appendix E provides detailed background information on dioxin and furan formation in wood and combination wood-fired boilers. This report provides information on different control strategies for dioxin/furan, and its distribution factors (emission factors) between flue gas and ash particles.

The Appendix F presents a detailed health risk analysis that identified two specific chemicals, acrolein and formaldehyde, whose hazard quotient exceeded, as well as exceeded the acceptable source impact level (ASIL). And due to exceedences of hazard quotient and ASIL for two chemicals, health risk analysis was carried out in greater details in order to characterize the risk they might pose. This analysis used EPA's risk-based models to determine acrolein and formaldehyde risk distributions for a typical person in the State of Washington, and based on this information, health risk analyses followed with recommendations and implementations of RACT for wood-fired boiler were made.

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# Pollutants of Concern from Wood-fired Boiler and Its Control Options

## 1. Background

Wood has always been an important boiler fuel in the forest products industry. Each year considerable quantities of timber are harvested and millions of tons of wood products manufactured. The paper and allied products industry comprises the majority of the industrial sector that burns wood fuel. Roughly equal amounts of wood residue are burned in wood products manufacturing facilities as in pulp and papermaking facilities. Wood residue burned as fuel in wood product facilities is mostly wood fines (planar shavings and sander dust) and wood chip rejects from screening operations. Wood residue burned as fuel in pulp and papermaking facilities is mostly bark, although the residue may also include sawdust, shavings, and rejects from lumber manufacturing processes. In general, the wood residue fuel is called hogged fuel. Most pulp and paper mills burn the hogged fuel in so-called bark boilers. These boilers may also burn coal, natural gas, fuel oil, or waste treatment plant sludge in combination with the wood residue.

### 1.1 Fuel Characteristics

Wood waste boilers throughout the state burn a variety of fuels in order to meet their heat needs. These boilers can be divided into two groups – those using only wood waste and those using wood waste plus other fuels. Choice of fuels is dependent on a number of factors which include: fuel economics, administrative permits, regulation requirements, boiler design, and fuel supply characteristics.

Approximately 3.3 million tons of wood wastes are combusted in Washington each year.<sup>1</sup> **Table 1** provides the percentage of boilers that burn wood and the percentage of wood that is burned by industry category. The lumber and wood products industries operate almost three-fourths of wood waste boiler units, but these industries do not use a majority of the wood combusted in Washington. Most of the larger boilers are in the paper and allied products industries.

**Table 1**

<b>Industry</b>	<b>% of Boilers</b>	<b>% Wood Combusted</b>
Lumber & Wood Products	72.6	39
Paper & Allied Products	22.6	45
Other	4.8	16

Based on the information available in the current literature, 24 percent of the boilers burn salt-laden wood. Of the boilers that combust salt-laden wood, 22 percent of their total wood fuel is salt-laden.<sup>2</sup> During the storing or transporting of logs in salt water, the salt content of the wood rises to 0.7 – 1.6 percent.<sup>2</sup> Salt particles that are adsorbed or entrained in the wood are very small particles (less than 1 micron). As a result, when salt-laden wood is burned, both the flue gas's fine particulate loading and plume opacity increases. Approximately one percent of the particulate matter generated by burning salt-

free wood is less than one micron in diameter.<sup>2</sup> Hazardous air pollutant emissions are also higher when burning salt-laden fuel. Polychlorinated dibenzo-p-dioxin/furan formation is about hundred-fold higher for salt-laden wood than for non-salty wood.

## 1.2 Boiler Design

The Dutch oven is widely used because it can burn fuels with very high moisture. The burning is done in two stages: drying and gasification and the combustion of gaseous products. The first stage takes place in a cell separated from the boiler section by a bridge wall. The combustion stage takes place in the main boiler section. In another type, the fuel cell oven, fuel is dropped onto suspended fixed grates and is fired in a pile. Unlike the Dutch oven, the fuel cell also uses combustion air preheating and repositioning of the secondary and tertiary air injection ports to improve boiler efficiency. In many large operations, more conventional boilers have been modified to burn wood waste, the most widely used is the spreader stoker. Fuel is dropped in front of an air jet, which casts the fuel out over a moving grate, spreading it in an oven, thin blanket. The burning is done in three stages in a single chamber: (1) drying, (2) distillation and burning of volatile matter, and (3) burning of carbon. Fluidized-bed combustors use a sand-bed medium to burn wood residues. These units are able to combust fuels (hogged to  $\leq 3$  inches) with moisture content up to 65% by weight.<sup>3</sup>

## 1.3 Air Pollutant Emissions

Actual emissions will depend on many variables, including:

- Composition of wood waste fuel and its variability,
- Type and amount of fossil fuel burned in combination with the wood waste (if any),
- Firing method and type of furnace,
- Extent of carbon reinjection, and
- Air pollution control systems.

Particulate matter emissions are the air pollutant most frequently associated with wood fired boilers. Almost all of the nitrogen oxide emissions in waste-wood burning come from fuel-bound nitrogen (i.e., from the composition of the wood fiber) because of the characteristically low combustion temperatures. They are generally much lower per unit of heat input than from fossil-fuel combustion sources, but can nonetheless be significant. Carbon monoxide emissions can be significant in terms of absolute quantity. However, since most wood-fired combustion systems are not located near intensive mobile source traffic areas, the emissions are generally not significant in terms of air quality health-based standards. Sulfur oxide emissions may become significant if large amounts of fossil fuels are co-burned with the wood.

The composition of wood waste depends largely on the industry from which it originates. Pulping operations, for example, produce great quantities of bark that may contain more than 70% by weight moisture, along with sand and other noncombustibles. Because of this, bark boilers in pulp mills may emit considerable amounts of particulate matter to the atmosphere unless they are well-controlled. On the other hand, some operations, such as furniture manufacturing, produce a clean dry wood waste, 5-10% by weight moisture, with relatively low particulate emissions when properly burned. Still other operations, such as sawmills, burn a varying mixture of bark and wood waste that results in particulate emissions somewhere between these two extremes.

The release of organic emissions from a combustion device can occur in two ways: (1) the release of unburned organic compounds from the waste and (2) the formation of new organic compounds during the combustion process.

If demolition debris is part of the wood waste fuel, additional air pollution control equipment may be required, depending on what and how much is burned. Demolition debris can contain plastics, paint, creosote-treated wood, glues, synthetics, wire, cable, insulation. Such materials can contribute to acid gas emissions (such as HCl), heavy metal emissions (including lead, copper, cadmium, chromium, and zinc), inorganic emissions (including arsenic, cyanides, and asbestos), and organic emissions (including formaldehyde, dioxins, and furans).

## **1.4 Factors Affecting Air Pollutant Emissions**

Combustion and the formation of emissions is a complicated process controlled by numerous variables. The three major areas that affect wood-fired boiler emissions are fuel quality, boiler design, and boiler operation.

### **1.4.1 Fuel Quality**

The importance of fuel size, size consistency, and fuel cleanliness cannot be overemphasized. Oversized pieces are difficult to distribute evenly in the furnace and tend to burn slowly. When suspension burning occurs, fine particles are easily entrained in the flue gases – leading to higher particle emissions. The size of the fuel should be consistent with equipment design, aiding distribution of fuel in the fire box and assuring equitable distribution of the underfire air. The cleanliness of the fuel must be considered in terms of whatever foreign matter is picked up during harvest and transport and then fed into the boiler. Ash content of wood itself is low; but material lodged in the bark during removal from the forest, or scooped up by the loader during handling, effectively increases the non-combustible fraction of the wood fuel. The effects of mixed fuels on emissions and emissions factors including in fly and bottom ashes are discussed in **Appendix E**.

## 1.4.2 Boiler Design

Wood-burning boilers can be designed with consideration for combustion efficiency and emissions limitation. Designers strive to minimize the gas velocity in the boiler by increasing the grate area. Lower gas velocities help reduce emissions by increasing the fuel residence time in the combustion zone and decreasing entrainment of fine particles by high speed air. Another factor that affects emissions is the method by which fuel is introduced into the boiler. Spreader strokes will have some suspension burning and generally higher emissions than methods that burn primarily on the grate. Particles burning in suspension are easily carried out of the boiler. It is a common experience with wood burning that a percentage of the fuel may be carried out of the boiler unburned, to be caught in the primary collector. Especially in large size boilers, the unburned carbon can be separated from the fly ash by a pre-collection hopper or a gravity separation device and re-injected into the boiler. Though this practice improves boiler efficiency, re-injecting char tends to increase the percentage of smaller particulate.

## 1.4.3 Boiler Operation

Boiler operating methods and firing techniques have a direct effect on stack emissions. Unlike most natural gas or light fuel oil fired boilers, wood-fueled installations require full-time operator attention to achieve maximum efficiency. For example, the rate of flow of combustion air can be automated to the flow of natural gas or oil fuel, but this is not practical with wood systems. If the boiler fireman consistently supplies less air than is needed, unburned fuel will result and smoke will be produced. Excess combustion air will reduce combustion efficiency and increase the total mass of combustion products. This increased mass results in higher velocities in the combustion zone, which causes the entrainment of particulate matter and reduces the fuel residence time. In addition to the quantity of combustion air, the method of its introduction can influence emissions. Wood combustion systems are often designed to introduce a percentage of the combustion air from beneath the grates and the remainder from above the grate line. The underfire air is necessary for combusting the fuel on the grates while the overfire air is used to combust the fuel volatile gases. While percentages of over-to-under air are a function of boiler design, a good fireman adjusts the air to meet the needs of particular fuels and operating conditions.

When a boiler is overloaded, a condition similar to that with high excess air develops. As the rated load is exceeded, air flow to the boiler is increased leading to higher velocities and more particle entrainment. Higher-than-normal emissions can be expected when a boiler is operated over its rating. Upsets in the boiler operation can cause temporary excess emissions. Upsets can occur when the load changes rapidly or when the moisture content of the fuel varies unexpectedly. Through upsets with wood-fired boilers are difficult to eliminate, proper corrective action by the operator can reduce their effect.

## 1.5 Controlling Air Pollutant Emissions

**Table 2** shows the most relevant pollutants that are expected to be emitted from the wood-fired boilers. They can be grouped by similar causes or controlling factors such that the feasible control mechanisms for one "surrogate" pollutant may be applied to all members of the group. These groupings are shown in Table 2. The surrogate groupings

are carbon monoxide (CO) or total hydrocarbon (as an indicator of good combustion practices or as a surrogate for products of incomplete combustion), particulate matter (P) as a surrogate for metals and dioxin/furans, oxides of nitrogen (NO<sub>x</sub>), and sulfur dioxide (S) for acid gases including SO<sub>3</sub> and HCl.

### 1.5.1 Carbon-Monoxide

Carbon-monoxide emissions are controlled by employing “good combustion practices” (time-temperature-turbulence). These practices include operational and incinerator design elements to control the amount and distribution of excess air in the flue gas to ensure that there is enough oxygen present for complete combustion. The design of modern efficient boilers is such that there is adequate turbulence in the flue gas to ensure good-mixing, a high-temperature zone (1600-1800 °F) to complete burnout, and a long enough residence time at the high temperature (one or two seconds). Even a well-designed and operated wood-fired boiler could have more than 100 ppm (hourly rolling average) CO in its stack gas.<sup>5</sup> The lower the CO concentration, the more effective and complete is the combustion process. The feed to the combustor is controlled to minimize fuel spikes that lead to fuel-rich firing.

Good combustion practices also limit PCDD/PCDF emissions exiting the boiler. This is accomplished by maintaining firing conditions that destroy PCDD/PCDFs found in the fuel and by destroying PCDD/PCDF precursors that may be formed from the combustion of other chlorinated organic compounds (for in-depth analyses, a separate report is attached for your additional information<sup>4</sup>).

### 1.5.2 Particulate Matter and Toxic Metals

The same mechanisms control particulate matter, as well as toxic metals. Unlike organics, metals are not destroyed during combustion. All of the metals fed into a combustion device are conserved, thus partition into one or more of the places:

- The bottom of the combustion device with the ash
- The bottom of the scrubber with the scrubber ash
- The bottom of the particulate control system with the fly ash
- The air when they are emitted from the stack.

Most metals, especially those that enter the system as solid waste, end up in the bottom ash. The fundamental principles that influence the behavior of metals in combustion devices are discussed here. Metals behavior in combustion is complex and follow one of the three pathways:

- Remain with the waste as a solid
- Become entrained in the gas stream
- Vaporize

In the first pathway, the metals remain with the waste throughout the entire process and end up as residuals or bottom ash. This is the pathway of least resistance. In the second pathway, the metal is entrained into the gas stream. If the waste is solid waste, the



amount that becomes entrained depends on many variables such as the velocity of the combustion gas. The higher the velocity, the more likely the particles are to be swept into the gas stream. The degree to which this particle entrained occurs depends on the size of the particles in the solid waste and how those particles behave as the organics burn - whether they break up and form friable, dusty particles that can easily become entrained, whether they stay with the residuals. The smaller particulate tends to become entrained, although the particles are still relatively large (i.e., 10 microns in size and larger). Particles in this size range are generally relatively easy to remove from the gas stream, downstream in the process. Since they are easily controlled, these entrained particles are not the ones of most concern in metal emissions.

The third, and most important, pathway is the vaporization route. Some toxic metals are volatile and have a significant vapor pressure. In the hot, burning environment of the combustion device, a portion of the metals in the waste vaporizes, changing from a liquid or solid state to a gas. This process depends on the temperature and on the chemical environment. A nonvolatile metal vaporizes if the metal comes into contact with another species and reacts to form a volatile compound. If chlorine or other halogens are present in the local surroundings, for example, the metals may undergo a chemical reaction and form chlorides, which are typically more volatile than the oxides of the metals. Those metal chlorides will subsequently vaporize.

The hot combustion gas stream cools as it exits the combustion chamber, causing vaporized metal to condense into particulate matter. The vaporized metal can condense in one of the two ways: homogeneously or heterogeneously. In homogeneous condensation, gas forms tiny fume particles, all by itself, in the tens-of-angstrom size range. These particles stay this size only briefly, very quickly growing to larger particle (typically 0.1 to 0.5  $\mu\text{m}$ ) by colliding with each other and coagulating, as well as by condensing with other vapor. Unfortunately, most types of air pollution control equipment (APCE) are least effective in this submicron size range. In heterogeneous condensation, the vapors condense onto the surfaces of existing particles, such as condensed fume or entrained fly ash. Heterogeneous condensation occur on whatever surface area is most prominent.

### **1.5.3 Nitrogen Oxides (NO<sub>x</sub>)**

Nitric oxide (NO) is a product of waste-wood-fuel combustion. It is a Class B toxic air pollutant under Chapter 173-460 WAC. It will slowly oxidize to nitrogen dioxide (NO<sub>2</sub>). NO is the predominant oxide of nitrogen from combustion process; NO<sub>2</sub> will be generated at approximately 5% of the quantity of NO generated. Nitrogen oxides contribute to gross atmospheric effects such as haze and smog.

Relative to other fuel sources, most of the NO<sub>x</sub> emissions from waste-wood-fired boilers originate from the nitrogen that is part of the chemistry of the wood. Nitrogen that is part of the chemistry of the fuel is called "fuel-bound nitrogen." Combustion in waste-wood-fired boilers is done at a relatively low temperature. For example, the average temperature in the burning fuel mass in a waste-wood-fired boiler might be around 1,500 °F. In a natural gas or fuel oil-fired boiler, the flame temperature might be 2,000 °F or higher. NO<sub>x</sub> formation from atmospheric nitrogen is very temperature-dependent.

Relatively little oxidation of atmospheric nitrogen takes place below about 1,700 °F. Formation of NO<sub>x</sub> from the fuel-bound nitrogen takes place by a relatively complex chemical pathway, is sensitive to oxygen concentration in the combustion zone, and non-linearly related to temperature. NO<sub>x</sub> emissions are more controllable to the extent that the oxygen concentration and temperature in the combustion zone are evenly distributed and controlled.

In waste-wood burning, the NO<sub>x</sub> formation process is complex, and can shift from oxidation to reduction and back again depending on the spot-temperatures and oxygen concentration in the fuel mass. However, as an approximation, the equilibrium for each NO<sub>x</sub> species based on using NH<sub>3</sub> as the SNCR promoter for NO<sub>x</sub> reduction is

- $2 \text{NH}_3 + 3 \text{N}_2\text{O} \Rightarrow 4 \text{N}_2 + 3 \text{H}_2\text{O}$
- $4 \text{NH}_3 + 6 \text{NO} \Rightarrow 5 \text{N}_2 + 6 \text{H}_2\text{O}$
- $8 \text{NH}_3 + 6 \text{NO}_2 \Rightarrow 7 \text{N}_2 + 12 \text{H}_2\text{O}$

Nitrogen oxide emissions are controlled by limiting their formation in the incinerator using staged combustion or applying selective noncatalytic reduction to reduce the NO<sub>x</sub> content in the flue gas. Staged combustion is accomplished by splitting up the introduction of combustion air into the boiler so that areas of fuel-rich and fuel-lean firing are established. This will lower the peak flame temperatures and limit the amount of oxygen available to react with nitrogen in the air at peak temperature. The introduction of additional secondary air downstream in the boiler will ensure complete combustion and minimize CO formation. Generally, staged combustion is effective in reducing NO<sub>x</sub> formation due to air-nitrogen conversion, but is not very effective for conversion of fuel-bound nitrogen to NO<sub>x</sub>.

The NO<sub>x</sub> present in the flue gas can be reduced by employing either a selective catalytic or noncatalytic reducing process. The selective catalytic reduction (SCR) process utilizes ammonia injection upstream of a catalytic reactor, at about 600-650 °F, to reduce NO<sub>x</sub> to nitrogen. Selective catalytic reduction has been applied to a wide range of combustion sources where 80-85% NO<sub>x</sub> reduction has been demonstrated. Selective noncatalytic reduction (SNCR) reduces flue gas NO<sub>x</sub> through a reaction with ammonia in a temperature range of 1700-1900 °F. The ammonia may be supplied as anhydrous ammonia, aqueous ammonia, or urea. At flue gas temperature above 1900 °F, the oxidation of ammonia to NO<sub>x</sub> increases and SNCR can actually result in an increase in overall NO<sub>x</sub>. At temperatures below about 1700 °F, NO<sub>x</sub> reduction falls off and ammonia breakthrough increases, leading to the potential for a visible ammonium-chloride plume.

#### **1.5.4 Sulfur Dioxide and Hydrogen Chloride**

High sulfur content coal or oil burning would cause significant SO<sub>2</sub> emission. Sulfur can be a constituent of wood-waste, particularly of sludge from the pulp and paper wastewater treatment plant. If sludge is burned along with wood, sulfur will oxidize to sulfur dioxide (SO<sub>2</sub>) and sulfur trioxide (SO<sub>3</sub>). All sulfur oxides have deleterious atmospheric effects. They are active participants in the generation of smog, and contribute to tree damage as elements of acid rain. Less than 5% of the sulfur oxide will be SO<sub>3</sub>. It is the less desirable sulfur oxide compound. It is readily soluble in water and

will form sulfuric acid, which is highly corrosive. Sulfuric acid mist is a Class B toxic air pollutant under Chapter 173-460 WAC.

When a chlorine-containing organic compound (organic chlorine) is burned, the chlorine will combine with hydrogen from water produced by burning material to generate hydrogen chloride (HCl). HCl is soluble in water and will readily form hydrochloric acid. As with SO<sub>3</sub>, HCl is readily soluble in water. It forms highly corrosive hydrochloric acid. As an air pollutant constituent, it can contribute to acid rain. It is a Class B toxic air pollutant under Chapter 173-460 WAC.

## 1.6 Pollutant of Concern Selection Process

### 1.6.1 Sources of information

The first step in the pollutant selection process was a search of different sources of emission data. The purpose of this step was to determine a comprehensive list of candidate chemicals for the pollutant of concern (POC) list. The intent here was to gain an overview of the likely pollutants and the range of reported amounts. Ecology reviewed information from the following sources:

- **Washington Administrative Code (WAC) Chapter 173-460 Controls for New Sources of Toxic Air Pollutants:** Ecology has a comprehensive list of toxic air pollutants (TAP) in WAC 173-460. Ecology's criteria for listing a TAP in WAC 173-460 is if Ecology has reason to believe that the compound/group of compounds is/are likely to be emitted from an air pollution source and the air emission of that compound/group of compounds could impact public health. The TAPs are identified as either a class A TAP (WAC 173-460-150) or a class B TAP (WAC 173-460-160) along with an acceptable source impact level (ASIL) for the respective TAP. An ASIL is concentration of a TAP that is used to evaluate the air quality impacts of emissions of that TAP from a single emission source. Class A TAPs are known, probable, and potential human carcinogens. Class B TAPs are compounds that fit the Ecology TAP criteria described above and are not known or probable carcinogens, simple asphyxiants, or nuisance particulates.<sup>6</sup>
- **Washington State Emission Inventory (1992 - 1997):** Emission reports from wood-fired boiler facilities are submitted from the industry and entered into this Ecology database. Every year the facilities update their emission inventory by reporting emissions of criteria and toxic air pollutants from each emission unit. This database has information about boiler design and age, emissions of criteria and toxic air pollutants, stack parameters, and the emission controls. Data compiled from the emission inventory is summarized in Tables 1 through 6.<sup>6</sup>
- **Title V Air Operating Permit (AOP) applications:** The AOP applications contain estimated criteria and toxic emission amounts for 1994. The 1994 toxic emission estimates are summarized in Table 7.<sup>6</sup>

- **National Council of the Paper Industry for Air and Stream Improvement (NCASI) Technical Bulletin 701 (dated October 1995):** Table 8 contains a listing of the names of toxic air pollutants emitted from wood-fired boilers that are reported in Technical Bulletin 701. Ecology will attempt to acquire the latest electronic version of this database and query it for emission data.<sup>8</sup>
- **Air Chief Version 9.0 CD ROM (EPA 454/C-01-003 dated Dec. 2001):** This database contains a compilation of AP-42 Air Pollutant Emission Factors and emission factors from the Factor Information Retrieval Data System. The database was developed (under contract to the Emission Factor and Inventory Group (EFIG) of the USEPA) to provide current emissions data compiled from existing EPA reports and databases. Tables 9 through 11 contain the names and respective emission factors of the pollutants reportedly emitted from wood-fired boilers.<sup>10</sup>
- **Toxic Release Inventory (TRI), (1998):** This U.S. Environmental Protection Agency (USEPA) database includes data from facilities across the nation that are required to report to the inventory under section 313 of the Emergency Planning and Right-To-Know Act (EPCRA or Title III of the Superfund Amendments and Reauthorization Act of 1986). Facilities are required to report the quantities of both routine and accidental releases of EPCRA section 313 chemicals. Queries were submitted using the Standard Industrial Classification (SIC) codes (2421, 2426, 2429, 2431, 2435, 2436, 2611, 2621, 2631, 4911, and 8062) that correspond to the boilers in the Washington State Emission Inventory. After these queries were conducted, Ecology selected only the toxic pollutants reported by Washington facilities (under SIC codes 2611 and 2621 in Tables 12 and 13) to further refine the list of toxics.<sup>6</sup>
- **Literature Search Database developed by Ecology's Air Quality Program Staff:** Air Program staff have reviewed and compiled references from literature related to criteria and toxic emissions and control of those emissions from wood-fired boilers. Staff compiled emission factor, source test data, and emission control information reported in the literature in that database. Staff will evaluate the emission factors, source test data, and emission control information in the database. Staff will review recent literature (obtained from Canada) which discusses dioxin/furan emissions from wood-fired boilers and similar types of combustion sources. This document does not contain any of the information compiled in the literature database.

### 1.6.2 Candidate Pollutants of Concern

The goal of the second step of the pollutant selection process was to identify a list of pollutants that could reasonably be identified as "Candidate Pollutants of Concern". Ecology staff did this by creating a spreadsheet listing all of the WAC 173-460 TAPs and identifying whether those TAPs were reported in any of the sources of data described above. Pollutants in the WAC 173-460 list that were not identified as pollutants by any of the other sources of data were eliminated from the list. The pollutants that remain on the list are TAPs listed in WAC 173-460 that are also identified in at least one of the other data sources described in the memo by Schwieters, et al.<sup>6</sup>

The attached **Table 2** presents the actual pollutants of concern from the wood-fired boiler. This list of POC was created by consolidating all the “Candidate Pollutants of Concern” described by Schwieters, et al.<sup>6</sup> (**Table 3**). This list of pollutants given in **Table 2** represents what is most significant emissions from the wood-fired boilers. For example, chlorine, chlorine dioxide, and chloroform have been deleted from the previous list, because these three pollutants are typically formed and emitted from the bleach processes. Vanadium is typically found in a combustion source when oil is burned. A recent source test report and emission data obtained from Kimberly-Clark’s hogged fuel boiler facility<sup>7</sup>, the NCASI reports<sup>8</sup>, and the data obtained from Toxic Release Inventory<sup>9</sup> helped to finalize the current list of pollutant of concern. Also, all the individual chemicals under PAHs (i.e., Benzopyrene, chlorophenols, ...) are listed as total PAHs. PAHs are products of incomplete combustion of organic materials. The pollutants listed in **Table 2** are most relevant and realistic as far as air toxic and criteria pollutant emissions from wood-fired boilers are concerned.

**Table 2. Updated List of Pollutants of Concern from Wood-Fired Boilers**

<b>Substance</b>	<b>Surrogate Controls</b>
Acetaldehyde	C
Alpha-pinene	C
Beta-pinene	C
<b>Carbon monoxide (CO)</b>	C
Formaldehyde	C
Methanol	C
Naphthalene	C
Toluene	C
Total phenols	C
Turpentine	C
<b>PAHs</b>	C/P
2,3,7,8 Tetrachlorodibenzo-p-dioxin (TCDD)	C/P
2,3,7,8-Tetrachlorodibenzo-p-dioxin	C/P
Hydrogen sulfide	C/S
<b>Nitrogen oxides (NOx)</b>	N
Beryllium	P
Cadmium and compounds	P
Chromium (II) compounds, as Cr	P
Chromium (III) compounds, Cr	P
Chromium (metal)	P
Chromium (total)	P
Chromium, hexavalent metal and compounds	P
Cobalt as Co metal Dust and fume	P
Cobalt carbonyl as Co	P
Copper, Dusts and mists, as Cu <sub>3</sub>	P
Copper, Fume	P
Iron	P
Lead arsenate, as Pb <sub>3</sub> (A <sub>2</sub> O <sub>4</sub> )	P
Lead chromate, as Cr	P
Lead compounds	P
Magnesium	P
Manganese	P
Molybdenum	P
Nickel and compounds	P
<b>Particulate matter (PM)</b>	P
Phosphorus	P
Selenium	P
Silver	P
Thalium	P
Zinc	P
Arsenic and inorganic arsenic compounds	P/S
Mercury	P/S
<b>Hydrochloric acid</b>	S
Sulfuric acid	S
<b>Sulfur dioxide</b>	S
<b>C</b> - Carbon monoxide (good combustion practices)	
<b>P</b> - Particulate matter	
<b>S</b> - Sulfur dioxide (acid gases)	
<b>N</b> - Nitrogen oxides	

**Table 3. Prior List of Candidate Pollutants**

Substance	Surrogate Controls	CAS#
(1,1,1-Trichloroethane)	C	1746-01-6
2,3,7,8 Tetrachlorodibenzo-p-dioxin (TCDD)	C	75-07-0
2,3,7,8-Tetrachlorodibenzo-p-dioxin	C	
2-Hexanone (MBK)	C	C7440-38-2
Acetaldehyde	C	71-43-2
Acetone	C	
Acrolein	C	50-32-8
Alpha-pinene	C	7440-41-7
Benzene	C	C7440-47-3
Benzo(a)pyrene	C	75-09-2
Benzo(b+k)fluoroanthene	C	50-00-0
Benzoanthracene	C	C7440-02-0
Benzoic acid	C	1746-01-6
Beta-pinene	C	79-01-6
Butylbenzphthlate	C	—
Carbon disulfide	C	107-02-8
Carbon monoxide (CO)	C	
Carbon tetrachloride	C	C7440-36-0
Chlorine	C	1309-64-4
Chlorine dioxide	C	C7440-39-3
Chloroform	C	
Chloromethane	C	65-85-0
Chlorophenols	C	
Chrysene	C	C7440-47-3
Cobalt hydrocarbonyl	C	
Cumene	C	10210-68-1
Cyclohexane	C	16842-03-8
Cyclohexanone	C	C7440-50-8
Dibutyl phthalate	C	7440-50-8
Dichlorofluoromethane	C	98-82-2
Dichloromethane (methylene chloride)	C	110-82-7
Ethyl alcohol (ethanol)	C	108-94-1
Formaldehyde	C	
Hexane (n-Hexane)	C	84-74-2
Hexane, other isomers	C	75-43-4
Hydrogen sulfide	C	64-17-5
Isopropyl alcohol (dimethylcarbinol, isopropanol, 2-propanol, sec propyl alcohol)	C	—
Methyl alcohol (methanol)	C	C7439-96-5
Methyl chloride (chloromethane, monochloromethane)	C	C7439-96-5
Methyl ethyl ketone (MEK)	C	
Methyl isobutyl ketone (MIBK)	C	67-56-1
Methyl mercaptan	C	74-87-3
m-Xylene a,a'-diamine	C	
Naphthalene	C	78-93-3
Napthalene	C	108-10-1
p-cymene	C	91-20-3
Phenol	C	

Substance	Surrogate Controls	CAS#
Styrene	C	C7440-22-4
Sulfuric acid	C	100-42-5
Toluene	C	7440-31-5
Toxaphene	C	108-88-3
Trichloroethylene	C	C7440-33-7
Turpentine	C	1314-62-1
Xylenes (m-,o-,p-isomers)	C	1330-20-7
Nitrogen oxides (NOx)	N	
Antimony & compounds as Sb	P	7440-43-9
Antimony trioxide, as Sb	P	56-23-5
Arsenic and inorganic arsenic compounds	P	67-66-3
Barium, soluble compounds Ba	P	108-43-0
Beryllium and compounds	P	8001-35-2
Cadmium and compounds	P	67-64-1
Chromium (II) compounds, as Cr	P	
Chromium (III) compounds, Cr	P	75-15-0
Chromium (metal)	P	7782-50-5
Chromium (total)	P	10049-04-4
Chromium, hexavalent metal and compounds	P	
Cobalt as Co metal Dust and fume	P	C7440-47-3
Cobalt carbonyl as Co	P	7440-47-3
Copper, Dusts and mists, as Cu <sub>3</sub>	P	
Copper, Fume	P	7440-48-4
Iodine	P	100-54-3
Lead arsenate, as Pb <sub>3</sub> (A <sub>2</sub> O <sub>4</sub> )	P	591-78-6
Lead chromate, as Cr	P	6/4/83
Lead compounds	P	7553-56-2
Manganese dust & compounds	P	67-63-0
Manganese fume	P	3687-31-8
Mercury	P	7758-97-6
Nickel and compounds (as nickel subsulfide or nickel refinery dust)	P	74-93-1
Particulate matter (PM)	P	
Phosphorus	P	108-95-2
Selenium compounds, as Se	P	7723-14-0
Selenium hexafluoride, as Se	P	C7782-49-2
Silver, Metal	P	7783-79-1
Silver, soluble compounds as Ag	P	7440-22-4
Thallium, soluble compounds, Tl	P	7664-93-9
Tin, Metal	P	C7440-28-0
Tin, Organic compounds, as Sn	P	7440-31-5
Tin, oxide & inorganic except SnH	P	C7440-31-5
Tungsten, Insoluble compounds	P	C7440-33-7
Tungsten, Soluble compounds	P	8006-64-2
Vanadium, as V <sub>2</sub> O <sub>5</sub>	P	1477-55-0
Zinc chloride fume	P	7646-85-7
Zinc chromates	P	13530-65-9
Zinc oxide, fume <sup>1</sup>	P	1314-13-2



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## **2.0 Qualitative Analysis of Control Technologies**

This chapter describes and summarizes available control technologies for each of the categories of pollutant of concern (*POC*). The purpose of the qualitative analysis is to screen out those emission reduction options that have little likelihood of being implemented and are unsuitable for further evaluation. Those options that remain will be further evaluated in the quantitative analysis that follows this chapter.

Criteria for eliminating emission reduction options from further consideration were identified in the Draft Source Category RACT Guidelines. These criteria are:<sup>1</sup>

- Option does not provide emissions control as effective as what is currently in place,
- The option is “technically infeasible.”<sup>2</sup>
- The option would tend to increase the emission rates of more contaminants of concern than it reduces, or the emissions reduction option will increase the emission rates of Toxic Air Pollutants (TAPs) above the respective small quantity emission rates (SQERs) or acceptable source impact levels (ASILs) while reducing the emission rates of contaminants of concern,
- The option would present a public and/or worker safety problem. An example of this would be long duct runs to transport materials that are subject to condensation and fire.
- The option would force a change in product type or quality that would cause a significant reduction in product marketability.

The balance of this chapter is divided into the following four sections: particulate-related controls, carbon monoxide related controls, acid gases and sulfur compounds controls, and nitrogen oxide controls. For each POC category, control technologies are described and evaluated using the criteria listed above. The results of this analysis are summarized on the last page of this chapter.

### **2.1 Particulate Matter**

The most important characteristic of particulate matter is the particle size. It is the property that has the greatest impact on the behavior of the particulate matter in control equipment, in the atmosphere, and in the respiratory tract. Particles important in air pollution control can range from the extremely small 0.05  $\mu\text{m}$  to more than 1000  $\mu\text{m}$ . Particulate matter of all sizes is regulated as total particulate. The  $\text{PM}_{10}$  is defined as all of the particulates are equal or less than 10  $\mu\text{m}$  in size. Health effects research has demonstrated that the composition of the particle can

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<sup>1</sup> Ecology, October 1997.

<sup>2</sup> *Technically infeasible* means that based on physical, chemical, and engineering principles, technical difficulties would prevent the successful use of the emission reduction option being considered for a particular emission unit. Two key concepts are important in determining whether an undemonstrated technology is feasible – “availability” and “applicability.” A technology is considered “available” if it has been demonstrated to perform according to specifications at a reasonable size in an actual industrial setting and can be obtained by the applicant through commercial channels or is otherwise available within the common sense meaning of the term. An available technology is “applicable” if it can reasonably be installed and operated on the source to be under consideration. A technology that is available and applicable is technically feasible. If commercially available at appropriate unit size and with verifiable reliability, emission reduction options that have been proven in pilot scale operations may be considered technically feasible.

be as important as the particle size. Certain elemental metals and metallic compounds found in some particulate emissions are especially toxic.

There are four main types of particulate control techniques. Within each of these categories there are many different design type:

1. Cyclone Collectors
2. Fabric Filters (FF) or Baghouse
3. Venturi (wet) scrubbers
4. Dry and Wet Electrostatic Precipitators (ESP)

### **2.1.1 Cyclone Separators:**

The cyclone collector or separator is one of the oldest and most commonly used devices for controlling primarily large-diameter particulate emissions. It comes in two different forms: (1) Single Cyclone and (2) Multiple-Cyclone. Cyclones are frequently used as pretreatment devices for high-efficiency particulate control devices, such as ESPs, venturi scrubbers, and FFs (baghouses). By placing a cyclone in front of these devices, the loading on the primary device is reduced, resulting in smaller equipment and more economical and safer fire concern designs.

Cyclone collectors are also used when product recovery is an important consideration for a facility's production efficiency. The cyclone units are very effective at recovering large-diameter materials from the exhaust streams. Another environmental advantage of cyclone collectors is that no liquid waste streams are generated from equipment operations. Collection efficiency is a strong function of particle size and increases with increasing particle size. Cyclone collectors are usually limited to particulate matter larger than approximately 5  $\mu\text{m}$ .

#### **2.1.1.1 Cyclones: How they work**

Particulate removal is achieved through the action of inertial forces, especially centrifugal. As the gas stream enters the top of the cyclone, a vortex is induced as it is forced to travel a circular path. Centrifugal forces cause the heavier particles to concentrate near the outer wall of the cyclone and particles of lesser mass to remain closer to the center of the vortex.

Frictional and gravitational forces then act on the particles closest to the wall, causing them to fall toward the bottom of the cyclone, where they are collected in a hopper. Within the lower segment of the cyclone, the direction of the gas-flow vortex is reversed, and an inner ascending vortex is formed. The inner vortex consists of comparatively particulate-free air, which is collected through an outlet duct located at the top of the cyclone.

In applications where many small cyclones are operating in parallel, the entire system is called a multiple tube cyclone, multicyclone, or multiclone. A multi-tube system is a group of smaller diameter vane-axial parallel cyclones within a common housing that shares a common inlet and discharges to a common plenum. By nature of their smaller diameters (usually range from 1 foot to as small as 2 inches), multi-tube cyclones are capable of producing greater centrifugal forces and better particulate separation for a given initial energy (velocity head) input. The multi-tube cyclone is generally used with large gas-flow rates. Properly designed units can be constructed to achieve 90% or even greater collection efficiency for fine particulates. Operation is, however, more expensive, since pressure drop increases as decreases cylinder diameter; greater the pressure drop, the greater the power cost would be.

### **2.1.1.2 Cyclones: Conclusion**

The single or simple cyclone used primarily for large-diameter particles and has limiting removal efficiencies (50-90%) for smaller particle size ranging from 10 – 5 micron ( $\mu\text{m}$ ). The multiple-cyclone (or multi-tube) which upon proper design can achieve a higher collection efficiency ( $\geq 90\%$ ) for particles in the 10 – 5  $\mu\text{m}$  range (11). Multi-cyclone operation is, however, more expensive, since pressure drop increases with a decrease in cylinder diameter; the greater the pressure drop, the greater the power cost. Cyclones themselves are generally not adequate to meet stringent air pollution regulations, but they serve an important purpose as precleaners for more expensive final control devices such as FFs and ESPs (11).

Single cyclone is being used as pretreatment in 6 units in the State. A simple single cyclone, has limiting removal efficiencies for smaller particle sizes (50-90% for 10 - 5  $\mu\text{m}$ ). The removal efficiency of particulate less than 5  $\mu\text{m}$  is very low<sup>1</sup>. Higher efficiency cyclones come with higher pressure drops, which require higher energy costs to remove the waste gas through the cyclone. Because the lack of adequate removal efficiency for fine particulate, this control technology would not be considered for RACT.

Multiple-cyclone is still a viable particulate control technology, but the question is whether such units would be adequately designed and operated to meet the new RACT standards! Since this technology has the potential to meet the standard for a certain capacity boiler and flowrate, this technology will move forward for further consideration.

### **2.1.2 Fabric filters (FF) or Baghouse**

#### **2.1.2.1 Fabric filters: How they work**

Fabric filters (or Baghouse) collect particulate matter on the surfaces of filter bags. Most of the particles are captured by impaction and sieving on already collected particles which are present as a dust layer on the bags. The fabric material itself can capture particles which have penetrated through the dust layers. Electrostatic attraction may also contribute to particle capture in the dust layer and in the fabric itself. There are two common types of fabric filters: (1) reverse-air; and (2) pulse jet. The *reverse-air* type fabric filter is used mainly for large industrial sources. In this type of unit, the particle-laden gas stream enters from the bottom and passes into the inside of the bag. In the *pulse jet* type unit, particle-laden gas flows around the outside of the bags, and a dust cake accumulates on the exterior surfaces. Due to multiple types of particle capture possible, fabric filters can be highly efficient for the entire particle size range.

Fabric filters (FF) have several attractions as a particulate control device. They are relatively insensitive to changes in particle composition caused by variations in fuel composition and combustion characteristics, and they are tolerant of short-term increase in gas volume. Also, fabric filters are effective in removing particulate matter, in the submicron range, and their outlet concentration is relatively independent of the inlet loading. FFs are limited to use where the flue gas temperature is within 300-400 °F and above the flue gas dew point.

Application of fabric filters have been limited on wood-fired boilers, despite the advantage of very high removal efficiency for fine particulates. The principal concern with the use of a fabric filter is the potential for fire damage resulting from burning cinders, temperature excursions, and/or operating upsets. Both glass and nomex bags have been used, with bag life generally not exceeding 18 months to 2 years. Reverse air-cleaned fabric filters generally operate at an air-to-

cloth ratio of 1-2 (acfm/ft<sup>2</sup>). Pulse jet-cleaned fabric filters generally operate with an air-to-cloth ratio in the range of 4 to 5. More discussion on advantages and disadvantages are given in Air Pollution Engineering Manual<sup>3</sup>.

### **2.1.2.2 Fabric filters: Conclusions**

Currently 14 bag houses are operating; two have no coarse particulate removals equipment reported, while most others have multi-clones. This control technology will move forward for evaluation of RACT.

### **2.1.3 Scrubbers**

Various scrubbers, including venturi scrubber, wet and dry scrubbers, and packed bed absorber, are used to control particulate, as well as controlling acid gases. The venturi scrubber is the most common one for particulate control and this process technology will be discussed here. The other scrubbers will be discussed later in the acid gas control section.

#### **2.1.3.1 Venturi scrubber: How they work**

The venturi scrubber which uses water is typically considered high-energy particulate-control device. Water is injected into a number of slightly modified scrubbers in a variety of ways. Some designs inject at the throat zone, others at the gas inlet, and still others upwards, against the gas flow in the throat. Some designs use supplemental hydraulically or pneumatically atomized sprays to augment target droplet creation<sup>3</sup>. Such venturi scrubbers are believed to capture particulates by three mechanisms: (1) impactions of the particle directly into a target droplet; (2) interception of the particle by a target droplet as the particle comes near the droplet; and (3) diffusion of the particulate through the gas surrounding the target droplet until the particle is close enough to be captured<sup>3</sup>. The overall particulate removal efficiency will depend on various parameters, including pressure drop, droplet sizes and concentration across the venturi throat, particle density, gas viscosity and density, and particle penetration. Wet scrubber will make wastewater and wet sludge for disposal – may be a dangerous waste.

#### **2.1.3.2 Venturi Scrubber: Conclusions**

Presently, there are 8 units using venturi scrubbers, and this technology will move forward for RACT consideration.

### **2.1.4 Dry and Wet Electrostatic Precipitators (ESP)**

In an ESP (wet or not), the particulates are attracted to electrodes where they agglomerate. Periodically, they are removed from the electrode surfaces by either shaking them off (dry ESP) or washing them off (wet ESP).

#### **2.1.4.1 Dry ESP: How they work**

The most common type of industrial ESP is the single-stage unit. In this unit, discharge electrodes are placed between grounded parallel plates spaced 8-12 inches apart, resulting in simultaneous charging and collection. By applying a high voltage to the discharge electrodes, a corona discharge occurs that results in the production of negatively ionized gas molecules. The electric field between the discharge electrodes and collection plate causes the ions to migrate toward the plates, intercepting particles present in the space. Deposition of the ions onto the particles charges them to a negative potential and they migrate toward the collection plates

through the influence of the electrostatic forces. In a dry ESP, particles collected on the plates are periodically removed by mechanical rapping.

The performance of the ESP is affected by a number of gas stream and particle characteristics. One important characteristic is the particle size, which determines the mechanism by which charging occurs. Particles of submicron size are predominately charged by a diffusional mechanism that becomes more effective as the particle size decreases, while larger particles are predominately charged by a contact mechanism. As a result of this, particle charging is least effective in the size range of 0.1 to 1.0  $\mu\text{m}$ . Because of the tendency for metals and chlorinated organics to be enriched in smaller particles, particular care must be taken to insure effective collection in this size range. Another parameter that affects collection in an ESP is particle resistivity. Particle resistivity determines how effectively a particle retains its charge and is affected by particle composition and surface deposits and by gas stream temperature and moisture content. Finally, ESP performance is affected both by the gas velocity through the collector and by the total gas flow.

#### **2.1.4.2 Wet ESP: How they work**

Wet precipitators are widely used in industrial applications for collection of fine particles or mists, such as sulfuric acid mists and for wood-fired boiler. Plate-type designs were widely used for industrial applications involving organic emissions, plastic curing, food processing, printing, textile finishing, and heat treating industries. Tubular wet precipitators have very high collection efficiency in submicron region. Unlike dry precipitators, wet precipitators do not require a rapping mechanism for removing the accumulations on the electrodes. In a wet ESP, removal is accomplished by an intermittent or continuous stream of water that flows down the plates, which also eliminate the fire concern. In the case of high particulate loadings, atomizing nozzles are used to continuously spray water into the precipitator to prevent sludge deposits on the collecting electrodes. The major advantages of wet ESPs lies in the removal of  $\text{SO}_x$ ,  $\text{H}_2\text{SO}_4$ ,  $\text{HCl}$ , micron-size particles, and other mists that may be contained in the gas.

#### **2.1.4.3 ESPs: Conclusions**

Increased interest in the wet ESP has arisen because of the acknowledged shortcomings of other high-efficiency particulate collectors. The venturi-scrubber, for example, is characterized by an extremely high energy consumption, which makes the venturi less attractive in an era of increasing energy costs. The dry ESP has dust resistivity limitations which restrict its usefulness in collecting certain classes of dusts. The fabric filter's usefulness is limited by the physical and chemical nature of the particulate. In addition, the filter materials itself may have restricted ranges of chemical resistance and temperature. The wet ESP overcomes many of the limitations of these other devices. The nature of the particles is of considerably less importance, and temperature has little effect on performance. Because the collector plate is continually washed, dust resistivity of the collected layer is no longer a problem and gaseous pollutants are also removed by the washing process; the only real limitation is the solubility of the gaseous component in the washing liquid. With these characteristics, along with its relatively low total power consumption, the wet ESP offers certain economic and technical advantages over more traditional equipment in certain application. This is especially true when a significant portion of the particulate is in the submicron range<sup>8</sup>.

Wet precipitators on wood-fired boilers are capable of achieving outlet grain loading similar to dry precipitators, that is, 0.01-0.02 gr/dscf corrected to 12%  $\text{CO}_2$  at power level typically in the

30-150 watts per 1000 acfm range<sup>3</sup>. The major disadvantage of wet ESPs lies in the handling of wastewater and wet sludge disposal – may be a dangerous waste.

There are 8 units currently installed and are using dry ESP. This technology will move forward and will be recommended for RACT.

At least 2 units have **wet ESP** installed, and this technology will move forward.

## **2.2 Acid gases**

The major acid gas emissions from hog fuel boilers are hydrochloric acid (HCl) and oxides of sulfur (SO<sub>x</sub>). One of the oxides of sulfur, sulfur trioxide (SO<sub>3</sub>) hydrolyzes in both the exhaust stack and in ambient air to form sulfuric acid mist. The control techniques generally used for acid gases are

- Fuel quality
- Venturi scrubber
- Wet scrubber (WS)
- Wet ESP
- Dry injection (DI)

### **2.2.1 Hydrogen chloride**

Hydrogen chloride (HCl) is an acid gas which can be generated in combustion process or waste combustors burning chlorine-containing materials. It is a gas at the normal stack concentrations. However, at very high concentrations, it can form submicron acid mist particles. HCl is extremely soluble in water. Due to its acidic properties, it is a strong irritant.

The concentration of HCl formed during fuel combustion is directly related to the chloride concentration of the waste or fuel being fired. Essentially chloride compounds are volatile. All of the chlorides are released in the early stages of combustion, and they can eventually react with a hydrogen atom to form HCl. HCl remains in the vapor phase and does not participate in heterogeneous nucleation. However, small quantities of HCl can adsorb on the surfaces of particles when the gas stream containing the HCl and particulate matter has cooled sufficiently<sup>1</sup>.

#### **2.2.1.1 Fuel Quality as an HCl control strategy**

HCl formation can also be controlled by reducing or eliminating chlorine content in mixed fuels. Elemental chlorine or chlorinated compounds present in mixed fuels would contribute HCl formation, as opposed to clean wood combustion.

#### **2.2.1.2 Venturi scrubber and Other Scrubbers for HCl control strategy**

Venturi scrubber operation for HCl control is same for controlling particulate except that scrubbing liquid must be alkaline to maximize gas absorption. This control technology will move forward for RACT consideration.

HCl can also be controlled effectively by two main types of scrubber systems: (1) absorbers, and (2) adsorbers. Due to its high solubility, HCl can be controlled efficiently in wet scrubbers. Virtually all types of wet scrubbers will perform adequately as long as they are properly designed for the concentrations in the gas stream. The most common type of wet scrubber absorber for HCl is the packed tower scrubber<sup>1</sup>. This type of unit has one or more beds of packing which is coated with scrubbing liquid flowing downward over the packing. Alkali is added to the recirculating scrubbing liquid to maintain the liquid pH in the range where high efficiency removal occurs.

HCl can be controlled by wet ESP. This technology is described in details in section A4.

HCl can also be controlled effectively in spray-dryer-type dry scrubbers and/or dry injection-type dry scrubbers. These will be described in this section. Usually, the removal efficiency for HCl is greater than the removal efficiencies for SO<sub>2</sub> in both types of dry scrubbing systems (Table 2).

Dry sorbent injection for acid gas control needs additional particulate control, including cyclone, baghouse or ESP.

### **2.2.1.3 Scrubbers: Conclusion**

There are about 16 non-venturi wet scrubbers installed in Washington boilers. They are used primarily for particulate control. Some acid gas control occurs, but is not intentional. These technologies will move forward for RACT.

No unit currently has a HCl control; however, venturi scrubber or wet scrubber would remove HCl. No unit has a dry sorbent injection control for HCl.

### **2.2.2 Sulfur Dioxide and Sulfuric Acid**

Sulfur dioxide is a colorless gas having the chemical formula, SO<sub>2</sub>. It is moderately soluble in water and aqueous liquids. It is formed primarily during the combustion of a sulfur-containing fuel or waste. Once released to the atmosphere, SO<sub>2</sub> reacts slowly to form sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), inorganic sulfate compounds, and organic sulfate compounds. A small fraction of the fuel sulfur remains in the bottom ash leaving the combustion processes. Almost all sulfur is converted to SO<sub>2</sub> which remains in the gaseous form throughout the combustion system. A small fraction of the SO<sub>2</sub> generated in the combustion zone is oxidized further to form sulfur trioxide (SO<sub>3</sub>). SO<sub>3</sub> concentrations are usually 0.5 to 2 percent of the SO<sub>2</sub> concentration<sup>1</sup>.

SO<sub>2</sub> is controlled primarily by four different techniques:

- Low sulfur content fuel
- Venturi scrubber
- Wet ESP
- Absorption
- Adsorption



## Low sulfur content fuel

For clean wood burning, SO<sub>2</sub> emission rates are negligible. Fuels with high sulfur content like coal, fuel oil, and Kraft mill sludge burning results in SO<sub>2</sub> emission rates that are based on the fuel sulfur contents.

### **Conclusion and Recommendation**

Burning of low sulfur content fuels to control SO<sub>x</sub> would move forward for RACT.

### **Venturi scrubber**

There are more than ten major types of wet scrubbers. One of the most common types of wet scrubbers is the venturi scrubber. Venturi scrubber operation for SO<sub>x</sub> control is same for controlling particulate except that liquid pH has to right for maximum gas absorption. Some details of the venturi scrubber operation is given in the particulate control section.

### **Conclusion and Recommendation**

One of the main advantages of venturi scrubbers is that they are often able to simultaneously collect particulate matter and gaseous pollutants, including acid gases. This technology would move forward for RACT consideration.

*Absorption* process utilizes the solubility of SO<sub>2</sub> in alkaline aqueous solutions to remove it from the gas stream. Once SO<sub>2</sub> has dissolved in solution to form sulfurous acid (H<sub>2</sub>SO<sub>3</sub>), it is reacted to form inorganic sulfates. By reacting the dissolved sulfur dioxide, it cannot diffuse out of the solution and be re-emitted.

*Spray dryer* absorbers utilizes the alkaline reagents to remove SO<sub>x</sub>, HCl, and chlorinated organics from the exhaust stream. There are two types of commonly used scrubbing systems are termed as “*wet scrubbing*” and “*dry scrubbing*”, depending on whether the reaction products are removed from the process in wet or dry form, respectively.

Oxides of sulfur, sulfurous and sulfuric acids can be controlled by wet ESP. This technology is described in details in section A4.

The *wet scrubber* (WS) for the removal of particulate matter has become unattractive because of the relatively high energy requirement to meet low outlet concentrations. Potential does exist, however, for their use in control of SO<sub>2</sub> and acid gases, although the possibilities for corrosion problems and the difficulties of dealing with the liquid wastes produced will likely limit their application. Applications of this type will be discussed in subsequent sections.

When a single-stage *wet scrubber* (WS-1) is used only as a gas scrubber, it would be generally be located downstream of a particle control device. Gases entering the scrubber are contacted with an alkaline solution that absorbs SO<sub>2</sub> and acid gases and reacts with them to form salts that are relatively insoluble. The solution exiting the scrubber is sequentially clarified, thickened to remove the salts and other collected solids. The sludge produced may also be stabilized by combining with fly-ash and/or lime before landfilling. The exiting gas stream, because of its low temperature and high moisture content, reheated before being discharged to the stack.

Several problems present themselves in single-stage wet scrubbing. Acid gases have a high affinity for liquid solutions and are quickly absorbed and reacted, significantly reducing solution pH. This lower pH solution is less desirable absorbent for the most slowly absorbed SO<sub>2</sub>, reducing collection effectiveness. Also, any halide salts or sulfates produced have high corrosive and scaling potential, making recycle of the scrubbing solution difficult. In addition, the presence of CaCl<sub>2</sub> in the scrubber liquor makes solids clarification and dewatering more difficult.

The above problems with simultaneous SO<sub>2</sub> and other acid gas absorption can be addressed by two-stage wet scrubbing (WS-2). The first stage, with a separate liquor loop, removes acid gases by water scrubbing. The second stage used alkaline solution and operates as an SO<sub>2</sub> scrubber with an outlet pH of 5-6. By separating the absorption processes SO<sub>2</sub> collection efficiency is increased, a more stable waste product is obtained and scrubbing solution recycle becomes viable.

**Packed bed absorbers** are the most common absorbers used for gas absorption. Packed columns disperse the scrubbing liquid over packing materials, which provides a large surface area for gas-liquid contact. Packed bed absorbers are most suited to applications where a high gas removal efficiency is required and the exhaust stream is relatively free from particulate matter. The gas stream moves upward through the packed bed against an absorbing or reacting liquor (solvent-scrubbing solution), which is injected at the top of the packing tower (for countercurrent). This results in the highest possible efficiency. Since the solute concentration in the gas stream decreases as it rises through the column, there is constantly fresher solvent available for contact. This provides the maximum average driving force for the diffusion process throughout the packed bed.

**Dry scrubber** (also known as *spray dryer*) utilizes alkaline reagents to remove SO<sub>2</sub>, acid gases (HCl and SO<sub>3</sub>) and chlorinated organics from the exhaust stream. The term “*dry scrubber*” refers to the condition of the dried particles (reaction products) approaching the particulate control system.

The most common reagent is hydrated lime (calcium hydroxide), usually prepared on site. Large spray chambers are used to ensure that all of the slurry droplets are evaporating. The atomized slurry entering the chamber mixes with the gas stream from the furnace. SO<sub>2</sub> and other acid gases in the exhaust stream are absorbed by the slurry droplets and react to form calcium salts. The fate of chlorinated organics in a spray dryer is not well understood, but it likely involves both condensation and sorption. Heat in the exhaust gas dries the slurry into a solid powder. A portion of the solids are collected in the bottom of the spray dryer; however, most are carried on to the dust collector, where additional sorption may occur. The dust collector may be either an ESP or a FF. Collection of chlorinated organics and some heavy metals is considerably improved when a fabric filter is used. If sorbent utilization is low, recycle of collected solids back to the feed tank may occur.

In many applications, the spray dryer type scrubbers offer the advantage of efficient removal of particulate, heavy metals, dioxins, furans, and acid gases at lower capital and operating costs than wet scrubbing systems. As a result, dry scrubbers are being selected increasingly over the more conventional wet scrubbers<sup>4,5</sup>.

### **Adsorption: Dry Injection (DI)**

SO<sub>2</sub>, HCl and chlorinated organics can also be collected by adsorption. In this case, a dry alkaline powder is pneumatically injected into a reactor vessel where it fluidizes and mixes the gas stream before carried on to the collection device. Normally, either an ESP or a FF would be used. The basic constraint in choosing a collector for use with dry injection is providing enough residence time for reaction with the dry reagent. With an ESP, little additional reaction is expected by the time the sorbent reaches the collector. Thus, larger reaction vessels may be required to provide the needed residence time, and recycling of the sorbent may be necessary to obtain full utilization with FFs, reaction continues as the gas passes through the filter cake, potentially reducing reactor size and eliminating the need for reagent recycling. New dry injection installations are expected to favor the use of FFs.

A dry injection (**DI**) type dry scrubber can be used on smaller systems than larger ones. The DI system is slightly less efficient, and it requires more alkali per unit of SO<sub>2</sub> (or other acid gas) collected. Another technique used for limiting the emissions of SO<sub>2</sub> is simply to switch to fuels that have less sulfur. The SO<sub>2</sub> emission rate is directly related to the sulfur levels in coal, oil, and other fossil fuels.

## **Conclusion and Recommendation**

No wood-fired boilers in Washington use this control. This technology will not be considered further for RACT.

### **Combination Scrubbers**

Some approaches to the control of SO<sub>2</sub> and acid gases use combinations of the systems previously described. Two such processes will be briefly described here: a spray dryer (**SD**) in combination with dry injection (**DI**) and a SD system in combination with two-stage wet scrubbing.

In a combined **SD/DI** system, the exhaust gas stream first enters an upflow **SD**, where it is contacted with atomized lime slurry. The quenched exhaust gases, along with most of the dried slurry, then enters a venturi reactor, where dry calcium silicate is injected, before being carried onto a fabric filter. The calcium silicate agglomerates the fly-ash and sorbent particles, resulting in lower pressure loss in the FF and, hence, longer filtration cycles. In addition, the calcium silicate is a reactive sorbent. The combination of a more reactive sorbent and longer retention times on the filter increases collection efficiency.

The significant improvement in a **SD** with two-stage wet scrubbing is the ability to convert the effluent from both scrubbing stages into a dry product for collection in either an **ESP** or **FF**. An additional option exists for raising the first stage scrubber pH to 3-4 and injecting sodium sulfate to oxidize NO to NO<sub>2</sub>. The NO<sub>2</sub> would then be collected in the second stage scrubber, along with SO<sub>2</sub>.

### **2.3 Nitrogen Oxides (NO<sub>x</sub>)**

Nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) are the oxides of nitrogen in hog fuel boiler emissions. They are formed simultaneously in combustion processes and other high temperature operations. NO has very low solubility in water. NO<sub>2</sub> is slightly soluble in water. NO<sub>2</sub> can form a dimer compound (N<sub>2</sub>O<sub>4</sub>), which has a distinct reddish-brown color. The main reason for

regulating the emissions of  $\text{NO}_x$  is to suppress the atmospheric photochemical reactions which create ozone and other reaction products and to reduce acid rain.

$\text{NO}_2$  is the main gas phase species responsible for the absorption of light in the photochemical reactions. Approximately 90 to 95% of the  $\text{NO}_x$  generated in combustion processes are in the form of NO. In the ambient atmosphere, the oxides of nitrogen appear to reach an equilibrium distribution around 25% NO and 75%  $\text{NO}_2$  (March 15, 2002 memorandum, "Use of the Ambient Ratio Method for Modeling Significant Ambient Impacts of  $\text{NO}_2$ ," Daniel J. deRoeck [Integrated Implementation Group, ITPID {C339-03} to Richard Daye [Air RCRA, and Toxics Division, Region VII]).

In power boilers, nitrogen oxides ( $\text{NO}_x$ ) are formed primarily in two-ways: (1) high temperature thermal fixation of nitrogen in the combustion air with excess oxygen, producing thermal  $\text{NO}_x$ ; and (2) conversion of nitrogen that is chemically bound in wood and mixed-fuels (including sludges, tires, coal, oil, etc), producing fuel  $\text{NO}_x$ . The amount of  $\text{NO}_x$  formed depends on peak flame temperature, nitrogen content of the fuel, quantity of excess air used for combustion, the degree of turbulence, and the residence time at high temperature. An increase in any of these factors results in increased  $\text{NO}_x$  formation. Unlike sulfur, not all of the fuel nitrogen compounds are released during combustion. A significant fraction of the fuel nitrogen remains in the bottom ash or in the fly-ash.

The techniques used to minimize  $\text{NO}_x$  emissions from stationary source combustion processes can be divided into three categories: (1) combustion modifications, (2) add-on control systems, and (3) fuel switching. Combustion modifications prevent the emission of  $\text{NO}_x$  by creating conditions that inhibit the  $\text{NO}_x$  formation reactions or that cause the  $\text{NO}_x$  formed to be reduced back to molecular nitrogen, while the gases remain in the high temperature furnace area. The add-on control systems inject an ammonia or urea reagent to chemically reduce the  $\text{NO}_x$  to molecular nitrogen in an area of the combustion process downstream of the furnace. Fuel switching involves the use of a fuel that inherently has low  $\text{NO}_x$  generating rates due to its combustion characteristics or fuel nitrogen characteristics.

### 2.3.1 $\text{NO}_x$ Control by Combustion Modifications

All of the combustion modifications attempt to suppress the formation of  $\text{NO}_x$  by controlling the peak flame temperatures, oxygen concentrations, and residence times in the active combustion zones. In essence, the distribution of the air and fuel is modified to reduce the rate of formation reactions and to create conditions that preclude these reactions. There are practical limits to essentially all of the combustion modification techniques for suppressing  $\text{NO}_x$  formation. These limits include carbon monoxide formation, increased combustible levels in the ash, boiler tube fouling, and corrosion.

A partial list of the combustion modifications which are used to reduce  $\text{NO}_x$  formation is provided below<sup>1</sup>:

- Effect of combustion air temperature
- Low excess air operation
- Off-stoichiometric or Two-stage combustion
- Effect of Furnace-burner configuration

- Flue gas recirculation
- Fuel-bound NO<sub>x</sub>

### 2.3.1.1 Effect of Combustion Air Temperature

In many industrial operations waste heat frequency is available to help preheat air entering a combustion process. The use of an air preheater in large-scale power plants is a typical example. Although this process leads to an appreciable energy savings, the added energy increase the flame temperature. Thus NO<sub>x</sub> emissions increase. Data from full-sized boiler tests indicate a threefold increase in NO<sub>x</sub> emissions when combustion air is preheated from 80 to 600 °F. A significant portion of the increase occurred in the upper range of temperature (from 450 to 600 °F), as expected from kinetic considerations.

### 2.3.1.2 Low Excess Air Operation

In a combustion system, a certain amount of excess air is required to ensure complete combustion of the fuel. The more efficient the burners are for air and fuel mixing, the less excess air is needed.

The level of excess air in an industrial or utility boiler will usually range from 3% to as high as 100%, depending on the type of fossil fuel and the boiler operating load. Gas-fired boilers can operate with excess air levels as low as 3-5% when the unit is near full load. Oil-fired units typically operate at excess air rates of 5-20%, depending on the type of oil and the load conditions. Pulverized coal-fired boilers operate at excess air rates of 20-50%. Obviously, the ability to utilize low excess air firing depends on the fuel characteristics. In essence, gas-fired boilers and most oil-fired boilers inherently use low excess air firing. In the case of pulverized coal-fired boilers, the ability to decrease excess air levels depends on the burner design characteristics, the variability of the coal quality, and the variability of the load.

Low excess air operation is not readily adapted to processes such as waste incinerators and spreader stoker boilers. In these cases, high excess air levels are needed for proper fuel burning on the grates.

Low excess air firing practices reduce NO<sub>x</sub> emissions by reducing the oxygen concentrations in the portion of the burner flame where gas temperatures are at a maximum. This inhibits the sets of reactions responsible for both thermal and fuel NO<sub>x</sub>. This method is easy to implement and actually slightly increases the efficiency of the furnace. However, there are problems with this combustion modification. Very low excess air firing can produce increased particulate and CO emissions, and fouling of boiler tube surfaces can occur if excess air levels are too low.

Low excess air firing practices are used in conjunction with other NO<sub>x</sub> combustion modification techniques. However, there are definite limits to the minimum excess air levels in these cases since minimum quantities of combustion air are needed for proper operation and other techniques based primarily on off-stoichiometric combustion.

NO<sub>x</sub> reductions averaging between 16% and 20% can be achieved on gas- and oil-fired utility boilers when the excess air is reduced to a level between 2% and 7%. NO<sub>x</sub> reductions averaging around 20% can be achieved on coal-fired utility boilers if the excess air is reduced to the 20% level<sup>1</sup>.

### 2.3.1.3 Off-Stoichiometric Combustion or Two-stage

During off-stoichiometric combustion, air and fuel mixtures are combusted in two separate zones. In one zone, the fuel is fired with less than a stoichiometric amount of air. This creates a fuel-rich local zone in the region of the primary flame. The second zone is an air-rich zone where the remainder of the combustion air is introduced to complete the combustion of the fuel. The heat in the primary flame zone is not as intense as with normal firing because combustion is incomplete. The air mixed with the fuel is sub-stoichiometric in the  $\text{NO}_x$  forming region of the flame, thus creating a low  $\text{NO}_x$  condition.

Staged combustion reduces  $\text{NO}_x$  emissions by a combination of several factors. First, a lack of available oxygen for  $\text{NO}_x$  formation in the fuel-rich stage is due to off-stoichiometric firing. Second, the flame temperature may be lower in the first stage than in single stage combustion. Third, the peak temperature in the second stage (air-rich) is lower. Staged combustion is an effective technique for controlling both thermal and fuel  $\text{NO}_x$  due to its ability to control the mixing of fuel with combustion air. The  $\text{NO}_x$  reduction effectiveness depends on good burner operation to prevent convective boiler tube fouling, unburned hydrocarbon emissions, and poor ignition characteristics that occasionally occur at excessively fuel-rich boiler operations. Fire-side boiler tube corrosion may occur when burning some coals or heavy oils under staged combustion conditions.

Staged combustion may be accomplished by using overfire air ports. These are separate air injection nozzles located above the burners. The burners are operated fuel-rich, and the overfire air ports maintain the remainder of the combustion.

In some boilers, a number of the burners are operated fuel-rich, and others are operated air-rich in a staggered configuration called biased firing. In the case where some burners are operated on air only, this modification is called burners-out-of-service.

On existing boilers, a steam load reduction will result with burners-out-of-service if the active fuel burners do not have the capacity to supply fuel for a full load. Most utility boilers installed since 1971 have been designed with over fire air ports so that all fuel burners are active during the staged combustion operation. Using staged combustion modifications on oil- and gas-fired boilers reduces  $\text{NO}_x$  emissions by approximately 30-40%. Modifying existing coal boilers has reduced  $\text{NO}_x$  emissions 30-50%<sup>1</sup>.

### 2.3.1.4 Effect of Furnace-burner Configuration

Burner configuration plays an important role in  $\text{NO}_x$  control. The highly turbulent cyclone-type coal burner, for example, leads to high  $\text{NO}_x$  concentrations. It is an example of a high heat-release rate device, which should be avoided. Tangential firing (units where heat sinks are in close proximity to the burner flame) has led to reported  $\text{NO}_x$  reduction of 50 to 60 percent over conventional firing techniques. The front-fired type of boiler has all burners on a single wall, while the Turbo-fired boiler is a modification of an opposed-firing furnace. Burner location is important due to the type of flame produced and the degree of turbulence involved<sup>8</sup>.

### 2.3.1.5 Flue Gas Recirculation

Flue gas recirculation (FGR) has been used to reduce thermal NO<sub>x</sub> emissions from large coal-, oil-, and gas-fired boilers. A portion (10-30%) of the flue gas exhaust is recycled back into the main combustion chamber by removing it from the stack and breeching and mixing it with the secondary air entering the windbox. In order for FRG to be effective in reducing NO<sub>x</sub> emissions, the gas must enter directly into the combustion zone. This recirculated gas lowers the flame temperature and dilutes the oxygen content of the combustion air, thus lowering NO<sub>x</sub> emissions.

Some operational problems can occur using flue gas recirculation. Possible flame instability, loss of heat exchanger efficiency, and condensation of partially oxidized compounds on internal heat transfer surfaces limit the usefulness of gas recirculation.

Flue gas recirculation requires greater capital expenditures than for low excess air and staged combustion modifications. High temperature fans (forced or induced draft), ducts, and large spaces are required for recirculating the gas.

NO<sub>x</sub> reduction of approximately 40-50% is possible with recirculation of 20-30% of the exhaust gas in gas- and oil-fired boilers. At high rates of recirculation (approximately 30%), the flame can become unstable, thus increasing carbon monoxide and partially oxidized organic compound emissions.

Studies have indicated that chemically bound nitrogen in hydrocarbon fuels, termed fuel nitrogen, is another major source of NO<sub>x</sub> formation. Wood and coal contain both chain and ring nitrogen-bearing compounds. It is significant that in most of these nitrogen-bearing organic compounds, the bonds between the nitrogen atom and the rest of the molecule are considerably weaker than the N-N bond in molecular nitrogen. Experiments have shown that the oxidation of fuel nitrogen is rapid. It is not surprising that fuel nitrogen can contribute large quantities of NO<sub>x</sub> in combustion process<sup>8</sup>.

These above mentioned combustion modifications are usually capable of reducing NO<sub>x</sub> levels 30 to 60% from the levels that would exist in less sophisticated combustion system designs. There are several practical limits to the combustion modifications. If the combustion conditions are altered too much, some partially oxidized organic compounds and CO can form due to impaired oxidation conditions. The combustion processes can also be either unstable or vulnerable to operating problems.

### 2.3.2 NO<sub>x</sub> Control by Add-on Controls

Due to the limitations of combustion modifications, add-on control systems are being developed to decrease NO<sub>x</sub> emissions below the levels possible by means of combustion modifications alone. There are two categories of the add-on control systems:

#### 2.3.2.1 Selective Catalytic Reduction (SCR)

SCR is a post-combustion process in which NO<sub>x</sub> in the flue gas is selectively reduced by reaction with ammonia (NH<sub>3</sub>) over a catalyst to produce nitrogen gas and water vapor. The optimum temperature range is 650 to 750°F, which corresponds to the temperature at the economizer outlet. SCR systems can be located between the economizer and air heater, between the hot ESP and air heater. The preferred location is between the economizer and air heater, which avoids the need to reheat the flue gas. NO<sub>x</sub> reductions of 80-90% have been achieved.

A number of issues affect SCR. Catalyst activity significantly influences SCR economics because catalyst cost constitutes 15-20% of the capital cost. Unreacted  $\text{NH}_3$  ( $\text{NH}_3$  slip) exiting the stack is undesirable, especially when firing high-sulfur fuels (0.5% of fuel), because SCR catalysts tend to oxidize  $\text{SO}_2$  to  $\text{SO}_3$  that can then react with  $\text{NH}_3$  to form ammonium bisulfate. The latter is a sticky solid that can corrode the SCR catalyst and plug downstream equipment such as air heaters. If the SCR unit were installed downstream of the FGD system, gas reheat would be required which would drive costs up.

### **2.3.2.2 Selective Noncatalytic Reduction (SNCR)**

Selective non-catalytic reduction (SNCR) injects either ammonia or urea into the flue gas within a temperature window of 1600°F – 2000°F to reduce  $\text{NO}_x$  to nitrogen and water. Multiple injection levels are used to maintain  $\text{NO}_x$  reduction efficiencies as the boiler load changes. At temperatures > 2000°F, ammonia and urea will react with oxygen to form additional  $\text{NO}_x$ . At low temperatures, excess ammonia can lead to formation of ammonium salts. SNCR typically removes 25 to 45% of the  $\text{NO}_x$  in the flue gas.

### **2.3.2.3 Add-on Controls: Conclusion**

SNCR is installed on one Washington wood-fired boiler. The installation was to meet LAER requirements. There are no wood-fired boilers using SCR.

## **2.4 Carbon-Monoxide:**

Carbon-monoxide emissions are controlled by employing “good combustion practices” (time-temperature-turbulence), also referred as best management practices (BMP). These practices include operational and incinerator design elements to control the amount and distribution of excess air in the flue gas to ensure that there is enough oxygen present for complete combustion. The design of modern efficient boilers is such that there is adequate turbulence in the flue gas to ensure good-mixing, a high-temperature zone (1600-1800 °F) to complete burnout, and a long enough residence time at the high temperature (one or two seconds). The lower the CO concentration, the more effective and complete is the combustion process. The feed to the combustor is controlled to minimize fuel spikes that lead to fuel-rich firing. Oxidation catalyst system can be employed as a CO control.

Good combustion practices also limit emission of PCDD/PCDF, PAH and other products of incomplete combustion exiting the boiler. This is accomplished by maintaining firing conditions that destroy any PCDD/PCDFs found in the fuel and by destroying organic compounds that lead to PCDD/PCDF precursors that may be formed from the combustion process<sup>9</sup>.

Good combustion practices, as a way to control carbon monoxide emissions, will be recommended for RACT consideration.

## **2.5 Dioxin**

Dioxin formation can be controlled by three major operations:

- Fuel characteristics
- Best combustion practices
- Activated carbon injection



### **2.5.1 Fuel Characteristics**

By maintaining fuel quality that would reduce or eliminate dioxin precursors, subsequent reduction or elimination of dioxin/furan formation can be achieved. In a supporting document, dioxin formation mechanisms and its emission factors for inland mixed wood residue (without and with salt-laden wood) burned without and with coal and bleached Kraft mill sludge is reported<sup>9</sup>.

### **2.5.2 Best Combustion Practices**

Dioxins and related compounds are byproducts of combustion formed by recombining other organic constituents and chemical reactions in the combustion effluent-gas stream. Generally, dioxins are formed in the cooler regions of the boiler flue gas, where condensation onto fly-ash particles can occur (deNovo synthesis and Deacon reaction mechanism). Certain metals can also act as catalysts and promote dioxin formation on the surfaces of fly-ash entrained in the gas stream<sup>6</sup>.

According to combustion studies, both dioxin and furan compounds contained in the fuel can be efficiently destroyed in combustors when the gas temperatures exceeds 1300 to 1400 °F. Locally this is demonstrated at the Spokane Municipal Incinerator Facility which meets the D/F limits in the permits and Federal Regulations with combustion control only<sup>10</sup>.

### **2.5.3 Activated Carbon Injection**

Facilities burning municipal waste, medical waste, and hazardous waste operating in Europe and USA have demonstrated that carbon injection is effective in removing dioxins from flue gases. The carbon injection (CI) system uses powdered activated carbon produced from reactivated granular coal-based carbons. The powdered carbon is injected into the system and adsorbs dioxins and other contaminants. The activated carbon is removed along with particulates and other solids in ESP/FFs. The collected fly ash and activated carbon is then disposed of with other plant solid wastes.

The CI system is more than 95 percent effective in reducing total dioxin emissions as shown in **Table 2**. The use of CI can also provide mercury-emission control if Hg is present. Capital investment costs for CI technology is similar to dry sorbent injection. In Europe, fixed-bed or entrainment-process systems, which require a several-million-dollar investment, are also used on incinerators<sup>7</sup>.

There is some question of the technical feasibility of CI on wood-fired boiler. No unit has been located that uses the control. However, the nature of the flue gas from wood-fired boiler is similar to the flue gas from municipal combustors. Carbon injection is a standard technique for D/F control worldwide. Thus, the use of CI is feasible.

### **2.5.4 Dioxins: Conclusion**

Presently, nobody uses dry carbon injection for dioxin control on wood-fired boilers. Carbon injection technology will move forward for further review. Maintaining fuel quality, and through good combustion practices dioxin/furan would be controlled. These techniques are

recommended and will move forward. A detailed review article on dioxin formation and its control is given in **Appendix E**.

**Table 3** summarizes above discussed technologies for controlling major pollutants of concern.

**Table 2.**  
**Collection Efficiencies of Various Control Technologies\***

<u>Control System(s)</u>	Collection Efficiency in Percent					
	Particulates	SO <sub>2</sub>	HCl	NOx	Metals	PCDD/Fs
Single Cyclone	50-90	-0-	-0-	--	40-80	20-40
Multi-clones	>90	-0-	-0-	--	80-90	25-50
Dry ESP	95.5 - 99.9	-0-	-0-	--	95-98	25-50
Wet ESP	95.5 - 99.9	80-95	85-98		95-98	25-50
SD/ESP	98.5 - 99.9	60-75	95-98		95-98	70-80
SD/FF	99.0 - 99.9	65-80	95-98		99+	90-99+
DI/ESP	98.5 - 99.9	60-70	(70 - 80)		95-98	(60-70)
DI/FF	99.0 - 99.9	70-80	80-90	---	99+	90-99+
SD/DI/FF	99.0 - 99.9	80-90	95-98	---	99+	90-99+
ESP/WS (1)	98.5 - 99.9	50-60	95+		95-98	(80-90)
ESP/WS(2)	98.5 - 99.9	90-95	(95+)		95-98	(90-99+)
SCR/SNCR				90+		
SD/CI/FF	99.0-99.9	85-95	(98+)		(99+)	(90-99+)

SD – Spray dryer; ESP – Electrostatic precipitator; FF – Fabric filter or Bag House, DI – Dry injection; WS – Wet scrubber (stage 1,2); CI- Carbon injection.

- Data obtained from studies on municipal and medical waste incinerators.

**Table 3.**  
**Summaries Technologies to be Considered for RACT Determination**

<b>Control Unit</b>	<b>PM</b>	<b>Acid Gases</b>	<b>CO</b>	<b>NO<sub>x</sub></b>	<b>D/F</b>
Multi-clones	√				√
Baghouse	√				√
Dry ESP	√				√
Wet ESP	√	√			√
Venturi Scrubber	√	√			√
Wet Scrubber	√	√			√
Dry Injection		√			√
Fuels and Good Combustion	√	√	√	√	√

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### **3.0 Control Cost, and Economic and Environmental Impacts Analyses**

After identifying and listing the available control options for all pollutants of concern, the next step is the determination of the energy, environmental, and economic impacts of each option and the selection of the final level of control for hogged fuel (wood and or combination wood-fired) boilers. First, economic impact analysis will be addressed. This analysis would address the economic impacts associated with the incremental costs of installing and operating alternative control systems above the economic impact associated with the system proposed as RACT. The calculated costs should also include all life-cycle costs necessary to install, implement, maintain, and operate RACT for the source category. Capital and expense costs are appropriate and include but are not necessarily limited to engineering, procurement, demolition, installation, operation, maintenance, utilities, insurance, taxes, and waste disposal. Costs should also include modifications to the process, such as using alternative materials or processes, if such modifications are necessary to achieve the required emissions reduction. All costs should be based on the life of the installation and should be reduced to an annualized cost for evaluation and comparison. Outlined below are economic considerations that address direct economic impacts on the firm. And towards the end of this report, impacts on local economic growth and/or socio-economic impacts will be addressed.

#### **3.1 Direct Economic Impacts on the Plant**

Direct economic impacts on the plant are mostly associated with the direct and indirect costs and total annualized cost. The total annualized costs for control systems is comprised of three elements: direct costs, indirect costs, and recovery credits. Direct costs are those which tend to be proportional to the quantity of exhaust gas processed by the control systems per unit time. These include costs for raw materials, utilities (steam, electricity, process and cooling water, etc.), waste treatment and disposal, maintenance materials, replacement parts, and operating, supervisory, and maintenance labor. Of these direct costs, costs for raw materials, utilities, and waste treatment and disposal are variable, in that they tend to be a direct function of the exhaust flow rate.

Semi-variable direct costs are only partly dependent upon the exhaust flow rate. These include all kinds of labor, overhead, maintenance materials, and replacement parts. Although these costs are a function of the gas flow rate, they are not linear functions. Even while control system is not operating, some of the semi-variable costs continue to be incurred. Indirect, or "fixed", annual costs are those whose values are totally independent of the exhaust flow rate, in fact, would be incurred even if the control system were shut down. They include such categories as administrative charge, property taxes, insurance, and capital recovery.

Annualized costs per ton of pollutant removal is the standard accepted by the USEPA and state/local air pollution control agencies as the gauge for determining economic justifiability of control technologies. The total annualized costs were computed using the EPA's air pollution control cost manual, and the control-cost spreadsheets<sup>1</sup>. The EPA control cost spreadsheets consider most aspects of cost evaluation, using operating parameters, design parameters, capital costs, and annual cost.

## 3.2 Particulate Matter

**Table 1** presents total annualized costs and costs per ton pollutant removed of particulate matter removed against exhaust gas flow rate and boiler steam capacity for four control options: (1) multi-cyclones (MC), (2) venturi scrubber (VS), (3) electrostatic precipitator (ESP), and (4) fabric filter (FF). Please note that capital costs due to auxiliary equipment (ductwork, etc) can vary significantly depending on each plant, and were not included in the annualized cost analysis. **Appendix A** presents total annualized cost for a chosen boiler exhaust flow rate at 18,685 dscfm. Cost effectiveness, or dollars per ton of pollutant reduction, is one of the key economic criterion used to determine if a control option is acceptable for use. Cost effectiveness is calculated as the TAC of the control option being considered divided by the baseline emissions minus the control option emissions rate.

The data in **Table 1** and **Figs. 1** and **2** indicate that the cost of removing PM would be less for both MC and VS compared to FF and ESP for smaller boiler (i.e., <3500 lb/hr) or lower exhaust flow rate (i.e., <150 dscfm). On the other hand, the cost of PM removal would be much greater for larger boilers (>15,000 lb/hr) using FF and ESP compared to MC and VS, respectively. It is also of interest to note that the annualized cost for the MC control option is higher than use of a VS for boiler sizes greater than about 200,000 lb/hr or flue gas flow rates greater than approximately 99,500 dscfm. In cost effectiveness calculations, PM removal efficiencies for MC, VS, FF, and ESP were 90%, 90%, 99.5% and 99.5%, respectively<sup>1,2</sup> (**Table 1**). In calculating the cost per ton of PM removal, it was assumed that particle laden exhaust gas from a typical hogged-fuel boilers has PM concentration of 4.0 gr/dscf<sup>1,13</sup>. Also assumed that 50% of this PM (mostly larger particles) in exhaust gas will be removed by a primary control, cyclone, before gas stream enters to a secondary control (i.e., MC, VS, ESP, and FF). Therefore, the exhaust gas out of the primary control (cyclone) entering to a secondary control unit typically has PM concentration equal to 2.0 gr/dscf (**Appendix B**).

### 3.2.1 Control Cost Effectiveness for Particulate Matter Emission Reduction

**Figure 3** presents the variations of cost effectiveness between four control options. As **Fig. 3** indicates that for lower flue gas flow rate (or smaller boiler size), VS control option would be the most expensive to operate, followed by FF, ESP, and MC. However, for higher flow rates (or for larger boilers), ESP would be the most expensive control option followed by FF, VS, and MC. **Appendix B** gives some detailed calculations on how tons per year and \$/ton-year numbers were derived for each and every PM control for a chosen flow rate (18,685 dscfm).

**Table 2** shows the levels of PM stack concentration for four control options. Amongst these levels of concentration, ESP and FF show the minimum emission level at 0.01 gr/dscf, while emissions from both VS and MC is 0.20 gr/dscf.

*Table 1*  
**Total Annualized Cost and Cost per Ton of PM Removals VS Flow Rate and Boiler Steam Capacity**

Flow Rate, dscfm	Steam, lb/hr	Cost, MC	Cost, VS	Cost, ESP	Cost, FF	T/Y,MC 90%	\$/TY, MC	T/Y,VS 90%	\$/TY, VS	T/Y,ESP 99.5%	\$/TY, ESP	T/Y,FF 99.5%	\$/TY, FF
1500	3500	18203	124592	66563	107370	101	180	101	1,229	112	594	112	958
6744	15000	37960	139485	147139	140647	456	83	456	306	504	292	504	279
18685	40000	82292	173398	296329	216415	1263	65	1263	137	1396	212	1396	155
21118	45000	91283	179983	320471	231852	1428	64	1428	126	1578	203	1578	147
67540	137776	264,428	298057	711959	595016	4566	58	4566	65	5045	141	5045	118
99478	200000	381768	376049	967426	797667	6725	57	6725	56	7431	130	7431	107
141109	280000	534321	475904	1316887	1061828	9539	56	9539	50	10541	125	10541	101
223023	435000	833661	668958	1996247	1581600	15076	55	15076	44	16660	120	16660	95
268464	520000	999392	774805	2355281	1869935	18148	55	18148	43	20054	117	20054	93
311500	600000	1156191	874473	2690738	2143013	21057	55	21057	42	23269	116	23269	92
365608	700000	1353146	999146	3107276	2486341	24715	55	24715	40	27311	114	27311	91

Assuming Grain Loading in the Boiler Exhaust Gas Stream = 4.0 gr/dscf

Multi-cyclone (MC) Efficiency = 90%

Venturi Scrubber (VS) Efficiency = 90%

Electrostatic Precipitator (ESP) Efficiency = 99.5%

Fabric Filter (FF) Efficiency = 99.5%

### **RACT Recommendation for PM Concentration**

**Table 2** presents stack concentrations of PM for four primary control technologies under the current RACT evaluation. The concentration values indicate that ESP and FF could both represent RACT for PM. Both controls are able to remove equivalent PM, as well as metals and dioxin at a reasonable cost. On the other hand, MC control option has the least capability to remove PM at the level capable of meeting the current standards for PM. Therefore, it is recommended that PM concentration would be in the range of **(0.01-0.20 gr/dscf)**.

**Table 2**  
**Stack Concentration Variation for Four PM Control Systems**

Control Systems	PM Concentration at Stack, gr/dscf
MC	0.20
VS	0.20
ESP	0.01
FF	0.01

### **3.2.2 Impact Analysis of PM Controls**

This section outlines the types of impacts that considered in this RACT determination. The energy and environmental impacts of alternative control systems are assessed.

#### **3.2.2.1 Energy Impact**

Energy impacts address the overall energy use associated with a control system and the direct effects of such energy use on the facility and the local community. Some specific considerations

for energy impacts would include energy consumption, impacts due to scarce fuels, locally available coal, wood, or any other fuel sources. To help make some assessments on energy impacts, some data have been gathered and presented in **Table 3**.

**Table 3**  
**Data for Different Fuels**

Fuels	MBtu/ton	Market Value, \$/ton	Reference
Wood (hard & soft)(dry)	18	33	APTI 427
Sludge (dry)	15	--	NCASI 580
Sludge (50% Moisture)	12	--	APTI 427
Paper Deinking Fiber	15	--	APTI 427
Coal (average)(dry)	20	30	APTI 427
Oil (#2)	39	300-450	APTI 427
Natural gas	44	160	APTI 427

**Table 3** shows that wood and coal are pretty even in terms of MBtu/ton and \$/ton. However, oil would be most expensive next to natural gas to replace wood, deinking fiber and sludge, considering its Btu and market values. It is important for any specific source to plan for alternative energy sources. Due to location of a specific plant, some of these fuel sources might not be available. Acquiring alternative fuels might add unreasonable costs, and these should be considered in an overall cost estimation. Another example of unusual circumstance might be the unavailability of water needed for a scrubbing system at a particular plant. Acquiring water might be an unreasonable cost for a specific facility, thereby justifying eliminating the use of a wet scrubber option on economic grounds at that facility.

### 3.2.3 Multi-media Environmental Impacts

This section discusses some factors to evaluate the potential for an adverse other media impact. Potential air quality impact, including human health effects and visibility, determined by air quality modeling, are addressed in a separate section of this RACT determination report.

#### 3.2.3.1 Impacts Due to PM Control and Emission

For some facilities, total PM emissions may be drastically reduced due to installation and operation of an improved PM control system. And due to this, long-term visibility and other environmental impacts in the region will be minimized. However, fine PM matter includes acidic compounds such as chlorides, sulfates and nitrates which contribute to acid deposition when removed from the atmosphere by dry and wet deposition. Some of these fine aerosols, principally sulfate and nitrate absorb and scatter light contributing poor visibility.

The NAAQS for PM<sub>10</sub> consist of an annual arithmetic mean not to exceed 50 µm/m<sup>3</sup>, and a 24-hour standard of 150 µm/m<sup>3</sup>, not to exceed more than once per year. The Washington State ambient air quality standard for PM<sub>10</sub> are identical to the federal standards.



### 3.2.3.2 Water Impact

Wet scrubbing systems and wet ESPs need water to operate. Water is lost through evaporation and entrainment in the scrubber and through routine discharges necessary to keep the scrubber water chemistry under control. Amount of water needed in scrubber, gas absorber, and wet ESP depends on the exhaust gas flow rate and exhaust gas temperature. Amounts of wastewater generated for different gas flow rates are estimated (EPA, 1996) and these data are given in the following **Table 4**.

**Table 4**  
**Water Feed Rate**

Gas Flow Rate dscfm	Water Flow Rate gpm
1,500	15
6,744	67
18,685	187
21,118	211
67,540	675
99,478	995
141,109	1,411
223,023	2,230
268,464	2,684
311,500	3,115

[Note: liquid-to-gas ratios in typically range between 8-10 gallons of water per 1000 cfm, pp. 258 (ref. 13)]

The facility would need to treat this wastewater for re-use; surface or subsurface water discharge.

### 3.2.3.3 Solid Waste Disposal

**Table 5**  
**Amount of Ash Generated at Different Size Boilers**

Gas Flow Rate, dscfm	Fly Ash Generated*, tons/yr	Total Ashes** (Fly & Bottom), tons/yr
1,500	224	784
6,744	1,008	3,528
18,685	2,792	9,772
21,118	3,155	11,043
67,540	10,092	35,322
99,478	14,864	52,024
141,109	21,085	73,798
223,023	33,324	116,634
268,464	40,114	140,399
311,500	46,544	162,904
365,608	54,629	191,202

\* - based on grain loading of 4.0 gr/acfm & maximum of overall 99.5% PM removal

\*\* - approximately 30% & 70% ash distribution between fly and bottom ashes<sup>6</sup>.

The ash content is 0.2-0.5% by weight for temperate woods. The principal elemental components of wood ash are calcium and potassium with lesser amounts of magnesium, sodium, manganese, and iron. Carbonate, phosphate, silicate, oxalate, and sulfate are likely anions<sup>4</sup>. Amount of fly and bottom ashes generate from hog-fuel boiler would depend on the type and composition of the fuels – wood species, corrugated box, recycled papers, fiber, sludge generally produce more ash than wood (due to filler materials used in paper manufacturing). According to pulp and paper mill hog-fuel boiler operation in Washington, about 2-3 % by weight of total ash is generated per ton of bone dry wood combusted<sup>5</sup>. Table 5 gives some estimated values of ash typically generate at various size boilers using wood fuel.

Wood fly ash usually contains trace amounts of dioxin. In recent years, more information has become available on the sources of dioxin, its impacts on human health and the environment, and the levels of dioxins in Washington State soils as well as various materials such as wood ash that are commonly spread on the land. However, Ecology's recent study showed that Washington's average soil dioxin level of 1.4 parts per trillion (pptr) appears to be well below the national average of 8 pptr as reported by the US EPA.

Due to its high pH (12.0 or above) wood ash is a corrosive material and sometimes it also has elevated levels of metals. As a result of these characteristics, wood ash is sometimes considered a hazardous waste. However, since 1994, a wood ash to be disposed in solid waste landfills rather than the more costly (out of state) hazardous waste landfills, or it can be applied to the land as a soil pH adjustment mechanism commonly called a "liming agent". The low pH (acidic) of some Washington soils require neutralization with a high pH material to improve productivity. Besides land application and soil amendment, other beneficial uses including, construction (especially bottom ash).

The quantity and quality of ash and other solid waste (e.g., sludge, biosolids, etc) that must be stored and/or disposed of or recycled or applied for some beneficial usage (e.g., fertilizer, soil amendment, cement production) are reported to Ecology. Historically, ash generated at all wood-fired and hog-fuel boiler facilities in Washington were managed or disposed in several ways, including on-site and off-site landfill, used as fertilizer, and other beneficial use.

**Appendix C** presents a summary of all ash production and handling at facilities with wood fired boilers in Washington<sup>11</sup>. The composition and other characteristics of ash and other solid waste (such as permeability, water retention, rewatering of dried materials, leachability of dissolved ions, pH, ability to support vegetation growth and hazardous characteristics) which are significant with regard to potential surface or ground water pollution need to be considered. On average, ash landfill disposal cost in Washington is \$77 per ton<sup>5,11</sup>.

### **3.2.3.4 Toxic Air Pollutants (TAPs) Consideration**

The complete list of pollutants of concern developed for the Pollutant of Concern Selection Process includes toxic air pollutants. For wood and combination of wood-fired boilers (hogged fuel), emissions of TAPs can be simply categorized into three categories identified as: (1) dioxin; (2) metals; and (3) others. Many of these TAPs, e.g., dioxins and metals, emitted from hogged fuel boilers are contained in or on the fly ash. Usually, fly ashes released during combustion are collected by PM control devices.

Ashes resulting from the combustion of wood residues in industrial boilers were characterized relative to PCDD/Fs and trace metals, and the results were summarized from various studies and reported by Someswar<sup>6,7</sup>. In an earlier report by Das<sup>8</sup> suggested that for combustion of inland wood residue or wood fuel with very low levels of chloride content (<0.03%, the PCDD/Fs level in the ashes is of no concern. However, higher levels of chloride in the fuel mix from whatever additional source (salt water, bleached kraft mill sludge, etc) have the potential to create higher levels of PCDD/Fs in ash. This report also summarized PCDD/Fs emission factors (reported as ng/kg of fly and bottom ash) for various fuel mix: (1) inland wood, bark, (2) wood, bark, bleached kraft mill (BKM) sludge, (3) wood, bark, BKM sludge, coal, oil, natural gas, and (4) salt-laden wood.

Das and Mahalingam<sup>9</sup> identified and investigated aspects of ash deposition and trace metals scavenging by ash particles and air toxic pathways in coal-fired boiler downstream operation. In particular, problems relating to condensation/nucleation, phoretic phenomena, and coagulation of metal species contained in the exhaust gas and ash particles were examined, using a previously developed code AEROSOL. This analysis thus tracks the fate of metals in entrained, deposited and emitted flyash. Some descriptions of each pathway and the process of scavenging PCDD/Fs and metals on ash particles are reviewed and described by Das<sup>10</sup>. These reports concluded that almost all of PCDD/Fs and trace species generated at post-combustion periods were scavenged by fly ash particles; and moreover, their concentration levels on ash particles were low enough, or some cases below detection and ash quality meets current regulatory criteria for landfill and/or land application<sup>6,7</sup>.

### 3.2.3.5 CO Emission

CO concentrations can vary significantly hour to hour depending on numerous factors. CO emissions depend combustion management practices. Many factors affect CO and combustion efficiency such as: excess air levels, boiler cleanliness, flame temperatures, fuel feed rate, fuel composition, fuel moisture contents, firing practices, primary air flow rates, boiler design, and boiler operation and maintenance. Many of the factors that influence NO<sub>x</sub> generation in a boiler also influence CO.

In general, high CO emission rates are indicative of poor combustion. Poor combustion results in increased fuel consumption problem due to soot deposition on boiler tubes and more fuel cost for the facility. Unless a facility is “fuel poor” with excess boiler capacity there is no substantial economic incentive for the boilers to be operated at maximum combustion efficiency. Maximum combustion efficiency is also indicated by low CO emissions. This point demonstrates the importance of having a continuous emission monitor (CEM) for CO to ensuring efficient operation for each boiler. Each boiler should be equipped with two CO CEMs. One CO monitor is to be installed as part of the stack gas monitoring equipment; the other one is to be installed in the boiler discharge duct. This CEM system will be used by each facility operator to ensure good combustion practice is maintained

The Federal and State ambient air quality standard for CO is 9 ppm – 8 hour average and 35 ppm – 1 hour average (9 ppm is equivalent to 10,000 µg/m<sup>3</sup>, 35 ppm is equivalent to 40,000 µg/m<sup>3</sup>). The emission factor for CO is obtained from AP-42 Section 1.6<sup>12</sup> presented in **Table 6**. These emission factors for CO will be used to assess maximum ambient air concentration within a

certain miles of any specific plant predicted by **SCREEN** model. The **SCREEN** modeled values of highest ambient concentrations are used for comparison with the federal and state ambient air quality standards, as well as to evaluate any health concern for populations around a model plant.

In summary, proper furnace design and good combustion control is RACT for carbon monoxide.

### 3.2.3.6 **NO<sub>x</sub> Impact and Control**

Nitrogen oxides (NO<sub>x</sub>) consists of nitrogen dioxide (NO<sub>2</sub>) and nitric oxide (NO). Although both nitrogen oxides are emitted from combustion processes. NO rapidly converts to NO<sub>2</sub> so total NO<sub>x</sub> is often measured as NO<sub>2</sub>. The National Ambient Air Quality Standard (NAAQS) for nitrogen dioxide is 0.053 ppm (100 µg/m<sup>3</sup>) annual average. The Washington State has established a standard with only two decimal places of 0.05 ppm (also 100 µg/m<sup>3</sup>) annual average. Emission factors for NO<sub>x</sub> were obtained from AP-42 Section 1.6<sup>12</sup>. The data indicate that emission factor for dry wood fired boilers is more than twice compared to three other fuel-based boilers. Uncontrolled NO<sub>x</sub> emissions from wood-waste boilers are typically less than 200 ppmv<sup>13</sup>.

These emission factors for NO<sub>x</sub> will be used to assess maximum ambient air concentration within a certain miles of any specific plant predicted by SCREEN model. The SCREEN modeled values of highest ambient concentrations are to be used for comparison with the federal and state ambient air quality standards, as well as to evaluate any health concern of population around a plant.

Primary controls for NO<sub>x</sub> were discussed in section 2 of this report<sup>17</sup>. Combustion process modifications reduce emissions of NO<sub>x</sub> by limiting the amount produced during the combustion process. This is accomplished through operational modifications such as boiler tuning and low excess air operation, and by design modifications such as low NO<sub>x</sub> combustion firing systems for gas, oil and pulverized coal, advanced combustion process, gas co-firing, gas conversion, and re-burning.

Furnace modifications such as overfire air, staged combustion and gas reburning can prevent the formation of NO<sub>x</sub>. These modifications can include additional overfire air ports, which divert approximately 20 percent of the total combustion air to a secondary burning zone above the wind box, thus creating a fireball at or near stoichiometric air conditions. This extends the duration of the primary combustion zone so a greater portion of the devolatilization will take place before entering the fireball, thus reducing thermal NO<sub>x</sub> production.

With gas reburning, natural gas is usually injected directly into the primary combustion zone to reduce the availability of oxygen. A significant portion of NO<sub>x</sub> precursors decompose and form other harmless nitrogen species. Overfire air is injected high enough in the furnace to allow sufficient residence time for the reburning reactions to reduce NO<sub>x</sub> and its precursors.

Flue gas recirculation (FGR) is another common and accepted method of NO<sub>x</sub> reduction. FGC primarily counteracts formation of thermal NO<sub>x</sub>, and is ineffective on boilers where NO<sub>x</sub> emissions originate from conversion of fuel-bound nitrogen. For wood and combination wood fuel boilers, the primary source of NO<sub>x</sub> is from combustion of nitrogen compound in the fuel rather than from the combustion air. Fuel NO<sub>x</sub> is formed as nitrogen contained in the wood and combination wood fuels is driven off in the volatilization process and comes in contact with

oxygen in the combustion air. This NO<sub>x</sub> formation reaction occurs very quickly. Fuel NO<sub>x</sub> formation can be suppressed by the delay mixing of fuel and air, allowing fuel-nitrogen compounds a greater residence time in fuel-rich conditions. But this is not applicable for wood-fired units, very few (if any) are suspension burners. It is important to keep in mind that good operating practices can be employed with any technology-based NO<sub>x</sub> control method<sup>13,14</sup>.

In summary, proper furnace design and operation is RACT for NO<sub>x</sub>.

### 3.2.3.7 Sulfur Dioxide and Sulfuric Acid

Sulfur dioxide is a colorless gas having the chemical formula, SO<sub>2</sub>. It is moderately soluble in water and aqueous liquids. It is formed primarily during the combustion of a sulfur-containing fuel or waste. Once released to the atmosphere, SO<sub>2</sub> reacts slowly to form sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), inorganic sulfate compounds, and organic sulfate compounds. A small fraction of the fuel sulfur remains in the bottom ash leaving the combustion processes. Almost all sulfur is converted to SO<sub>2</sub> which remains in the gaseous form throughout the combustion system. A small fraction of the SO<sub>2</sub> generated in the combustion zone is oxidized further to form sulfur trioxide (SO<sub>3</sub>). SO<sub>3</sub> concentrations are usually 0.5 to 2 percent of the SO<sub>2</sub> concentration<sup>1</sup>. All sulfur dioxides have gross atmospheric effects, including the generation of smog and tree damage. There are a number of cost effective control technologies for controlling SO<sub>x</sub>, including low sulfur content fuel, venturi scrubber, wet ESP, absorption and adsorption. A detailed description of each control technology is given in a supporting document titled: Qualitative Analysis of Control Technologies.

For clean wood burning, SO<sub>2</sub> emission rates are negligible. Fuels with high sulfur content like coal, fuel oil, and Kraft mill sludge burning results in SO<sub>2</sub> emission rates that are based on the fuel sulfur contents. It is also important to mention that the presence of sulfur (S), as well as chlorine (Cl) and the ratio of (S/Cl) in the feed-stocks can decrease the downstream formation of chlorinated organic compounds, particularly dioxins and furans. Thus, co-firing municipal solid waste or combination wood waste with coal, because S species from coal, may reduce dioxins/furans emissions (Das).

In summary, burning of low sulfur content fuels to control SO<sub>x</sub> would be the proposed RACT.

**Table 6**  
**Total Annualized Cost and Cost per Ton of Acid Gases Removals**  
**VS Flow Rate and Boiler Steam Capacity**

Flow Rate, dscfm	Steam, lb/hr	Cost, GA	T/Y, GA 99%	\$/T, GA
1500	3500	52831	39	1349
6744	15000	125487	176	713
18685	40000	283330	488	580
21118	45000	329452	551	598
67540	137776	926322	1763	525
99478	200000	1242614	2596	479
141109	280000	1734343	3683	471
223023	435000	2698592	5821	464

268464	520000	3232344	7007	461
311500	600000	3737327	8130	460
365608	700000	4371668	9542	458

Gas Absorber (GA) Efficiency = 99%

**Table 6** presents the total annualized cost and cost effectiveness for acid gases (mostly SO<sub>x</sub> and small amount of HCl) using gas absorber (GA) as a viable control option. **Figure 4** shows the variations in cost effectiveness in dollar per ton vs flue gas flow rate for controlling acid gases. **Table 6** and/or **Fig. 4** also show that for low exhaust flow rates (or smaller boiler) costs per ton of acid gases removal are much higher compared to cost per tons for higher flow rate (or larger boiler size). However, there was an exception computed data displayed in **Table 6** which indicates that at 21,118 dscfm, the cost effectiveness was lower (598 \$/ton) compared to 581 \$/ton at 18,685 dscfm.

### 3.2.3.8 Volatile Organic Compounds (VOCs)

With proper design and operation of the hog fuel boiler, almost all VOCs will be destroyed during combustion at a very high temperature zone, and in only trace amounts of VOCs will be emitted at stack due to condensation. VOCs are the results of incomplete combustion and are virtually eliminated when the boiler is designed and operated properly. In summary, proper design and operation is considered RACT for VOCs for hog fuel boilers.

### 3.2.3.9 Contribution of NO<sub>x</sub>, SO<sub>x</sub> and VOCs to Ozone/Smog in Urban Areas

Nitrogen oxides and volatile organic compounds (VOC) are precursors of tropospheric (ground level) ozone, a criteria pollutant that reduces lung function, damages the respiratory system, and sensitizes the lungs to other irritants at high enough concentrations. It should be noted here that most VOC compounds are destroyed in the high temperature operating zone of the boiler; however, some trace amounts of certain VOC species (due to incomplete combustion) will condense in the exhaust system.

### 3.2.3.10 Visibility Impairment

The Clean Air Act established a national visibility protection goal of preventing any further and remedying of any existing impairment of visibility in Class I federal areas in which impairment results from anthropogenic pollution. Both  $\text{NO}_x$  and  $\text{SO}_x$  contribute to regional haze and disturbance of the biochemical cycling of other nutrients and metals in eco-systems. Nitrogen deposited on the land contributes to the land becoming nitrogen-saturated causing more available nitrogen to run off into nearby waters leading to increased acidification of both the soils and waters. Increased nitrate nitrogen removes calcium and magnesium from soil<sup>14,15</sup>.

Sulfates and nitrates are secondary aerosols formed from conversion of  $\text{SO}_2$  and  $\text{NO}_x$  to particulate form. The rates of conversion in the atmosphere depends upon a number factors, including weather conditions, relative humidity and availability of chemicals like ammonia in the atmosphere<sup>16</sup>. Both sulfate ( $\text{SO}_4$ ) and nitrate ( $\text{NO}_3$ ) aerosols are considered to be  $\text{PM}_{2.5}$  (particles of diameter less than 2.5  $\mu\text{m}$ ). In presence or in absence of humidity, these fine aerosols in atmosphere absorb and scatter lights that can cause poor visibility in the region.

### 3.3 Emission Rate and Ambient Impact Concentration by Dispersion Modeling

Air quality impact analyses are carried out using Gaussian dispersion models – models that use the basic assumption of Gaussian dispersion. There are several such models, and different models are applicable to different source types and terrain.

The primary reference for selection of models is EPA's *Guideline on Air Quality Models*.<sup>18</sup> It identifies the models that have been developed and validated by EPA and are considered reliable for use in determining ambient air quality. The most commonly used model is SCREEN 3, which has been used for this project.

**SCREEN3** is the latest (1995) version of an EPA model used to screen sources for potential worst-case concentrations SCREEN is a very easy-to-use model that can be applied to a single source and provides estimates of the worst-case (highest) impacts expected from that source's emissions. If the generally conservative results obtained with SCREEN3 are able to demonstrate that impacts from a proposed project are insignificant, no additional modeling is typically needed. SCREEN3 allows estimates of pollutant concentrations to be made for a single point or area source in areas of flat to complex terrain. In dispersion modeling terms, complex terrain is defined as terrain whose elevation exceeds the release height of the sources being modeled.

**Table 7** presents the results of modeled estimated emission rates at stack condition in gram per second for  $\text{NO}_x$ ,  $\text{SO}_2$ , and CO. The emission rates were based on the EPA's AP-42 Section 1.6 for wood waste combustion in boilers<sup>12</sup>. These emission rates for  $\text{NO}_x$ ,  $\text{SO}_2$ , and CO were calculated for the entire range of stack flow rates, including small, medium and large facilities. These data will be used to evaluate ambient concentrations for 24-hr and yearly average using the 1-hr ambient concentration predicted by the SCREEN-3 model (**Appendix D**). **Table 8** presents the maximum 1-hr ambient concentration (based on 1.0 g/s) obtained by dispersion modeling for the hog fuel boiler stack conditions at Daishawa, Simpson Tacoma, Simpson Shelton, Grays Harbor Paper Number 6, and Grays Harbor Paper Number 8. These estimated

data give some idea about what pollutant concentration will be at a varying distance from the stack. For example, at Daishawa stack flow rate of 1500 dscfm and at a distance of 100 meter from the stack, the modeled, ground level NO<sub>x</sub> ambient concentration would be 0.33E-04 µg/m<sup>3</sup> (based on 1.0 g/s emission rate). The model estimated ambient concentration would then be a multiplied factor of emission rate presented in **Table 7**.

The stack information and data used to run the SCREEN model were obtained from the Olympic Air Pollution Control Authority and Ecology's Industrial Section. The techniques used in the dispersion modeling analysis are consistent with the U.S. EPA procedure<sup>18</sup>. The EPA's guideline for determination of good engineering practice stack height for determining whether building downwash will occur or not was followed. Stack located more than 5L (where L is building's height or projected width) from the building are not subject to the effects of building downwash. For all mills concerned, no downwash or elevated terrain effects on ambient air concentrations were considered. It should be noted that any downwash of the plume can result in elevated ground-level concentration.

The SCREEN model also predicted a pollutant's maximum concentration at a given distance under a set of stack condition and meteorological condition. **Table 9** presents the predicted maximum concentration at Daishawa, Simpson Tacoma, Simpson Shelton, Grays Harbor Paper Number 6, and Grays Harbor Paper Number 8 boilers. To obtain a running 24-hr average and the yearly average, 1-hr maximum concentration value was multiplied by 0.4 and 0.1, respectively<sup>19</sup>.



**Table 7**  
**Modeled Estimated Stack Emission Rates in g/s for PM, NO<sub>x</sub>, SO<sub>2</sub>, and CO**

Stack Flow, dscfm	PM, g/s	NO <sub>x</sub> g/s	SO <sub>2</sub> g/s	CO g/s
1500	0.07	0.5	0.4	0.5
6744	0.29	2	2	2
18685	0.81	6	5	6
21118	0.91	7	5	7
67540	2.92	21	17	22
99478	4.30	31	25	33
141109	6.10	43	35	46
223023	9.64	69	56	73
268464	11.61	83	67	88
311500	13.47	96	78	102
365608	15.81	113	91	120

Based on Stack Concentrations: PM = 0.04 gr/dscf; NO<sub>x</sub> = 500 ppmv; SO<sub>2</sub> = 200 ppmv; CO = 600 ppmv,  
Av. (MW)<sub>NO<sub>x</sub></sub> = 31.6; (MW)<sub>SO<sub>2</sub></sub> = 64; (MW)<sub>CO</sub> = 28 g/s = 4.3x10<sup>-5</sup>\*dscfm (for PM) g/s = 1.9455x10g/s =  
1.946x10<sup>-8</sup>\*dscfm\*MW\*ppmv (for gases)

**Table 8**  
**SCREEN3 Model Output at 1.0 g/s Pollutant Emission Rate and Predicted Concentration at Varying Distances for Five Facilities**

Distance, M	Daishowa 1-hr Conc. (µg/M <sup>3</sup> )	Simpson Tacoma 1-hr Conc. (µg/M <sup>3</sup> )	Simpson Shelton 1-hr Conc. (µg/M <sup>3</sup> )	Grays Harbor Paper #6 1-hr Conc. (µg/M <sup>3</sup> )	Grays Harbor Paper #8 1-hr Conc. (µg/M <sup>3</sup> )
100	0.33E-04	0.26E-07	0.16E-01	0.75E-02	0.91E-07
500	6.69	1.71	7.63	9.19	5.45
1000	5.44	3.22	6.09	8.14	5.20
1500	4.82	2.43	4.76	6.34	3.87
2000	4.17	1.94	4.05	5.77	3.61
2500	3.67	1.74	3.55	5.22	3.13
3000	3.41	1.71	4.07	5.14	3.00
4000	3.31	1.43	4.61	5.55	2.69
5000	3.43	1.30	4.60	5.34	2.33
6000	3.39	1.29	4.43	4.99	2.17
7000	3.26	1.21	4.20	4.62	2.19
8000	3.09	1.11	3.95	4.26	2.15
9000	2.92	1.04	3.85	4.09	2.08
10000	2.75	1.06	3.77	3.96	2.00

**Table 9**  
**1-hr Maximum Ambient Concentration Predicted by the SCREEN Model**

Facility	Distance at Maximum Conc., M	Maximum 1-hr Conc., µg/M <sup>3</sup>
Daishowa	458	6.85
Simpson Tacoma	928	3.28
Simpson Shelton	420	7.96
Grays Harbor #6	354	9.94
Grays Harbor #8	720	6.34

Fig. 1 Flue gas Flowrate VS Annualized Control Cost for PM

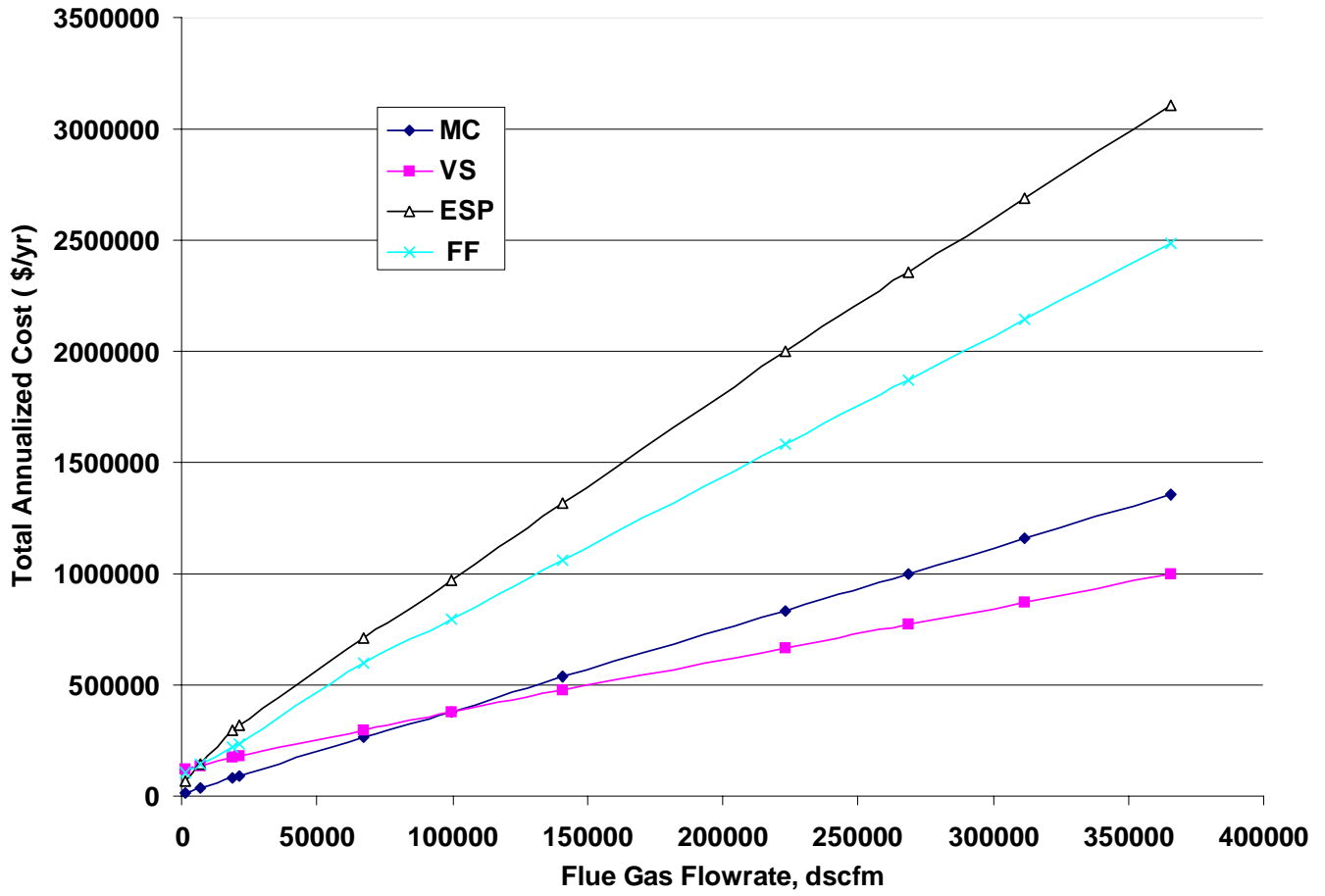
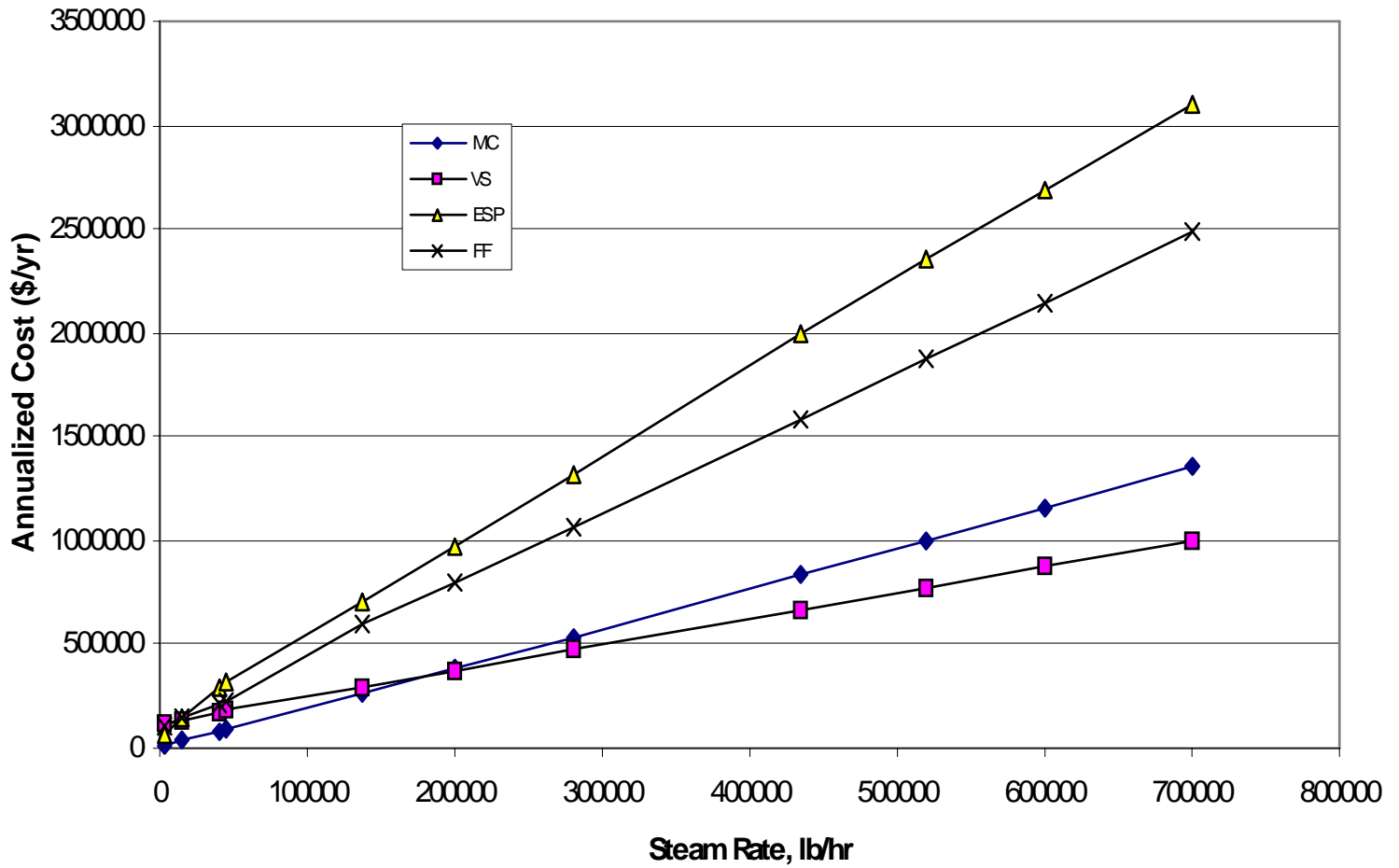
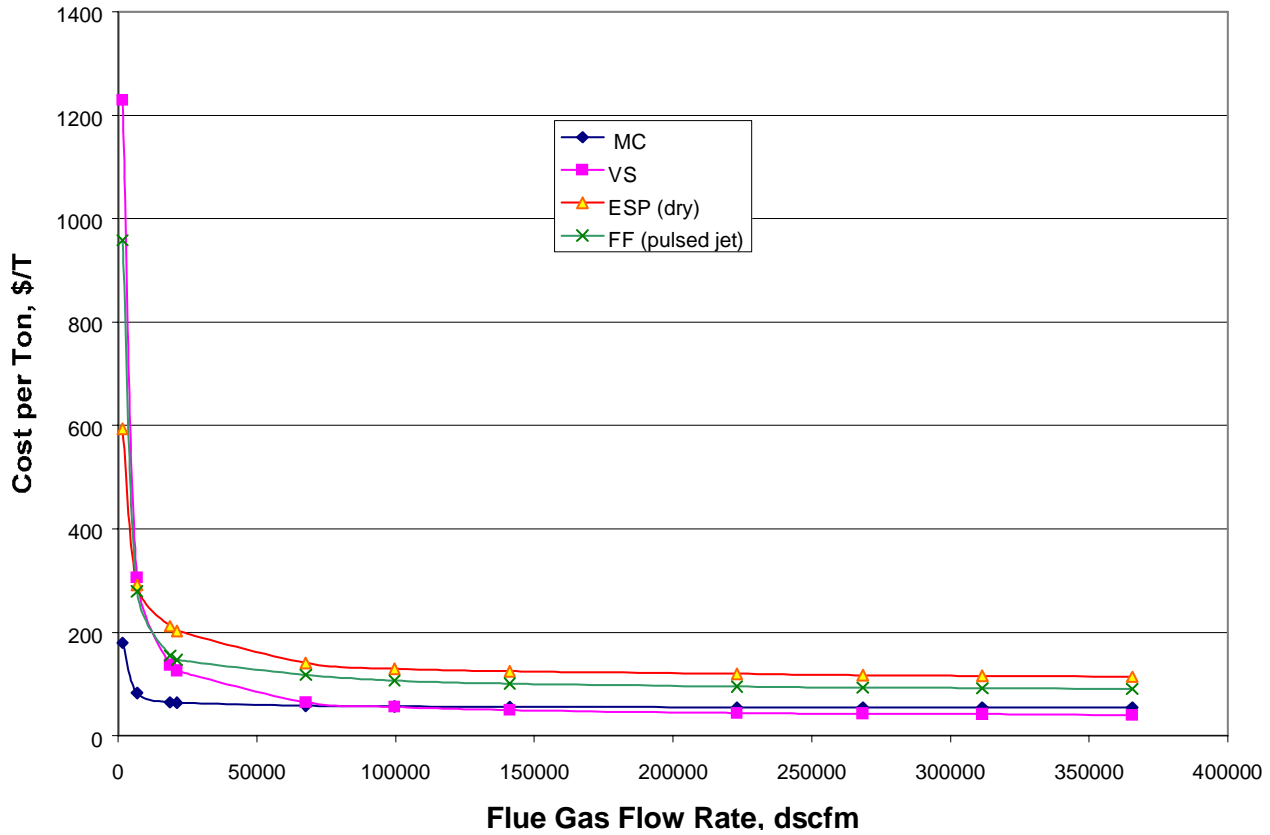


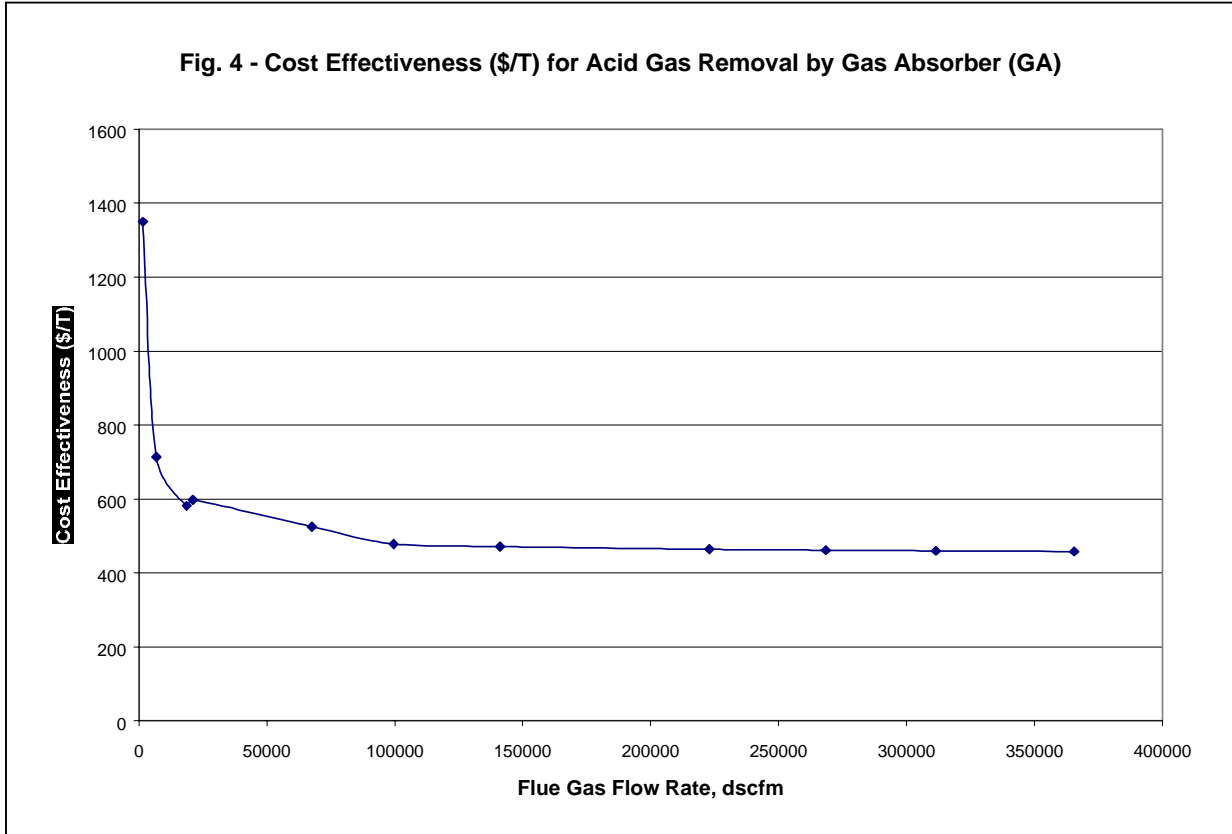
Fig. 2 - Steam Rate VS Annualized Control Cost for PM





**Figure 3 - Flue Gas Flow Rate VS Cost Effectiveness for PM Using Four Control Technologies**





## APPENDIX A

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### TOTAL ANNUAL COST SPREADSHEET PROGRAM--MECHANICAL COLLECTORS [1]

COST BASE DATE: August 1988 [2]

VAPCCI (Fourth Quarter 1998--FINAL): [3] 116.5

#### INPUT PARAMETERS

-- Inlet stream flowrate (acfm):	<b>18,685</b>
-- Inlet stream temperature (oF):	100
-- Inlet gas viscosity (lb-ft/min):	0.044
-- Particle density (lb/ft3):	1000
-- Gas density (lb/ft3):	0.0709
-- Cyclone inlet velocity (ft/min):	5000
-- Inlet dust loading (gr/scf): [4]	4.00
-- Overall control efficiency:	0.900
-- Material of construction (see list below):[5]	1

#### DESIGN PARAMETERS

-- Cyclone pressure drop (in. w.c.):	5.90
-- Cyclone inlet area (ft2):	3.737
-- Critical particle diameter (microns):	82.6

#### CAPITAL COSTS

Equipment Costs (\$): [6]	
-- Mechanical collector	21,441
-- Rotary air lock	3,100
-- Auxiliaries (ductwork, etc.)	0
-- Total (base)	24,541
' (escalated)	32,533
Purchased Equipment Cost (\$):	35,135
Total Capital Investment (\$):	43,919

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#### ANNUAL COST INPUTS

Operating factor (hr/yr):	8000
Maintenance labor rate (\$/hr): [7]	14.26
Maintenance labor factor (hr/sh):	0.25
Electricity price (\$/kWhr):	0.059
Dust disposal cost (\$/ton):	20
Overhead rate (fractional):	0.60
Annual interest rate (fractional):	0.07
Control system life (years):	20
Capital recovery factor (system):	0.0944
Taxes, insurance, admin. factor:	0.04

ANNUAL COSTS				
Item	Cost (\$/yr)	Wt.Fact.	W.F. (cond.)	
Maintenance labor	3,5 65	0.044	----	
Maintenance materials	3,5 65	0.044	----	
Electricity	9,4 05	0.116	----	
Overhead	4,2 78	0.053	0.140	
Taxes, insurance, administrative	1,7 57	0.022	----	
Capital recovery	4,1 46	0.051	0.073	
-----				
Total Annual Cost (w/o dust dispos.)	27, 72 4	0.329	0.329	
Dust disposal	54, 56 8	0.671	0.671	
-----				
<b>Total Annual Cost (w/dust disposal)</b>	<b>82, 29 2</b>	<b>1.000</b>	<b>1.000</b>	

Notes:

- [1] Data used to develop this spreadsheet were taken from the book ESTIMATING COSTS OF AIR POLLUTION CONTROL (CRC Press/Lewis Publishers, 1990).
- [2] Base equipment costs reflect this date.
- [3] VAPCCI = Vatavek Air Pollution Control Cost Index (for mechanical collectors) corresponding to year and quarter shown. Base equipment cost, purchased equipment cost, and total capital investment have been escalated to this date via the VAPCCI and BLS data.
- [4] Measured at 70 oF and 1 atmosphere.
- [5] Enter one of the following numbers: carbon steel--'1';{Note: numbers for other materials of construction will be provided later. }
- [6] Cost equations apply to inlet areas between 0.2 and 2.64 ft<sup>2</sup>. For larger inlet areas, see other cyclones spreadsheet (TCI-MC-L.WK1).
- [7] By assumption, no operating or supervisory labor is required with mechanical collectors (cyclones).



Appendix A cont.....

TOTAL ANNUAL COST SPREADSHEET PROGRAM- (VENTURI) SCRUBBERS [1]

COST BASE DATE: June 1988 [2]

VAPCCI (Fourth Quarter 1998--FINAL): [3] 109.8

INPUT PARAMETERS

-- Inlet stream flowrate (acfm):	<b>18685</b>
-- Inlet stream temperature (°F):	325
-- Inlet moisture content (molar, fraction):	0.20
-- Inlet absolute humidity (lb/lb b.d.a.): [4]	0.155
-- Inlet water flowrate (lb/min):	121.2
-- Saturation formula parameters: [5]	
Slope, B:	3.335
Intercept,A: #####	##
-- Saturation absolute humidity (lb/lb b.d.a.):	0.2006
-- Saturation enthalpy temperature term (°F):[6]	157.8
-- Saturation temperature (°F):	157.6
-- Inlet dust loading (gr/dscf):	4.00
-- Overall control efficiency (fractional):	0.95
-- Overall penetration (fractional):	0.05
-- Mass median particle diameter (microns): [7]	1.7
-- 84th % aerodynamic diameter (microns): [7]	3.4
-- Particle cut diameter (microns): [7]	0.44
-- Scrubber liquid solids content (lb/lb H2O):	0.25
-- Liquid/gas (L/G) ratio (gpm/1000 acfm):	5.0
-- Recirculation pump head (ft of water):	100
-- Material of construction (see list below):[8]	1

DESIGN PARAMETERS

-- Scrubber pressure drop (in. w.c.): [9]	24.73
-- Inlet dry air flow rate (dscfm): [10]	10424
-- Inlet (= outlet) air mass rate (lb/min):	781
-- Water recirculation rate (gpm):	93
-- Outlet water mass rate (lb/min):	157
-- Outlet total stream flow rate (acfm):	16073
-- Scrubber liquid bleed rate (gpm):	2.04
-- Scrubber evaporation rate (gpm):	4.26
-- Scrubber liquid makeup rate (gpm):	6.30

**CAPITAL COSTS**

Equipment Costs (\$):	
-- Scrubber (base)	34,526
' (escalated)	43,232
-- Other (auxiliaries, e.g.)	0
-- Total	43,232
Purchased Equipment Cost (\$):	51,013
Total Capital Investment (\$):	97,435

**ANNUAL COST INPUTS**

Operating factor (hr/yr):	8000
Operating labor rate (\$/hr):	12.96
Maintenance labor rate (\$/hr):	14.26
Operating labor factor (hr/sh):	2
Maintenance labor factor (hr/sh):	1.5
Electricity price (\$/kWhr):	0.059
Chemicals price (specify) (\$/ton):	0
Process water price (\$/1000 gal):	0.20
Wastewater treatment (\$/1000 gal):	3.80
Overhead rate (fractional):	0.60
Annual interest rate (fractional):	0.07
Control system life (years):	10
Capital recovery factor (system):	0.1424
Taxes, insurance, admin. factor:	0.04

**ANNUAL COSTS**

Item	Cost (\$/yr)	Wt. Fact.	W.F.(cond.)
Operating labor	25,920	0.149	----
Supervisory labor	3,888	0.022	----
Maintenance labor	21,384	0.123	----
Maintenance materials	21,384	0.123	----
Electricity--fan	33,911	0.196	----
Electricity--recirculation pump	1,274	0.007	
Chemicals	0	0.000	----
Process water	605	0.003	----
Wastewater treatment	3,716	0.021	----
Overhead	43,546	0.251	0.670
Taxes, insurance, administrative	3,897	0.022	----
Capital recovery	13,873	0.080	0.102
<b>Total Annual Cost (\$/yr)</b>	<b>173,398</b>	<b>1.000</b>	<b>1.000</b>

Notes:

- [1] Data used to develop this program were taken from 'Estimating Costs of Air Pollution Control' (CRC Press/Lewis Publishers, 1990).
- [2] Base equipment costs reflect this date.
- [3] VAPCCI = Vatavuk Air Pollution Control Cost Index (for wet scrubbers) corresponding to year and quarter shown. Base equipment cost, purchased equipment cost, and total capital investment have been escalated to this date via the VAPCCI and control equipment vendor data.
- [4] Program calculates from the inlet moisture content.
- [5] By assumption, the saturation humidity (hs)-temperature (ts) curve is a power function, of the form:  $hs = A*(ts)^B$ .
- [6] To obtain the saturation temperature, iterate on the saturation humidity. Continue iterating until the saturation temperature and the saturation enthalpy term are approximately equal.
- [7] Both the 'mass median' and '84th percentile aerodynamic' diameters are obtained from a log-normal distribution of the inlet stream particle diameters. The particle cut diameter is a graphical function of the penetration, the mass median diameter, and the standard deviation of the particle size distribution. (For detailed guidance in determining these particle sizes, see "Wet Scrubbers: A Practical Handbook" by K.C. Schiffner and H.E. Hesketh (CRC Press/Lewis Publishers, 1986). A condensed procedure is given in "Estimating Costs of Air Pollution Control" by W.M. Vatavuk (CRC Press/Lewis Publishers, 1990).)
- [8] Enter one of the following numbers: carbon steel--'1'; rubber-lined carbon steel--'1.6'; epoxy-coated carbon steel--'1.6'; fiber-reinforced plastic (FRP)--'1.6'.
- [9] The scrubber pressure drop is extremely sensitive to the particle cut diameter. Hence, the user must determine the cut diameter with great care.

Appendix A cont....

TOTAL ANNUAL COST SPREADSHEET PROGRAM--ELECTROSTATIC PRECIPITATORS (ESP)[1]

COST BASE DATE: Second Quarter 1987 [2]

107.7

VAPCCI (Fourth Quarter 1998--FINAL): [3]

INPUT PARAMETERS:

-- Inlet stream flowrate (acfm):	<b>18,685</b>
-- Inlet stream temperature (oF):	325
-- Particulate type: coal fly ash	
-- ESP type: flat plate	
-- ESP 'options' included? ('yes'=1; 'no'=0):	1
-- Inlet particulate loading (gr/ft3):	4
-- Particulate mass median diameter (microns):	7
-- Most penetrating particle size (microns):	2
-- Particle rapping puff size (microns):	5
-- Particulate resistivity (ohm-cm):	#####
-- Overall PM collection efficiency (fraction):	0.999
-- PM migration velocity (cm/s):	16.0
-- Sneakage factor:	0.07
-- Rapping reentrainment factor:	0.124
-- Gas free space permittivity (F/m):	#####
-- Average field/sparking field adjust. factor:	0.7937
-- ESP pressure drop (in. w.c.):	0.38
-- Material of construction (see list below):[4]	1

DESIGN PARAMETERS

-- Overall penetration:	0.001
-- Specific collection area #1 (ft2/1000 acfm):	219.3
-- Gas viscosity (kg/m-s):	2.3973E-05
-- Electric field at sparking (V/m):	#####
-- Average electric field (V/m):	#####
-- Loss factor:	0.19
-- Number of collecting sections in ESP:	6
-- Section 'Lookup Table':	

Efficiency:	No. Sections:
-----	-----
0	2
0.965	3
0.990	4
0.998	5
0.999	6

- Average section penetration: 0.3162
- Section collection penetration: 0.1607
- Particle size change factor, D (micron): 0.3162
- Particle size change factor, MMD<sub>rp</sub> (micron): 1.530

-- Section parameters:

Section #	MMD <sub>i</sub>	SCA <sub>i</sub>
1	7	12.32
2	4.504	19.15
3	3.748	23.02
4	3.519	24.51
5	3.450	25.01
6	3.429	25.16

- Specific collection area #2 (ft<sup>2</sup>/1000 acfm): 656.23
- SCA #2/SCA #1 (SCA ratio): 2.99
- SCA Ratio 'Lookup Table':

No. Sections	SCA Ratio (avg.)
2	2.60
3	2.65
4	2.89
5	2.96
6	3.09

- SCA Ratio (avg.)-THIS STREAM: 3.09
- SCA = SCA Ratio (avg.) x SCA #1: 677.7
- Total collector plate area (ft<sup>2</sup>): 12663

#### CAPITAL COSTS

Equipment Costs (\$):

- Basic ESP 230,838
- ESP 'standard options' 103,877
- Auxiliaries (ductwork, etc.) 0
- Total (base) 334,714
- ' (escalated) 508,463
- Purchased Equipment Cost (\$): 599,986
- Total Capital Investment (\$): 1,343,968

ANNUAL COST INPUTS:

Operating factor (hr/yr):	8640
Operating labor rate (\$/hr):	12
Operating labor factor (hr/sh):	1.0
Electricity price (\$/kWhr):	0.06
Dust disposal (\$/ton):	20
Annual interest rate (fraction):	0.07
Control system life (years):	20
Capital recovery factor:	0.0944
Taxes, insurance & admin. factor:	0.04

Item	ANNUAL COSTS (\$/yr): Cost (\$/yr)	Wt. Factor	W.F. (cond.)
Operating labor	12,960	0.044	----
Supervisory labor	1,944	0.007	----
ESP coordinator labor	4,320	0.015	----
Maintenance labor	4,125	0.014	0.126
Maintenance materials	6,000	0.020	----
Electricity	13,401	0.045	----
Dust disposal	55,350	0.187	----
Overhead	17,609	0.059	----
Taxes, insurance, administrative	53,759	0.181	----
Capital recovery	126,861	0.428	0.642
<b>Total Annual Cost</b>	<b>296,329</b>	<b>1.000</b>	<b>1.000</b>

Operating Labor Factor 'Lookup Table'

Plate Area (ft <sup>2</sup> ):	Factor (hr/sh):
0	0.5
10000	1.0
100000	1.5
1000000	2.0

Notes:

- [1] This spreadsheet was developed based on data and procedures in Chapter 6 of the OAQPS CONTROL COST MANUAL (4th Edition). However, modifications were made to SCA calculation procedure (SCA #2) to correct equation discontinuities and other anomalies.
- [2] Base equipment costs reflect this date.
- [3] VAPCCI = Vatavuk Air Pollution Control Cost Index (for electrostatic precipitators) corresponding to year and quarter shown. Base equipment cost, purchased equipment cost, and total capital investment have been escalated to this date via the VAPCCI and control equipment vendor data.
- [4] Enter one of the following numbers: carbon steel--'1'; 316 stainless steel--'1.3'; Carpenter 20 (CB-3)--'1.9'; Monel-400--'2.3'; Nickel-200--'3.2'; titanium--'4.5'.

Appendix A cont....

TOTAL ANNUAL COST SPREADSHEET PROGRAM--FABRIC FILTERS (or Bag House)[1]

COST BASE DATE: Second Quarter 1998 [2]

VAPCCI (Fourth Quarter 1998--FINAL): [3] 110.9

INPUT PARAMETERS:

-- Inlet stream flowrate (acfm):		<b>18,685</b>
-- Inlet stream temperature (oF):		325
-- Inlet stream temperature, adjusted--pulse jet only (oF):		275
-- Dust type: Coal fly ash		
-- Inlet dust loading (gr/ft3):		4.0
-- Dust mass median diameter (microns):		7
-- Filtration time (min):		10
-- Dust specific resistance (in.H2O/fpm/lb/ft2):		15
-- G/C ratio factors (shaker & reverse-air):		
	A:	2.0
	B:	0.9
	C:	1.0
-- G/C ratio factors (pulse-jet):		
	Material:	9.0
	Application:	0.8
-- G/C ratio factors (cartridge filters):		
	A:	2.1
	B:	0.8
	C:	0.75
	D:	0.9
	E:	1.075
-- Cleaning pressure, psig (pulse-jet only):		100
-- Fraction of bags cleaned (shaker & rev-air):		0.1
-- Insulation required? ('yes'=1;'no'=0):		1
-- Stainless steel required? ('yes'=1;'no'=0):		0
-- Bag material: Fiberglass		
-- Fabric effective residual drag (in. H2O/fpm):		1.1
-- Bag prices (\$/ft2): (from table below, for bag material selected above only) [4]		
Cleaning Mech.	Bag Diam. (in.)	Price (\$/ft2)
<hr/>		
Pulse jet--BBR	4.5 to 5.125	1.69
	6 to 8	1.55
Pulse jet--cart.	4.875	0.00
	6.125	0.00
Shaker--strap	5	0.00
Shaker--loop	5	0.00
Reverse air w/o rings	8	0.95
	11.5	0.75
-- Cost of auxiliary equipment (ductwork, fan, stack, etc.), (\$):		89,500

DESIGN PARAMETERS

-- Gas-to-cloth ratio (acfm/ft <sup>2</sup> cloth area):		
	Shaker:	1.80
	Reverse-air:	1.80
	Pulse-jet:	4.69
	Cartridge:	1.22
-- Net cloth area required (ft <sup>2</sup> ):		
	Shaker:	10381
	Reverse-air:	10381
	Pulse-jet:	3985
	Cartridge:	15328
-- Gross cloth area required (ft <sup>2</sup> ):		
	Shaker:	15571
	Reverse-air:	15571
	Pulse-jet:	3985
	Cartridge:	15328
-- Area per bag--reverse-air (ft <sup>2</sup> ) (8-in. x 24-ft):		50.3
-- Number of bags--reverse air:		310
-- Area per bag--shaker (ft <sup>2</sup> ) (5-in x 8-ft):		10.5
-- Number of bags--shaker		1487
-- Area per bag--pulse jet (ft <sup>2</sup> ):	Small (4.5-in. x 8-ft)	9.42
	Large (5.125-in. x 10-ft)	13.42
-- Number of bags/cages (pulse-jet only):	Small bags	423
	Large bags	297
-- Area per bag--cartridge (ft <sup>2</sup> ):		153
-- Number of bags--cartridge:		101
-- Bag pressure drop (in. w.c.):		
	Shaker:	2.26
	Reverse-air:	2.26
	Pulse-jet:	3.31
	Cartridge:	1.47
-- Baghouse shell pressure drop (in. w.c.):		3.00
-- Ductwork pressure drop (in. w.c.):		4.00



CAPITAL COSTS

Equipment Costs (\$):

Item:	Cost (\$):				
	Shaker	Rev-air	P-J (mod)	P-J (com)	P-J (cartridge)
Baghouse	0	109,714	48,944	30,849	0
Bags--small	0	11,678	6,734	6,734	0
" --large			6,176	6,176	
Insulation	0	26,851	9,927	10,699	0
Stainless	0	0	0	0	0
Cages-small [5]	0	0	2,531	2,531	0
" -large	0	0	3,278	3,278	0
Auxiliaries	0	89500	89,500	89,500	0
Total--small[5a]	0	237,743	157,636	140,313	0
" --large:			157,824	140,502	
PEC(\$)-base:	0	280,537	186,010	165,570	0
' '-esc.:	0	286,215	189,775	168,921	0
TCI (\$):	0	621,086	411,812	366,558	0
(\$/acfm):	0	33	22	20	0

ANNUAL COST INPUTS:

Operating factor (hr/yr):	8640
Operating labor rate (\$/hr):	17.26
Maintenance labor rate (\$/hr):	17.74
Operating labor factor (hr/sh):	0
Maintenance labor factor (hr/sh):	1
Electricity price (\$/kWhr):	0.0671
Compressed air (\$/1000 scf):	0.25
Dust disposal (\$/ton):	25
Annual interest rate (fraction):	0.07
Control system life (years):	20
Capital recovery factor:	0.0944
Bag life (years):	2
Capital recovery factor (bags):	0.5531
Taxes, insurance, admin. factor:	0.04

Item	Shaker	ANNUAL COSTS (\$/yr):			
		Reverse-air	P-J (modular)	P-J (common)	P-J (cartridge)
Oper. labor	0	0	0	0	0
Supv. labor	0	0	0	0	0
Maint. labor	0	19,159	19,159	19,159	0
Maint. matl.	0	19,159	19,159	19,159	0
Electricity	0	60,886	20,222	20,222	0
Compr. air	0	0	4,843	4,843	0
Bag repl.	0	8,192	6,641	6,641	0
Dust dispos.	0	69,188	69,188	69,188	0
Overhead	0	22,991	22,991	22,991	0
Tax,ins.,adm	0	24,843	16,472	14,662	0
Cap. recov.	0	57,228	37,739	33,467	0
<b>Total Annual</b>	0	281,647	<b>216, 415</b>	210,333	0

Appendix A cont...

TOTAL ANNUAL COST SPREADSHEET PROGRAM--GAS ABSORBERS FOR ACID GAS CONTROL  
[1]

COST BASE DATE: Third Quarter 1991 [2]

VAPCCI (Fourth Quarter 1998--FINAL): [3] 110.4

INPUT PARAMETERS:

Stream parameters:

-- Inlet waste gas flowrate (acfm):	<b>18,685</b>
-- Inlet waste gas temperature (°F):	325
-- Inlet waste gas pressure (atm.):	1
-- Pollutant in waste gas:	Acid Gases (HCl; SO <sub>x</sub> )
-- Inlet gas poll. conc., y <sub>i</sub> (mole fraction):	0.001871
-- Pollutant removal efficiency (fraction):	0.99
-- Absorbent:	Aqueous caustic soda
-- Inlet pollutant conc. in absorbent:	0
-- Waste gas molecular weight (lb/lb-mole):	28.85
-- Absorbent molecular weight (lb/lb-mole):	18.00
-- Inlet waste gas density (lb/ft <sup>3</sup> ):	0.0503
-- Absorbent density (lb/ft <sup>3</sup> ):	62.4
-- Absorbent specific gravity:	1.00
-- Waste gas viscosity @ inlet temp. (lb/ft-hr):	0.044
-- Absorbent viscosity @ inlet temp. (lb/ft-hr):	2.16
-- Minimum wetting rate (ft <sup>2</sup> /hr):	1.3
-- Pollutant diffusivity in air (ft <sup>2</sup> /hr):	0.725
-- Pollutant diffusivity in absorbent (ft <sup>2</sup> /hr):	0.000102

Packing parameters:

-- Packing type:	2-in. ceramic Raschig rings
-- Packing factor, F <sub>p</sub> :	65
-- Packing constant, alpha:	3.82
-- Packing constant, beta:	0.41
-- Packing constant, gamma:	0.45
-- Packing constant, phi:	0.0125
-- Packing constant, b:	0.22
-- Packing constant, c:	0.24
-- Packing constant, j:	0.17
-- Surface area-to-volume ratio, a (ft <sup>2</sup> /ft <sup>3</sup> ):	28
-- Packing cost (\$/ft <sup>3</sup> ):	20

DESIGN PARAMETERS:

-- Material of construction (see list below):[4]	1
-- Inlet pollutant concentration (free basis):	#####
-- Outlet pollutant concentration (free basis):	#####
-- Out. eq. poll. conc. in absorbent., $X_o^*$ (op. line):	#####
-- Theoretical operating line slope (Ls/Gs,min.):	0.0116
-- Ls/Gs adjustment factor:	1.5
-- Actual operating line slope (Ls/Gs, act.):	0.0174
-- Gas flowrate, Gs (free basis, lb-moles/hr):	1953
-- Absorbent flowrate, Ls (free basis, lb-mol/hr):	33.97
-- Gas flowrate, Gmol,i (lb-moles/hr):	1956
-- Absorbent flowrate, Lmol,i (lb-moles/hr):	33.97
-- Outlet actual pollutant conc. in absorbent, $X_o$ :	0.1067
-- Gas poll. conc. in eq. w/ $X_o$ ( $Y_o^*$ ):	0.0001
-- Outlet absorbent poll. conc. (mole fract. basis):	0.0964
-- Gas poll. conc., $Y_o^*$ (mole fract. basis):	0.0001
-- Outlet gas poll. conc., $y_o$ (mole fract.):	#####
-- Slope of equilibrium line (m):	0.00104
-- Absorption factor (AF):	16.77
-- ABSCISSA (column diameter calculation):	#####
-- ORDINATE (column diameter calculation):	0.2061
-- Superficial gas flowrate, Gsfr,i (lb/sec-ft <sup>2</sup> ):	0.5725
-- Flooding factor, f:	0.7
-- Column cross-sectional area, A (ft <sup>2</sup> ):	39.05
-- Superficial liquid flowrate (lb/hr-ft <sup>2</sup> ):	15.66
-- Minimum liquid flowrate (lb/hr-ft <sup>2</sup> ):	2271
-- Column diameter, D (ft):	7.051
-- Number of transfer units, Ntu:	4.831
-- Gas film transfer coefficient, Hg (ft):	2.556
-- Liquid film transfer coefficient, Hl (ft):	1.064
-- Height of a transfer unit (ft):	2.620
-- Packing depth (ft):	12.654
-- Column total height (ft):	27.72
-- Column surface area (ft <sup>2</sup> ):	692.1
-- Column gas pressure drop (in. w.c./ft packing):	0.980
-- Column liquid pressure drop (ft of H <sub>2</sub> O):	60
-- Packing volume (ft <sup>3</sup> ):	494.1

**CAPITAL COSTS:**

Equipment costs (\$):	
-- Gas absorber	79,588
-- Packing	9,882
-- Auxiliaries (ductwork, etc.)	0
	-----
-- Total (base)	89,470
' (escalated)	103,773
Purchased Equipment Cost (\$):	122,452
Total Capital Investment (\$):	269,395

**ANNUAL COST INPUTS:**

Operating factor (hr/yr):	8000
Operating labor rate (\$/hr):	15.64
Maintenance labor rate (\$/hr):	17.20
Operating labor factor (hr/sh):	0.0
Maintenance labor factor (hr/sh):	0.5
Electricity price (\$/kWhr):	0.0461
Absorbent material (caustic) price (\$/ton):	300
Absorbent carrier ( water) price (\$/1000 gal):	0.20
Wastewater trtmt cost (\$/1000 gal):	3.80
Overhead rate (fraction):	0.6
Annual interest rate (fraction):	0.07
Control system life (years):	15
Capital recovery factor (system):	0.1098
Taxes, insurance, admin. factor:	0.04

**ANNUAL COSTS:**

Item	Cost (\$/yr)	Wt. Factor	W.F.(cond.)
Operating labor	0	0.000	----
Supervisory labor	0	0.000	----
Maintenance labor	8,602	0.032	----
Maintenance materials	8,602	0.032	----
Electricity	15,271	0.057	----
Absorbent material (caustic)	191,519	0.662	----
Absorbent carrier (water)	439	0.002	----
Wastewater treatment	8,343	0.029	----
Overhead	10,322	0.038	0.102
Taxes, insurance, administrative	10,743	0.040	----
Capital recovery	29,488	0.109	0.149
<b>Total Annual Cost</b>	<b>283, 330</b>	<b>1.000</b>	<b>1.000</b>

NOTES:

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- [1] This program has been based on data and procedures in Chapter 9 of the OAQPS CONTROL COST MANUAL (5th edition).
- [2] Base equipment costs reflect this date.
- [3] VAPCCI = Vatavuk Air Pollution Control Cost Index (for gas absorbers) corresponding to year and quarter shown. Base equipment cost, purchased equipment cost, and total capital investment have been escalated to this date via the VAPCCI and control equipment vendor data.

## APPENDIX B

### Calculation of tons per year (T/Y) and Dollars per ton (\$/T)

#### Case 1:

##### Multi-cyclone (MC)

##### Basis: 1 minute:

Inlet particulate matter (PM) concentration per minute = 2.0 gr/dscf

(Where dscf = dry standard cubic feet per minute)

$$= \frac{2 \times 60 \times 24 \times 365}{7000} \left( \frac{lb}{dscfm \cdot Y} \right)$$

(where 7000 grains (gr) = 1 lb)

$$= \frac{2 \times 60 \times 24 \times 365}{7000 \times 2000} \left( \frac{T}{dscf \cdot Y} \right)$$

(where 1 ton = 2000 lbs)

$$= 0.0751 \left( \frac{T}{dscf \cdot Y} \right)$$

For 90% removal efficiency

$$= 0.0751 \times 0.9$$

$$= 0.0676 \left( \frac{T}{dscf \cdot Y} \right)$$

For an inlet exhaust gas flow rate = 18,685 dscfm

$$T/Y = 0.0676 \times 18,685 = 1263$$

Total annualized cost for MC at 18,685 dscfm

$$= \$82,292 \text{ (Table 1)}$$

$$\therefore \$/T = \frac{82292}{1263} \approx 65$$

#### Case 2:

##### Venturi Scrubber (VS)

Input particulate matter (PM) loading to venturi scrubber per minute = 2.0 gr/dscf

$$\therefore T/Y = \left( \frac{2 \times 60 \times 24 \times 365}{7000 \times 2000} \right) dscf = 0.0751 \text{ dscf}$$

For 18,685 dscfm

$$\begin{aligned} T/Y &= 18685 \times 0.0751 \\ &= 1403 \end{aligned}$$

For 90% removal efficiency

$$T/Y = 1403 \times 0.9 \approx 1263$$

Annualized cost at 18685 dscfm = \$173398 (Table 1)

$$\therefore \$/T = \frac{173398}{1263} = 137$$

## Appendix B cont...

### Case 3:

#### Electrostatic Precipitator (ESP)

Input particulate matter (PM) loading to ESP and FF per minute = 2.0 gr/dscf

$$\therefore T/Y = \left( \frac{2 \times 60 \times 24 \times 365}{7000 \times 2000} \right) dscf = (0.0751) dscf$$

For 18,685 dscfm

$$\begin{aligned} T/Y &= 18685 \times 0.0751 \\ &= 1403 \end{aligned}$$

For 99.5% removal efficiency for both ESP and FF

$$T/Y = 1403 \times 0.995 \approx 1396$$

Annualized cost at 18685 dscfm = \$296329 (Table 1)

$$\therefore \$/T = \frac{296329}{1396} = 212$$

### Case 4

#### Fabric Filter (FF)

Input particulate matter (PM) loading to FF per minute = 2.0 gr/dscf

$$\therefore T/Y = \left( \frac{2 \times 60 \times 24 \times 365}{7000 \times 2000} \right) dscfm = (0.0751) dscfm$$

For 18,685 dscfm

$$\begin{aligned} T/Y &= 18685 \times 0.0751 \\ &= 1403 \end{aligned}$$

For 99.5% removal efficiency for FF

$$T/Y = 1403 \times 0.995 \approx 1396$$

Annualized cost at 18685 dscfm = \$216415 (Table 1)

$$\therefore \$/T = \frac{216415}{1396} = 155$$



Case 5:

Gas absorber for acid gases (AG)

Inlet gas pollutant concentration and mole fraction  $\approx 0.002$  (Appendix B)

T/Y of acid gases removed:

$$= (\text{lb/ft}^3) \left( \frac{\text{dscf}}{\text{min}} \right) (\text{mole fraction}) \left( \frac{60 \times 24 \times 365}{2000} \right)$$

$$= \frac{0.0503 \times 0.002 \times 60 \times 24 \times 365}{2000} \text{ dscfm}$$

$$\text{T/Y} = 0.0264 \times \text{dscfm}$$

For 99% removal

$$\begin{aligned} \text{T/Y} &= 0.0264 \times 0.99 \times \text{dscfm} \\ &= 0.0261 \times \text{dscfm} \end{aligned}$$

For exhaust gas flow rate  $\approx 18,685$  dscfm

$$\text{T/Y} = 0.0261 \times 18,685 = 488$$

Total annualized cost for AG at 18,685 dscfm

$$= 283,300 \text{ (Table 2)}$$

$$\therefore \text{\$/T} = \frac{283,300}{488} = \mathbf{580}$$

APPENDIX C

Currently Land Apply	Facility	Address	City	State	Zip	Contact	Phone	Send Results	1999 Ash Production	Range	Current Ash Management	Past Ash Management	Future Ash Management	Hog Fuel Source	Hog Fuel Supplier	Burn Salty Hog?
Y	Abitibi	4302 CHAMBERS CREEK RD	STEILACOOM	WA	98388	Ken Campbell			14,000 tons/year		used as fertilizer in Lewis & Grays Harbor County	Cover for Thurston Co. Landfill				no
N	Avista Utilities - Kettle Falls	P. O. BOX 3727	SPOKANE	WA	99220	Hank Nelson	509/495-8532 ext 4613	No	40,426 tons/year	37-42 tons	Onsite ash monofill	not changed	same	off-site	~50 sources, US & Canada	no
Y	Boise Cascade Unspecified								12,700 tons/year		1/2 compost ash with clarifying sludge & apply to private cottonwood trees; 1/2 to private landfill	same as now				no
	Boise Cascade-Kettle Falls Plywood	610 W. 3RD AVE	KETTLE FALLS	WA	99141	Victor Kollock										
	Boise Cascade-Wallula	P.O. BOX 500	WALLULA	WA	99363	Dennis Ross										
	Boise Cascade-Yakima	PO BOX 51	YAKIMA	WA	98901	Les Fillgrove										
N	Brooks Manufacturing	PO BOX 7	BELLINGHAM	WA	98227	John Ferlin	360/733-1700	Yes	713 lb/year	400-700 lb/year	landfilled	same	no	on-site		no
N	Buffelen Woodworking	PO BOX 1383	TACOMA	WA	98401	Joe Guizzetti	253/627-1191	Yes	Estimate 12 tons/year or 13.52 yd <sup>3</sup> /year	pretty consistent	landfilled	same	no	on-site		no
N	Cascade Hardwood	PO BOX 269	CHEHALIS	WA	98532	Gord Chaffey	360/748-0178	Yes	60 tons/year	45-65 tons?	ash combined with hog fuel & sold as fuel	same since 1986	same	on-site	natural gas	sometimes/ 10-20%
	City of Tacoma Public Works (steam plant)	PO BOX 11007	TACOMA	WA	98411	Lori Hannon	253/502-2288									
	Colville Indian Precision Pine	PO BOX 3293	OMAK	WA	98841	Ron Holen	509/826-1921									
Y	Cowlitz Stud-Randle	10166 Hwy 12	RANDLE	WA	98377	Angus Lowe	360/497-0205 ext 333	Yes	about 10 yd <sup>3</sup> /week dry & 30yd <sup>3</sup> /week wet	producing less ash now that burner	taking wet & dry ash to Randle and spreading on log yard; working with DeGoede Bulb Farm concerning	same	looking for productive avenues; see notes on DeGoedes Bulb Farm	on-site		no

Control Cost, and Economic and Environmental Impacts Analyses  
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Currently Land Apply	Facility	Address	City	State	Zip	Contact	Phone	Send Results	1999 Ash Production	Range	Current Ash Management	Past Ash Management	Future Ash Management	Hog Fuel Source	Hog Fuel Supplier	Burn Salty Hog?
										is more efficient	their potential use for land reclamation/soil amendment					
N	Daishowa America	PO Box 271	PORT ANGELES	WA	98362	Paul Perlwitz	360/457-4474	Yes	38000 yd <sup>3</sup> /year	38,000 - 42,000 yd <sup>3</sup> /year	private ash monofill	landfilled	10 years space left in landfill; looking at secondary sludge reuse; looking at market for retail soil amendment	yes	8-9 sources; Portack, Shear Bros., Allen Logging, Willis, Herman Bros., Olympic Wood Products	have in past; not many now if any
N	Fred Tebb & Sons	PO BOX 2235	TACOMA	WA	98401	Marlene DeMarko	253/272-4107	Yes	12 tons	6 - 12 tons	landfilled	same		on-site		no
N	Ft. James	NE 4TH AND ADAMS	CAMAS	WA	98607	Steve Young			7,700 tons/year		private landfill; still registered as fertilizer	Used as a fertilizer in Clark County				Natural tree bark & urban wood waste accepted as feedstock
N	Georgia Pacific West	PO BOX 1236	BELLINGHAM	WA	98227	Kip Whitehead	360/733-4410	Yes	about 5000 tons/year	4100-6000 tons/year wet weight	landfilled at Rabanco	not changed in 10 years	no plans to change (don't want liability)	5-10% from onsite; rest from offsite	from chip contracts, hog fuel brokers; a lot from Canada	guessing 0-20% salty
Y	Grays Harbor Paper LP	801 23RD ST	HOQUIAM	WA	98550	Bob Martin			7,000 tons/year		Applied as fertilizer to own land	?				Also use primary clarifier solids as liming agent
?	Guy Bennett Lumber	P.O. BOX 670	CLARKSTON	WA	99403	Mark Spear	509/758-5558	Yes	No record of how much		Dispose of on-site		looking at different management practices			
Y	Hampton Lumber, Cowlitz Division - Morton	302 State Rte 7	MORTON	WA	98356	Angus Lowe	360/497-0205 ext 333	Yes	about 10 yd <sup>3</sup> /week dry & 30yd <sup>3</sup> /	producing less ash now that burner is more efficient	taking wet & dry ash to Randle and spreading on log yard; working with DeGoede Bulb Farm concerning	same	looking for productive avenues; see notes on DeGoedes Bulb Farm	on-site		no

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Currently Land Apply	Facility	Address	City	State	Zip	Contact	Phone	Send Results	1999 Ash Production	Range	Current Ash Management	Past Ash Management	Future Ash Management	Hog Fuel Source	Hog Fuel Supplier	Burn Salty Hog?
									week wet		their potential use for land reclamation/soil amendment					
Y	Hardel Plywood	PO Box 566	CHEHALIS	WA	98532	Warren Krug	360/740-0232	Yes	about 273 tons/year	new facility - think may be consistent	ship ash to little hanford farms in centralia for soil conditioner	same; fairly new facility	not at this time; current practice easier; other option would be landfilling	95% from onsite	buy from Ace (additive for alder wood dust)	no
Y	High Cascade Lumber	520 SOUTH 28TH ST	WASHOUGAL	WA	98671	Robert Evert	509/427-4222	Yes	27000 lbs/mo wet weight		surface application for soil building onsite	were landfilling	no	buy hog fuel	other mills - HC Rainier, Hamilton Bros.	not known
Y	High Cascade Veneer	PO BOX 869	CARSON	WA	98610	Robert Evert	509/427-4222	Yes	18-20 tons/year	50-75 lb/day @ 330-350 day/year (my calc = 8.25 - 13.13 tons/year?)	blending with log yard debris and applying onsite since 1995	was going to solid waste landfill	may be merchandizing as soil amendment (off site)	on-site		no
	Hoquiam Plywood	PO BOX 737	HOQUIAM	WA	98550	Richard Blackmun	360/533-3060									
	Jeld-Wen Fiber of WA	PO Box 548	White Swan	WA	98952	Ken Kiest	509/874-2255									
N	Kimberly-Clark	2600 FEDERAL AVE	EVERETT	WA	98201	Christine Kurtz			100 tons/day		Rabanco landfill	Mixed with Everett biosolids for land applications			Also burn their sludge	
Y	Koenig FA & Sons	33523 SR #2	SULTAN	WA	98294	Darcy Koenig	360/793-1711	Yes	guessing 55 gal barrel full/week, maybe 200 lb/week so about 10,000 lb/year based on 50 week year (my	fairly consistent	some in trash; land applied (dumped) on ground onsite	no	no	buy some hog fuel	one, a cabinet shop	no

Control Cost, and Economic and Environmental Impacts Analyses  
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Currently Land Apply	Facility	Address	City	State	Zip	Contact	Phone	Send Results	1999 Ash Production	Range	Current Ash Management	Past Ash Management	Future Ash Management	Hog Fuel Source	Hog Fuel Supplier	Burn Salty Hog?
									calc)							
N	K-Ply	PO Box 2318	PORT ANGELES	WA	98362	Randy Sanford	360/457-4421	Yes	never measures; guessing 12-16 yd <sup>3</sup> /mo or 1 dump truck/mo	sometimes more when dirtier fuel, but fairly consistent	landfilled	no	did a boiler upgrade over July 4th, should be more efficient - see what happens with ash	buy some hog fuel	Herman Bros. & Daishowa	very little; do get some wood from barges but not rafted
?	Laymans Lumber	P.O.BOX 235	NACHES	WA	98937	George Layman	509/653-2221	Yes	1 ton/year	fairly consistent	stored on site	same for past 20 years	no	on-site		no
N	Longview Fibre	P.O. BOX 639	LONGVIEW	WA	98632	Tom Vaught	360/575-5908	Yes	22,300 yd <sup>3</sup> /year	18000 - 28000 yd <sup>3</sup> /year	landfilled at Cowlitz County lanfill - they use as landfill cover	closed onsite landfill in 1980's	no, landfill may close someday	off-site	WA, OR, ID small indept loggers	almost none
N	Longview Fibre	17400 WINTON RD	LEAVENWORTH	WA	98826	Don Ledbetter	509/763-3759	Yes	189 tons/year		Landfilled since June 2000	on-site land application	no	on-site		no
Y	Mayr Brothers, owned by Quality Veneer	PO Box 180; QV is at 720 Olive Way, Ste 1500	HOQUIAM; QV in Seattle	WA	98550 ; 98101	Bill Pink; John Spicher	360/532-7490; 206/493-2155	Yes	18250-23725ft <sup>3</sup> /year	fairly consistent	stockpiled onsite & land-mulched/tilled onsite; will sell if too much onsite, usually to potting soil places	no	no	on-site		no
Y	Morton Forest Products	PO Box I	MORTON	WA	98356	Glenn Patrick	503/205-7618	Yes	50-150 yd <sup>3</sup> /year	same	1 year stockpile on site; working on using as soil amendment at local nursery (deGoede). deGoede also has on-site boiler and uses ash for soil amendment (have experience using ash for soil amendment).	no	95% on-site; most from onsite	5% seasonally from other their other facilities, esp Tumwater Lumber Co.		no
N	Mt. Baker Plywood	2929 Roeder Ave.	BELLINGHAM	WA	98225	Tim Shannon	360/733-3960	Yes	about 365 yd <sup>3</sup> /year - depends on moisture content	not much, maybe +/- 20 tons/year	send to landfill	changed in 1993; before dumped onsite; mitigated	no plans to change	on & off site	Dillion Industries; Canada	no, check opacity
	Notes: Blue shading indicates facilities have not responded.															
	NW Hardwoods	300 GALVIN RD	CENTRALIA	WA	98531	Nathan Kilby										
	NW Hardwoods	120	LONGVIEW	WA	98632	Chris	360/557-									

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Currently Land Apply	Facility	Address	City	State	Zip	Contact	Phone	Send Results	1999 Ash Production	Range	Current Ash Management	Past Ash Management	Future Ash Management	Hog Fuel Source	Hog Fuel Supplier	Burn Salty Hog?
		INDUSTRIAL WY	W			Olsen	6678									
	NW Hardwoods	PO BOX 429	SEDRO WOOLLEY	WA	98284	Bob Shoff	360/856-5594									
N	NW Hardwoods	PO BOX 7	ARLINGTON	WA	98223	BJ Nersten	360/435-8502	Yes	57.6 tons/year	fairly consistent	ash combined with hog fuel & sold as fuel	no	no	on-site		not sure
N	Oeser Company	PO Box 156	BELLINGHAM	WA	98227	Ron Durbin	360/734-1480	Yes	about 6-8 tons/year	varies within this range	ash sent to "sanitary services" where they reincinerate it	done this for past 6-7 years; before this was land applied on-site	no	on-site		no
Y	Pacific Hardwoods	PO BOX 5805	Portland	OR	97228	Glenn Patrick	503/205-7618	Yes	estimate 25-75 yd <sup>3</sup> /year	same	local farmers using as soil amendment	for several years	no	on-site		no
	Pacific Veneer	100 N DECATUR	ABERDEEN	WA	98520	Charlie Garrott	360/538-1060									
N	Port Townsend Paper	P.O.BOX 3170	PORT TOWNSEND	WA	98368	Alice McConaughy	360/379-2079	Yes	4000 yd <sup>3</sup> /year	varies maybe +/- 100 yd <sup>3</sup> /year	onsite landfill in limited use fill	since 1970's	no	buy hog fuel	can send list of suppliers	no
	SDS Lumber	PO BOX 266	BINGEN	WA	98605	John Chaney	509/493-2155									
N	Shakertown 1992	PO BOX 400	WINLOCK	WA	98596	Brian Gebbard deferred to Paul Beauchemin, environmental consultant	360/785-3501; EnviroChem 604/986-0233	Yes	1.5-4 tons/year	same	municipal waste landfill			on-site		no
N	Simpson Tacoma Kraft	PO BOX 2133	TACOMA	WA	98421	Greg Narum			Chris = 5000 tons/year; Ficklin = 10225 yd <sup>3</sup> /year	Ficklin = 7900-10225 yd <sup>3</sup> /year	Dayton Landfill					25% salty hog fuel
N	Simpson Timber NW Operations	PO Box 460	SHELTON	WA	98584	Jerry Ficklin	360/427-4738	Yes	12,740 yd <sup>3</sup> /year	9020 - 15025	Dayton Landfill	since 1994	will be applying to	95% on-site	usually buy from other	<1.5% might be

Control Cost, and Economic and Environmental Impacts Analyses  
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Currently Land Apply	Facility	Address	City	State	Zip	Contact	Phone	Send Results	1999 Ash Production	Range	Current Ash Management	Past Ash Management	Future Ash Management	Hog Fuel Source	Hog Fuel Supplier	Burn Salty Hog?
										yd <sup>3</sup> /yr			Dept of Ag to reclaim ash from landfill for soil amendment		Simpson sites	salty (bark)
	Smith Street Mill	3600 SMITH ST	EVERETT	WA	98201	Robert Buse										
N	Stimson Lumber Company	634 HWY 395 SOUTH	COLVILLE	WA	99114	John Chipot	509/684-1138	Yes	1920 yd <sup>3</sup> /year	very little variance	Stevens Co. Landfill since 1/1/2000	were giving away 20:1 ash:mulch for soil amendment	want to return to mulching; possible selling for cost recovery	on-site		no
N	Summit Timber	PO BOX 368	DARRINGTON	WA	98421	Jim Reece	360/436-1411	Yes	0 - not operational for 3 years	maybe was 30 yd <sup>3</sup> /year	not current	onsite landfill	looking at potential startup; landfill still permitted	on-site		no
Y	Vaagen Bros Lumber-Colville	565 WEST 5TH	COLVILLE	WA	99114	Randy Erdman	509/684-5071	Yes	62 tons/year	50-70 tons/year	Scott - may be spreading on farmer fields as part of U of Idaho study; Erdman - stores in pit outback; a farmer also spreads on farm with good results; some soil composting - a nursery picks up and uses for potting soil	same for quite awhile	no	on-site		no
N	Vaagen Bros Lumber-Republic	PO BOX 357	REPUBLIC	WA	99166	Dave Scott	509/775-3346	Yes	never measured; maybe 50 tons/year	20% variance?	Onsite ash landfill	same	same	on-site		
Y	Wayne-Dalton Corporation	2001 INDUSTRIAL DR	CENTRALIA	WA	98531	John Ver Valen	360/736-7651	Yes	1 ton/year	fairly consistent	land applied (on ground)	no; on ground for last 15 years	yes, within 2-3 months will be landfilled	most onsite		no
	West Coast Forest Products	19406 68TH DR NE	ARLINGTON	WA	98223	Gary	360/435-2175 ext 202									
N	Western State	9601	TACOMA	WA	98498	Irvin	253/7	Yes	? Pellet burning		local landfill		trying to shut down boiler in 2-5 years; only			

Control Cost, and Economic and Environmental Impacts Analyses  
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Currently Land Apply	Facility	Address	City	State	Zip	Contact	Phone	Send Results	1999 Ash Production	Range	Current Ash Management	Past Ash Management	Future Ash Management	Hog Fuel Source	Hog Fuel Supplier	Burn Salty Hog?
	Hospital	STEILACOOM BLVD SW				Warner	56-2519		boiler is back up to emergency oil furnace					burns wood stove type pellets		
N	Weyerhaeuser Statewide								500+ tons/day (9 boilers)		private landfill	Some land application, also Mt. Solo landfill				
N	Weyerhaeuser-Cosmopolis	PO BOX 1000	COSMOPOLIS	WA	98537	Dennis Davies					private landfill	Some land application, also Mt. Solo landfill				
N	Weyerhaeuser-Longview	PO BOX 188	LONGVIEW	WA	98632	Tom Smith					private landfill	Some land application, also Mt. Solo landfill				
	Weyerhaeuser-Raymond	51 ELLIS ST.	RAYMOND	WA	98577	Robert Gudyka										
	Weyerhaeuser-Snoqualmie	7001 396TH AVE SE	SNOQUALMIE	WA	98065	Russ Proffitt										
Y	Wilkins, Kaiser, & Olsen	PO Box 8	CARSON	WA	98610	Robert Evert	509/427-4222	Yes	2000 lbs/wet weight (1400 lb/wet weight dry weight ?)	est 56000-70000 lb/year dry weight (assuming 30% of 2000lb/wk ww)	land application for run off control & soil building onsite	no; boiler 3 years old	no	on-site		no
Y	Zosel Lumber	PO Box 2580	OROVILLE	WA	98844	Howard Zosel	509/476-2111	NO	guessing 30 tons/year (runs 5 mo/year)	fairly steady for several years	applying to log yard on haul roads (on-site)	always on-site spreading; sometimes up to 2-3 ft deep or spread thin	would like to burn less to have less ash to manage	on-site		no



## Appendix – D

\*\*\* SCREEN3 MODEL RUN \*\*\*  
 \*\*\* VERSION DATED 95250 \*\*\*

### Daishowa America

#### SIMPLE TERRAIN INPUTS:

SOURCE TYPE = POINT  
 EMISSION RATE (G/S) = 1.00000  
 STACK HEIGHT (M) = 38.4000  
 STK INSIDE DIAM (M) = 2.1300  
 STK EXIT VELOCITY (M/S) = 10.6000  
 STK GAS EXIT TEMP (K) = 337.0000  
 AMBIENT AIR TEMP (K) = 293.0000  
 RECEPTOR HEIGHT (M) = 1.4000  
 URBAN/RURAL OPTION = RURAL  
 BUILDING HEIGHT (M) = .0000  
 MIN HORIZ BLDG DIM (M) = .0000  
 MAX HORIZ BLDG DIM (M) = .0000

BUOY. FLUX = 15.393 M<sup>4</sup>/S<sup>3</sup>; MOM. FLUX = 110.802 M<sup>4</sup>/S<sup>2</sup>.

#### \*\*\* FULL METEOROLOGY \*\*\*

\*\*\*\*\*

#### \*\*\* SCREEN AUTOMATED DISTANCES \*\*\*

\*\*\*\*\*

#### \*\*\* TERRAIN HEIGHT OF 0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES \*\*\*

DIST (M)	CONC (UG/M <sup>3</sup> )	STAB	U10M (M/S)	USTK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
100.	.3300E-04	1	3.0	3.3	960.0	88.91	27.86	15.80	NO
200.	1.141	1	3.0	3.3	960.0	88.91	51.34	31.59	NO
300.	5.336	1	3.0	3.3	960.0	88.91	73.20	49.59	NO
400.	6.728	1	2.5	2.7	800.0	99.01	94.31	73.24	NO
500.	6.685	1	1.5	1.6	480.0	139.42	116.67	108.56	NO
600.	6.650	1	1.0	1.1	320.0	189.93	139.75	159.91	NO
700.	6.741	1	1.0	1.1	320.0	189.93	158.34	217.68	NO
800.	6.347	1	1.0	1.1	320.0	189.93	176.78	286.30	NO
900.	5.812	1	1.0	1.1	320.0	189.93	195.05	365.70	NO
1000.	5.440	3	3.0	3.4	960.0	86.91	104.04	62.69	NO
1100.	5.326	3	3.0	3.4	960.0	86.91	113.31	68.14	NO
1200.	5.228	3	2.5	2.9	800.0	96.62	122.85	74.13	NO
1300.	5.070	3	2.5	2.9	800.0	96.62	131.95	79.48	NO
1400.	4.946	3	2.0	2.3	640.0	111.17	141.55	85.73	NO
1500.	4.817	3	2.0	2.3	640.0	111.17	150.50	91.00	NO
1600.	4.654	3	2.0	2.3	640.0	111.17	159.40	96.25	NO
1700.	4.487	3	1.5	1.7	480.0	35.43	169.26	103.13	NO
1800.	4.402	3	1.5	1.7	480.0	135.43	178.02	108.28	NO
1900.	4.294	3	1.5	1.7	480.0	135.43	186.74	113.42	NO
2000.	4.169	3	1.5	1.7	480.0	135.43	195.42	118.54	NO
2100.	4.035	3	1.5	1.7	480.0	135.43	204.07	123.66	NO
2200.	3.896	3	1.5	1.7	480.0	135.43	212.68	128.78	NO
2300.	3.754	3	1.5	1.7	480.0	135.43	221.25	133.88	NO

DIST (M)	CONC (UG/M**3)	STAB	U10M (M/S)	USTK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
2400.	3.708	3	1.0	1.1	320.0	183.94	231.87	142.38	NO
2500.	3.670	3	1.0	1.1	320.0	183.94	240.31	147.34	NO
2600.	3.625	3	1.0	1.1	320.0	183.94	248.71	152.30	NO
2700.	3.575	3	1.0	1.1	320.0	183.94	257.09	157.26	NO
2800.	3.522	3	1.0	1.1	320.0	183.94	265.45	162.21	NO
2900.	3.466	3	1.0	1.1	320.0	183.94	273.78	167.16	NO
3000.	3.409	3	1.0	1.1	320.0	183.94	282.08	172.10	NO
3500.	3.125	3	1.0	1.1	320.0	183.94	323.25	196.74	NO
4000.	3.312	5	1.0	1.6	10000.0	101.60	179.97	52.94	NO
4500.	3.402	5	1.0	1.6	10000.0	101.60	199.90	55.82	NO
5000.	3.434	5	1.0	1.6	10000.0	101.60	219.60	58.56	NO
5500.	3.424	5	1.0	1.6	10000.0	101.60	239.10	61.18	NO
6000.	3.386	5	1.0	1.6	10000.0	101.60	258.40	63.70	NO
6500.	3.328	5	1.0	1.6	10000.0	101.60	277.53	66.12	NO
7000.	3.256	5	1.0	1.6	10000.0	101.60	296.49	68.46	NO
7500.	3.177	5	1.0	1.6	10000.0	101.60	315.29	70.72	NO
8000.	3.093	5	1.0	1.6	10000.0	101.60	333.96	72.91	NO
8500.	3.006	5	1.0	1.6	10000.0	101.60	352.48	75.04	NO
9000.	2.918	5	1.0	1.6	10000.0	101.60	370.88	77.12	NO
9500.	2.831	5	1.0	1.6	10000.0	101.60	389.16	79.14	NO
10000.	2.746	5	1.0	1.6	10000.0	101.60	407.32	81.11	NO

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND 100. M:

458.	6.847	1	2.0	2.2	640.0	114.17	106.98	92.83	NO
------	-------	---	-----	-----	-------	--------	--------	-------	----

DWASH = MEANS NO CALC MADE (CONC = 0.0)  
 DWASH = NO MEANS NO BUILDING DOWNWASH USED  
 DWASH = HS MEANS HUBER-SNYDER DOWNWASH USED  
 DWASH = SS MEANS SCHULMAN-SCIRE DOWNWASH USED  
 DWASH = NA MEANS DOWNWASH NOT APPLICABLE, X<3\*LB

\*\*\*\*\*  
 \*\*\* SUMMARY OF SCREEN MODEL RESULTS \*\*\*  
 \*\*\*\*\*

CALCULATION PROCEDURE	MAX CONC (UG/M**3)	DIST TO MAX (M)	TERRAIN HT (M)
SIMPLE TERRAIN	6.847	458.	0.

\*\*\*\*\*  
 \*\* REMEMBER TO INCLUDE BACKGROUND CONCENTRATIONS \*\*  
 \*\*\*\*\*

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## Appendix E

# Review of Dioxin/Furan Formation, and Its Emission Factors Based On Wood Waste and Mixed Fuels Use In Pulp and Paper Industry Boilers

### Summary

This appendix discusses dioxin and furan (PCDD/F) formation in wood and combination wood-fired boilers. The related distribution factors for PCDD/F between flue gas and ash were derived from a variety of articles published in peer reviewed journals, as well as from databases developed by EPA (ICCR), Ecology, and National Council of Paper Industry for Air and Stream Improvement, Inc. (NCASI). HCl emissions at any wood waste or fossil fuel boilers in Washington appear to be insufficient to justify regulation. There is no link between the amount of HCl formed during combustion and the amount of PCDD/F emitted from combustion. Commercial data consisting of more than 1900 tests indicate that there is not a strong relationship between chlorine feed and flue gas PCDD/F concentration. The majority of the data shows no relationship between PCDD/F and chlorine feed rate or its surrogate uncontrolled HCl leaving the combustion chamber. For every case with an increase of chlorine, there is a counter-example. Whatever effect chlorine feed has on PCDD/F concentrations is masked by combustion design and operating factors that are more significant. Recent studies demonstrated that the presence of sulfur along with chlorine (S/Cl) in the mixed fuels (coal, BMK sludge) would scavenge PCDD/Fs formation/emission. Furthermore,, the firing of sulfur content coal and/or BKM sludge does not adversely impact the level of PCDD/F emissions from wood-fired boilers. In fact, the data suggests there are some positive effects from the burning of these sulfur-containing fuels as far as PCDD/F emissions are concerned.

The emission factor for inland mixed wood residue (no-salt-laden wood) fired without and with coal and bleached Kraft mill (BKM) sludge is reported approximately 0.60 ng per kilogram of fuel burned. The solid waste discharge factors for fly and bottom ashes for inland wood, bark mixed fuels, and salt-laden wood are presented in Table 6 towards the end of this report,

### Introduction

This is a review of the distribution of PCDD/F of wood-fuel origin between combustion exhaust gas (flue gas) and ash. The objective is to determine fuels-based-emission-factors for dioxin/furan using Ecology database and other available data. This information will support a determination of reasonably available control technology (RACT) for wood-fired boilers in Washington State.

Polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) are a group of tricyclic compounds substituted with one to eight chlorine atoms. This results in 210 different compounds: 75 PCDDs and 135 PCDFs. PCDDs and PCDFs are very stable compounds and have long residence times in the environment and in organisms, including humans. Their solubility in water promotes accumulations in sediments and organisms. Dioxins pose a risk of cancer from exposure through inhalation, ingestion, and skin (dermal) absorption. **Figures 1a and 1b** show the structure and

numbering system for dioxin and congeners. Seventeen congeners are more toxic than the others. These toxic congeners all have chlorine atoms at the 2,3,7, and 8 positions. The most toxic of all dioxins is 2,3,7,8-tetrachloro dibenzo-p-dioxin (2,3,7,8-TCDD). The 16 other dioxins and furans with chlorines at the 2,3,7 and 8 positions have been assigned toxicity values relative to 2,3,7,8-TCDD.

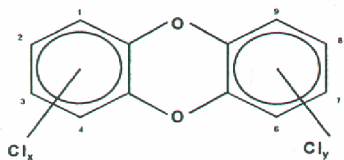


Figure 1a. Molecular Structure of PCDD

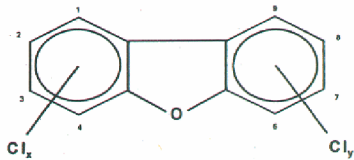


Figure 1b. Molecular Structure of PCDF

### **Figures 1a and 1b - Molecular Structures of PCDD and PCDF**

These relative toxicity values are called toxicity equivalency factors (TEFs). 2,3,7,8-TCDD is assigned a TEF of 1, and the other congeners are assigned values of less than 1. TEFs are used to express the total toxicity of dioxins when the concentration of each congener is multiplied by its TEF and the respective products are added up (called “dioxin toxicity equivalents” or “TEQs”).

Dioxin/furans are formed as by-products in certain industrial processes (e.g., associated with the manufacture of pulp, paper, and pesticides), and as products of incomplete combustion when chlorine and complex mixtures containing carbon are present. Dioxin/furans are emitted from combustors that burn wood and combination wood, medical waste, municipal solid waste, hazardous waste, sludge, and recycled oil (from motor vehicles and metal recovery processes). PCDDs and PCDFs are found in fly and bottom ashes and flue gas from wood-fired boilers. The level of PCDD/Fs emissions varies depending on the characteristics of fuels that are burned. PCDD/Fs do not exist at temperatures above 1800°F. PCDD/Fs are formed in the post combustion zone as the gases cool off (between 500-850°F). Some metals (particularly copper) are important components of fly ash that can catalyze the formation of PCDD/Fs. Metals enter an incinerator as trace species in the fuel matrix from various sources (i.e., municipal/medical solid waste, oil, coal). An understanding of the fate of the metallic species at high temperatures is essential in devising appropriate control technologies to prevent their emission. The degree of volatilization from the feed matrices and the speciation into different chemical forms, which in turn affects the aerosol formation and growth mechanisms, are important steps in the overall process resulting in emissions.

### **Mechanism of Formation**

Since the discovery of PCDD/Fs in Municipal Waste Incinerator (MWI) fly ash and flue gas in 1977, more attention has been paid to the formation of these compounds<sup>1,2</sup>. Theoretical calculations by Shaub and Tsang<sup>1,2</sup> showed that formation is unlikely to take place through homogeneous gas phase reactions. Instead they proposed a heterogeneous fly ash catalyzed mechanism of formation in the post combustion zone of the incinerator.

Chlorinated aromatic compounds can be intermediates in the formation of PCDD/Fs. The correlation between some chlorinated compounds and PCDD/Fs present in a municipal waste incinerator support this route of formation<sup>3</sup>. A strong correlation between the presence of chlorinated benzene and the formation of PCDD/Fs has been reported<sup>3</sup>. A reaction catalyzed by fly ash resulted in the formation of PCDD/Fs. The amount of PCDD/Fs increased when fly ash was heated to approximately 500°F in an excess oxygen atmosphere ( $\leq 1.0\%$ ). The report concluded, in this case, PCDD/Fs are probably formed from residual carbon present on the fly ash surface.

The origin of carbon that results in PCDD/F formation is important. For example, soot and sugar coal are less reactive than charcoal.<sup>4</sup> In addition, ions of heavy metals or the transition metal group are essential for PCDD/Fs formation reaction. Copper has been identified as the strongest catalyst. The addition of only 0.08%  $\text{Cu}^{2+}$  gives rise to a significant amounts of PCDD/Fs.<sup>4,5</sup> The catalytic action of  $\text{CuCl}_2$  is poisoned by  $\text{NH}_3$ , which results in lower PCDD/F amounts in the presence of  $\text{NH}_3$ . It is important to understand the fate of metallic species in combustion environments. An understanding of the fate of the metallic species at different temperatures is also essential in the process of cutting down dioxin formation, as well as, in devising appropriate control strategies for preventing their emissions.

Das<sup>6</sup> described different pathways of formation PCDD/F, and the process of scavenging PCDD/Fs and metal species on ash particles. The paper concluded that almost all of PCDD/Fs and trace metal species generated at post-combustion periods and their concentration levels were low enough, or in some cases, below detection limit, and ash quality met current regulatory criteria for landfill and/or land application.

## Fuel Characteristics

Wood waste boilers throughout the state combust a variety of fuels in order to meet their particular heat needs. Choice of fuels is dependent on a number of factors which include: fuel economics, administrative permits, regulation requirements, boiler design, and fuel supply characteristics. Annual heat inputs for these boilers can be divided into two groups:

1) those using only wood waste and 2) those using wood waste plus other fuels.

In Washington, approximately 3.3 million tons of wood wastes are combusted each year.<sup>7</sup>

**Table 1** provides the percentage of boilers that burn wood and the percentage of wood that is burned by industry category. The lumber and wood products industries operate almost three-fourths of wood waste boiler units, but these industries do not utilize a majority of the wood combusted in Washington. Most of the larger boilers are represented by the paper and allied products industries.

**Table 1**

<b>Industry</b>	<b>% of Boilers</b>	<b>% wood Combusted</b>
Lumber and Wood Products	72.6	39
Paper and Allied Products	22.6	45
Other	4.8	16

Based on the information received, 24 percent of the boilers combust salt-laden wood. Of those, 22 percent of their total wood fuel is salt-laden.<sup>8</sup> During the storing or transporting of logs in salt water, the salt content of the wood rises to 0.7 – 1.6 percent.<sup>8</sup> Salt particles that are adsorbed or entrained in the wood are very small particles (less than 1 micron). As a result, when salt-laden wood is combusted both the flue gas's fine particulate loading and plume opacity increases. Approximately one percent of the particulate matter generated by the combustion of typical "clean" or non-salt laden wood is less than one micron in diameter.<sup>8</sup> Another concern of salt-laden fuel is the increased potential of hazardous air pollution formation. The formation of polychlorinated dibenzo-p-dioxin/furan increases about a factor of a hundred for each ton of salt-laden wood combusted compared to non-salty wood.

This report summarizes all of the dioxin/furan emission data that are currently available in various sources relative to combustion of a variety of fuels: (1) 100 percent waste wood, (2) combination fuel firing mostly waste wood and coal, (3) combination fuel firing mostly waste wood, coal and bleached Kraft mill sludge.

## Results and Discussion

According to a recent study by the **American Society of Mechanical Engineers (New York)**<sup>9</sup>, there is no link between the amount of chlorine in municipal waste and the amount of dioxin emitted during incineration. The study concluded that limiting the chlorine content of combustion feed-stocks had no or little effect on the quantity of dioxin emitted. This explains why co-firing of PVC results in no more PCDD/F formation/emission than other materials in incinerators/combustors. Most of the chlorine from PVC is split off as HCl, which has no measurable effect on PCDD/F formation at the concentrations found in incinerators/combustors. Recently, **Rigo and Chandler**<sup>10</sup> conducted an extensive laboratory, bench and pilot scale



research highlighting the role chlorine plays under carefully controlled, high concentration conditions. Commercial data, more than 1900 tests, indicate that there is no strong relationship between chlorine feed and flue gas PCDD/F concentration. The majority of the data shows no relationship between PCDD/F and chlorine feed rate or its surrogate uncontrolled HCl leaving the combustion chamber. For every case with an increase of chlorine, there is a counter-example. Whatever effect chlorine feed has on PCDD/F concentrations is masked by combustion design and operating factors that are more significant.

A separate study on the role of inorganic chlorine in the formation of PCDD/F from residual carbon on incinerator fly ash reported that if fly ashes were doped/impregnated with KCl and HCl and with copper as a catalytic material, a positive correlation with the amount of PCDD/F was observed<sup>11</sup>. Another report has suggested that the presence of sulfur (S) and chlorine (Cl) and the ratio of (S/Cl) in the feed-stocks can decrease the downstream formation of chlorinated organic compounds, particularly PCDD/Fs.<sup>12</sup> Thus, co-firing municipal solid waste or combination wood waste with coal, because S species from coal, may reduce PCDD/Fs emissions. This article reports that the depletion of molecular chlorine (Cl<sub>2</sub>), an active chlorinating agent, by SO<sub>2</sub> through a gas-phase reaction appears to be a significant inhibition mechanism in addition to previously reported SO<sub>2</sub> deactivation of copper catalysts. Lindbauer and co-workers<sup>13</sup> proposed that when considering the influence of addition of sulfur compounds on PCDD/F, the governing parameter is SO<sub>3</sub>, not SO<sub>2</sub>. The PCDD/F formation inhibition occurs due to masking of catalytic dust particle surface due to sulphatization with SO<sub>3</sub>. An experimental study was carried out for reducing PCDD/F formation by sorbent injection<sup>14</sup>. The experimental results are controversial. When sorbent was added, the HCl level was always decreased; but the PCDD/F level could be increased, decreased or remain unchanged. The reason for this phenomenon is not clear; possibly, the flue gas HCl level is not a controlling factor with respect to PCDD/F formation<sup>15</sup>.

HCl is formed when chlorine or sodium chloride (salt) containing materials are burned.-It is important to separate HCl from the flue gas as soon as it forms; otherwise, HCl gas can lead to the formation of a number of chlorinated organic compounds. These can contribute in the formation of PCDD/Fs downstream of combustors. The PCDD/Fs do not exist at temperature of more than 1800 °F. The PCDD/Fs are formed in the post combustion zone as the gases cool off (between 500-850 °F). In Washington, the most common sources of chlorine compounds in hog fuel boiler emissions are from the use of salty hog fuel, the combustion of chlorine containing pulp mill wastewater sludges and mixed waste paper. Some source test data reported in the literature indicates the re-pulping of recycled bleached paper results in dioxins being leached from the waste paper pulp and entering the wastewater. Thus, the combustion of mixed waste paper leads to the emissions of HCl.

In conclusion, except when burning salty wood hog fuels, waste wood-fired boilers would only produce a trace amount of HCl. HCl has no measurable effect on PCDD/F formation at the concentrations typically found in incinerators/combustors.

## Summary of PCDD/Fs Emission from Wood Waste and Mixed-Fuels Fired Boilers

There are four types of fuels considered for the following summaries of all dioxin/furan emission data currently available in articles in published journals, from the NCASI report and ICCR database. The four types of fuels fired in most of the boilers tested are:

(a) wood only, (b) wood and coal, (c) wood, coal and bleach kraft mill (BKM) sludge, (d) wood and BKM sludge.

The NCASI report on PCDD/F emissions are expressed in terms of World Health Organization (WHO) toxic equivalent factors (WHO-TEF). However, the rest of the emission data is given in International TEFs. The key differences between the WHO-TEFs and the International TEFs are shown below:

	WHO – TEF	I-TEF
1,2,3,7,8-PCDD	1.0	0.5
PCDD	0.0001	0.001
PCDF	0.0001	0.001

The relative toxicity values are called toxicity equivalency factors (TEFs). 1,2,3,7,8-TCDD is assigned a TEF of 1.0, and the other congeners are assigned values of less than 1.0. TEFs are used to express the total toxicity of dioxins when the concentration of each congener is multiplied by its TEF and all the products are added up.

**Tables 2-6** summarize all of the dioxin emission data gathered from the sources mentioned above. **Table 2** presents PCDD/F emissions and emission factors from various published literatures.

**Table 2. Summary of PCDD/F Emissions From Industrial Boilers Firing 100% Wood Residues – in WHO-TEFs**

Boiler Code →	<i>WFBA</i>	<i>WFB B</i>	<i>WFBC</i>	<i>WFBC</i>	<i>CBA</i>	<i>WFB E</i>	<i>WFB F</i>
Final Control Device	MC	ESP	ESP	ESP	MC	MC	ESP
WHO-TEF TEQ, ng/dscm @ 12% CO <sub>2</sub>	2.2E-01	1.2E-01	2.5E-01	2.5E-01	3.1E-01	3.4E-04	3.8E-04

Boiler Code →

	<b>CBF,# 5</b>	<b>CBF,# 4</b>	<b>WFBG</b>	<b>WFBH</b>	<b>WFGI 1</b>	<b>WFB 12</b>	<b>WFB 13</b>
Final Control Device	ESP	ESP	WET ESP	SCRBR	SCRBR	SCRBR	SCRBR
WHO-TEF TEQ, ng/dscm @ 12% CO <sub>2</sub>	4.6E-02	1.8E-01	5.3E-01	4.6E-03	3.8E-02	4.7E-04	1.8E-03
			<u>avg</u>	<u>max</u>	<u>min</u>	<u>no.</u>	
WHO-TEF TEQ, ng/dscm @ 12% CO <sub>2</sub>			1.4E-01	5.3E-01	3.4E-04	14	
			<u>avg</u>	<u>max</u>	<u>min</u>	<u>no.</u>	
WHO-TEF TEQ, ug/Kg wood*			6.0E-04	2.3E-03	1.5E-06	14	

**Rules for treating non-detects**

If all the runs for an isomer gave NDs then ND = 0. Otherwise, ND = half the detection limit.

**Notes**

\*Assuming 1850 SCF CO<sub>2</sub> per million Btu, 9000 Btu/lb dry wood & 50% wood moisture  
 MC – multiclone; ESP – electrostatic precipitator, SCRBR – wet scrubber

**Table 3 Summary of PCDD/F Emissions From Combination Boilers Firing Wood Residues**

TYPE OF FUEL MIX	MILL CODE	NO. OF RUNS	PCDD/F EMISSIONS		CONTROL DEVICE	<b>OTHER INFORMATION</b>
			RANGE ng WHO TEQ/DSCM @	AVG 12% CO <sub>2</sub>		
WOOD/COAL/BKM SLUDGE (6 to 10%)	CBC	3	0.005 to 0.069	2.8E-02	ESP	51 to 64% COAL, 30 to 39% WOOD
WOOD/COAL/BKM SLUDGE (7 TO 8%)	CBA	3	0.022 to 0.034	2.8E-02	ESR	29 to 31% COAL, 62 to 63% WOOD
WOOD/COAL/BKM SLUDGE (<10%)	CBE	3	5.3E-04 to 0.017	6.1E-03	ESR	>90% COAL + WOOD
WOOD/BKM SLUDGE (<5.0%)	CBE	3	4.6E-05 to 1.8E-04	1.4E-04	ESP	
WOOD/BKM SLUDGE (33.0% by mass)	CBI	2	0.049 to 0.13	8.7E-02	EGF	
WOOD/COAL (43%)	CBB	3	0.004 to 0.011*	2.5E-03	ESP	57% WOOD RESIDUE
WOOD/COAL (33%)	CBA	1		1.5E-02	ESR	67% WOOD RESIDUE
WOOD/COAL (% UNKNOWN)	CBE	1		1.8E-02	ESR	
WOOD/COAL (50%)	CBH	2	4.1E-05 to 3.7E-04	2.0E-04	ESP	50% WOOD RESIDUE
WOOD/COAL (30%)	CBJ	2	1.4E-03	1.4E-03	ESP	70% WOOD RESIDUE
COAL + RECYCLE SLUDGE (5 to 10%)	CA	2	3.0E-04 to 1.5E-03	8.9E-04	ESP	90 to 95% COAL
<b>Average of all combination boilers</b>			4.1E-05 to 0.13	1.7E-02		

**Table 4 Impact of BKM Sludge on Wood/Coal Boiler Upon PCDD/F Emissions**

BOILER DESCRIPTION TEST DATE & CODE	SPREADER STOKER WITH MULTICLONES & ELECTROSCRUBBER JULY 1990, CBA			
	Run 2	Run 4	Run 5	Run 6
STEAM RATE, KPPH	530.9	503.7	531.8	559.4
COAL	33.2%	30.8%	30.9%	29.4%
WOOD RESIDUE	66.8%	61.9%	62.0%	62.8%
SLUDGE	0%	7.5%	7.1%	7.8%
SAMP VOL, DSCF	79.2	70.1	76.7	79.9

	ng/dscm @ 12% CO <sub>2</sub>			
	coal & wood	coal, wood residue & sludge		
TOTAL WHO-TEF TEQs	1.5E-02	2.2E-02	3.0E-02	3.4E-02
	avg	avg		
	1.5E-02	2.8E-02		

BOILER DESCRIPTION CONTROL DEVICE TEST DATE MILL CODE	SPREADER STOKER ELECTROSCRUBBER OCTOBER 1990 CBE			
	Run 1	Run 2	Run 3	Run 4
FLOW RATE, DSCFM	3E+05	3E+05	3E+05	3E+05
COAL/WOOD RESIDUE	100%	>90%	>90%	>90%
SLUDGE	0%	<10%	<10%	<10%
PARTICULATE, gr/dscf	0.0101	0.0088	0.0129	0.0078
SAMP VOL, DSCF	130.1	129.0	132.5	134.9

	ng/dscm @ 12% CO <sub>2</sub>			
	coal & wood	coal, wood residue & sludge		
TOTAL WHO-TEF	0.017	0.016	0.001	0.000
	avg	avg		
TOTAL WHO-TEF	0.017	0.0057		

**Rules for treating non-detects**

If all runs gave NDs, ND = 0; If at least one run gave detect, then ND = ½ detection limit;

**Table 5**  
**Comparison of Uncontrolled PCDD/F Emissions From Combustion of Combinations**  
**of Wood, Coal & BKM Sludge in Mill CBA Combination Bark Boiler**

BOILER DESCRIPTION SAMPLE LOCATION TEST DATE, CODE, REF	SPREADER STOKER AIR PREHEATER EXIT, BEFORE ELECTROSCRUBBER, AFTER MULTICYCLONE JULY 1990, CBA, 2								
	wood only		coal/wood		coal, wood & sludge			wood & sludge	
Run No. STEAMING RATE, KPPH COAL WD RESIDUE SLUDGE	1 502 0.0% 100% 0.0%	2 531 33.2% 66.8% 0.0%	4 504 30.8% 66.8% 0.0%	5 532 30.9% 62.0% 7.1%	6 559 29.4% 62.8% 7.8%	7 515 0.0% 93.5% 6.5%	8 520 0.0% 92.5% 7.5%		
	2,3,7,8 TCDD Equivalents, ng/dscm @ 12% CO <sub>2</sub>								
	wood only		coal/wood		coal, wood & sludge			wood & sludge	
WHO-TEF/93 TEQs	0.312	0.158	0.342	0.879	0.843	0.910	0.882		
WHO-TEF/93 TEQs, AVG	0.312	0.158	0.688			0.896			

Rules for treating non-detects

If all runs gave NDs, ND = 0; if at least one run gave detect, then ND = ½ detection limit;

**Tables 2-5** show data obtained from the NCASI report<sup>16</sup>. **Table 2** summarizes available PCDD/F emission data corresponding to 100 percent wood residue combustion in 14 steam-generating industrial boilers. For the 14 boilers in **Table 2**, the boiler capacities ranged from as low as  $30 \times 10^3$  lb stream/hr to as high as  $455 \times 10^3$  lb/hr. The boilers tested included two fuel cells, one fluidized bed, one pulverized coal (firing only wood) and ten grate boilers. The boilers were equipped with different kinds of final particulate control devices, including three with only multiclones, six with electrostatics precipitators (ESPs), one with a wet ESP, and four with wet scrubbers. To the best of the information available, all wood residue fuel fired in these 14 boilers corresponded to inland wood residue and not coastal or salt-laden residue. The summary data in **Table 2** shows that the average PCDD/F concentrations in emissions from 100% wood-fired industrial boilers ranged from  $3.4 \times 10^{-4}$  to  $0.53$  ng TEQ/dscm @12% CO<sub>2</sub>, averaging about  $0.4$  ng/TEQ/dscm. Assuming (a) a heat value of 9000 Btu/lb dry wood and (b) average wood residue fuel moisture content of 50%, this translates to a range of about  $1.5 \times 10^{-6}$  to  $2.3 \times 10^{-3}$  μg TEQ/kg-wood as fired, averaging an emission factor about  $6.0 \times 10^{-4}$  μg/kg (=0.60 ng/kg).

**Table 3** summarizes available PCDD/F emission data corresponding to combination fuel firing in pulp and paper industry boilers (mostly wood with other fuels). Summary data are presented for three boilers firing wood, coal and bleached Kraft mill (BKM) sludge; two boilers firing wood residue with BKM sludge only; five boilers firing wood residue with coal; and one boiler firing coal with a 100% recycle mill sludge. For the three boilers burning wood, coal and sludge, where the sludge amount fired ranged from 6.4 to 10.2 percent of heat input, the average PCDD/F emissions ranged from 0.006 to 0.028 ng TEQ/dscm @12% CO<sub>2</sub>, averaging about 0.02 ng/dscm. To convert to units of μg/kg of fuel fired, the specific composition of each source's fuel mix needs to be considered. These data show that the average PCDD/F emissions for wood/coal/BKM sludge firing could even be less than 0.60 ng/kg, found in 100 percent wood-firing conditions. For the two boilers firing wood residue with BKM sludge, PCDD/F emissions ranged from  $1.4 \times 10^{-4}$  to 0.087 ng TEQ/dscm @12% CO<sub>2</sub>, averaging about 0.044 ng/dscm. BKM sludge firing with wood residue alone seems to result in lower PCDD/F emissions than 100 percent wood combustion. This result has also been confirmed by Luthe, Karidio and Uloth<sup>17</sup> and by Raghunathan and Gullett<sup>12</sup> who attributed to this effort, at least in part, to the presence of sulfur in the sludge. For the five boilers firing wood residue with coal only, average PCDD/F emissions ranged from  $2.0 \times 10^{-4}$  to 0.018 ng TEQ/dscm @12% CO<sub>2</sub>, averaging about 0.007 ng/dscm. Average emissions for the coal-wood combination firing conditions appear to be less than for the 100 percent wood-firing condition, possibly due to the beneficial effect of coal sulfur either in scavenging the chlorine available for chlorination of dioxin precursors<sup>18</sup> or in making unavailable metal catalytic sites such as Cu (II) by converting them to CuSO<sub>4</sub> and rendering them inactive<sup>19</sup>.

**Table 4** provides a comparison of PCDD/F emissions from firing wood residue and coal with and without BKM sludge. **Table 5** presents test results on the impact of firing BKM sludge in two boilers (7 to 10 percent sludge), with the rest of the fuel being wood residue and coal. PCDD/F emissions from the mill CBA boiler during all four tests (one without sludge) were <0.034 ng TEQ/dscm @12% CO<sub>2</sub>, which is considerably lower than most emission data for even 100 percent wood residue combustion. PCDD/F emissions from the mill CBE boiler during all four tests (one without sludge) were < 0.020 ng TEQ/dscm @12% CO<sub>2</sub>, again quite low. The slight increase from 0.015 ng/dscm in the mill CBA boiler to 0.028 ng/dscm and the slight decrease from 0.017

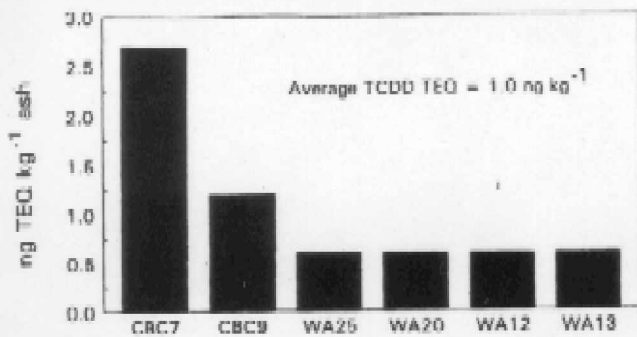
ng/dscm (one run) to ng/dscm (three runs) in the mill CBE boiler, both when burning BKM sludge, are perhaps statistically insignificant.

**Table 5** provides a summary of tests conducted on the mill CBA boiler for uncontrolled PCDD/F emissions when the following fuel combinations were fired: (a) wood only, (b) wood and coal, (c) wood, coal, and BKM sludge, (d) wood and BKM sludge. All tests were conducted at the air preheater exit location, before the pollution control device (electroscrubber). These concentrations of PCDD/Fs are indicative of relatively uncontrolled PCDD/F emissions. The uncontrolled emissions ranged from 0.16 to 0.91 ng TEQ/dscm @12% CO<sub>2</sub>. In this set of tests there appears to be a small increase of the uncontrolled emissions resulting from BKM sludge burning.

A comparison of uncontrolled PCDD/F emissions from the mill CBA boiler given in **Table 5** for (a) coal/wood/BKM sludge combustion and (b) coal/wood combustion with controlled emissions after the control device (electroscrubber) for the same fuel combinations fired given in **Table 3** provides estimates of PCDD/F removal efficiencies across the electroscrubber. PCDD/F TEQs were removed at 95.9 percent and 90.5 percent efficiencies across the electroscrubber for the coal/wood/sludge and coal/wood combination firing scenarios, respectively.

In summary it can be concluded that the firing of coal and/or BKM sludge does not seem to adversely impact the level of PCDD/F emissions from a wood-fired boiler. In fact, the data often suggest some positive effects from burning of these sulfur-containing fuels as far as PCDD/F emissions are concerned.

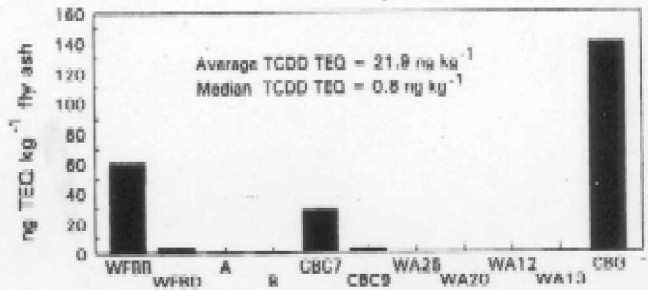




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Figure 2.

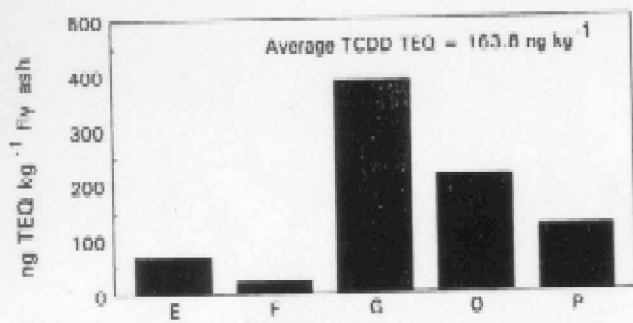
PCDD/Fs in bottom ashes from six bark/wood fired boilers – U.S. industrial sources.



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Figure 3.

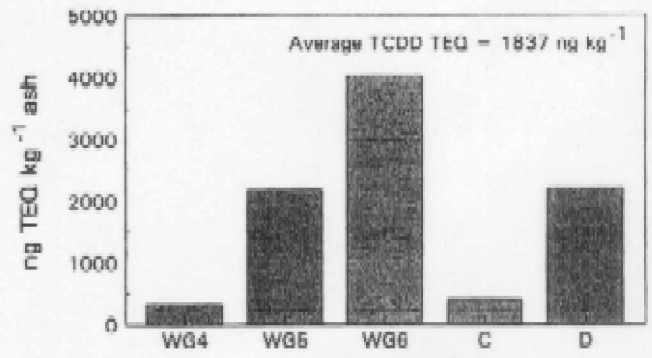
PCDD/Fs in fly ashes from 11 bark/wood fired boilers – U.S. industrial sources.



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Fig. 4.

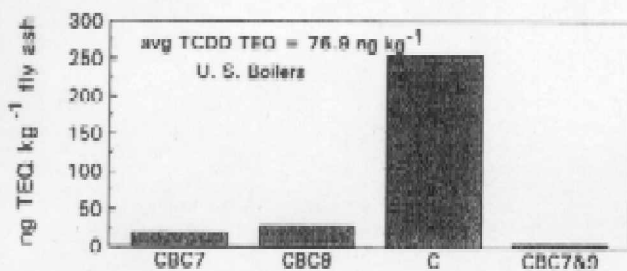
PCDD/Fs in fly ashes from bark/wood fired boilers - Scandinavian industrial sources.



MILL CODE

Fig. 5.

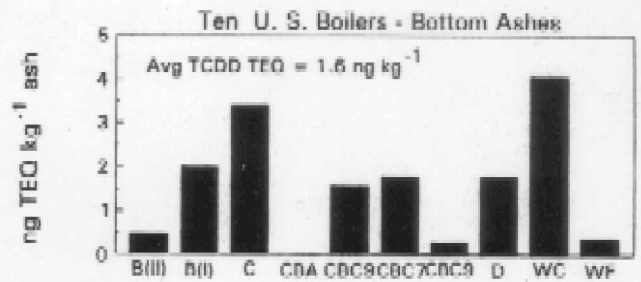
PCDD/Fs in five fly ashes from salty wood combustion – U.S. and Canadian industrial sources



MILL CODE

Fig. 6.

PCDD/Fs fly ashes from five European boilers firing with BKM



MILL CODE

Fig. 5.

PCDD/Fs TEQ concentrations in in fly ashes and bottom ashes from boilers firing with several combination wood wastes

## PCDD/Fs in Inland Wood Residue Boiler Ashes

The release of PCDD/Fs from various sources into the environment has been investigated extensively, especially the release from various combustion sources. Kuykendal et al summarized the combustion ash sample PCDD/Fs data obtained during the Tier 4, Combustion Sources, USEPA National Dioxin Study. Data for 74 sites representing 22 combustion source categories were included. In the source category of wood-fired boilers, eight ash sites were sampled with a total of 10 ashes tested for the various PCDD/F isomers. The levels of PCDD/Fs found in two bottom ashes and four multi-clone ashes during the Tier 4 testing program were all either at non-detect or at very low concentration. The data from most facilities tested did not burn salt-laden wood residue. Three baghouse ash samples and one scrubber water discharge ash contained very high levels of PCDD/Fs. All the sources were reportedly burning salt-laden wood residue. Most facilities in the USA do not burn salt-laden wood residue.

Ashes resulting from the combustion of wood residues in industrial boilers were also characterized relative to PCDD/Fs and the results were summarized in a recent publication by Someshwar<sup>20</sup>. The results from various studies on PCDD/Fs in inland wood ashes summarized by Someshwar are shown in **Figures 2-7**. The six bottom ashes shown in **Figure 2** had negligible levels of PCDD/Fs TEQs. The 11 fly ashes shown in **Figure 3** had PCDD/Fs levels ranging from 0.6 to 140 ng/kg TEQ, with an average of 21.9 ng/kg and a median of only 0.8 ng/kg (note that **1 ng/kg = 1 ppt**). PCDD/Fs TEQs in five fly ashes from boilers burning bark or wood waste in two European countries are shown in **Figure 4**. The total TEQs in these ashes are higher than in their U.S. counterparts, ranging from 22 to 390 ng/kg, and averaging about 164 ng/kg. It has been reported that chloride levels of 250 mg/kg may be higher than inland wood residues and barks burned in the USA. The PCDD/F concentrations in five salt-laden wood-fired boiler fly ashes are summarized in **Figure 5**. Ash TEQs ranged from 340 to 4029 ng/kg, averaging about 1837 ng/kg. The TCDD TEQ concentrations in four U.S. bark boiler fly ashes when BKM sludge was also burned with the bark are shown in **Figure 6**. Also shown in **Figure 6** are fly ash TEQ concentrations in five European bark boiler ashes when BKM sludge was co-fired in these boilers. The ash TEQs in these five boilers ranged from 10 to 1200 ng/kg and averaged about 396 ng/kg. Grate boiler fly ashes (Mill G) clearly contained much higher levels of TCDD TEQs than either bubbling fluidized bed (Mill E) or circulating fluidized bed boiler (Mill F) fly ashes. More efficient combustion in fluidized bed boilers is probably responsible for lower fly ash PCDD/F concentrations. The PCDD/F TEQ concentrations in bottom ash and fly ash are summarized for 10 combination bark boiler bottom ashes and 18 combination bark boiler fly ashes in **Figure 7**. All boilers burned small quantities of BKM sludge. Bottom ashes averaged about 1.6 ng/kg. The 18 fly ashes from boilers burning various combinations of wood residue and BMK sludge with fuel oil, natural gas, and coal ranged in PCDD TEQ content from 0.9 to 607 ng/kg and averaged about 143 ng/kg. The following table summarizes PCDD/F levels attached on fly and bottom ashes produced from four different combination fuels.

**Table 6**

Fuel	Emission Factors for US Boilers	
(a) Wood, Bark	22 ng/kg	(fly ash)
(a) Wood, Bark	1 ng/kg	(bottom ash)
(b) Wood, Bark, BKM sludge	77 ng/kg	(fly ash)
(b) Wood, Bark, BKM sludge	2 ng/kg	(bottom ash)
(c) Wood, Bark, BKM sludge, Coal, Oil, & Natural gas	143 ng/kg	(fly ash)
(c) Wood, Bark, BKM sludge, Coal, Oil, & Natural gas	1.6 ng/kg	(bottom ash)
(d) Salt-laden wood	1837 ng/kg	(fly ash)

The **Table 6** summarizes PCDD/F levels attached on fly and bottom ashes produced from inland wood, bark, salt-laden wood, coal, oil, and natural gas burned with and without BKM sludge. Results show that fly ash from salt-laden wood and BKM mixed fuels have higher concentrations of PCDD/F compared to inland wood and bark.

Mantykoski et al in Finland did a study on combustion products of biosludge from pulp mill<sup>21</sup>. They reported that an average concentration of PCDD/Fs in fly ash samples was 10 ng/kg. This result is in concurrence with the data reported by NCASI. NCASI's Technical Bulletin<sup>22</sup> presented the results of a study designed to investigate the effects of burning sludge of bleached mill origin, and mixed with bark, on the presence of PCDD/Fs in boiler and control device(s) ashes. In this study, four bleached Kraft mills were chosen. Each of these mills combusted waste treatment sludge (from 0 to 33% by weight) along with bark in combination power boilers. Many ash samples were collected from each mill's sampling ports at different control equipment and analyzed for PCDD/Fs as TEQs. The results are summarized from **Tables 3** and **5** as follows:

Analytes	Cyclon Fly	Cyclon Bottom	Wet Scrub	ESP	Dewatered Sludge
	ng/kg	ng/kg	ng/kg	ng/kg	ng/kg
PCDD/Fs TEQs	3	ND	1.03	4	49

These results indicate that the PCDD/F concentrations in both the cyclone fly and bottom ashes and ashes from ESP are low. However, analysis done on dewatered raw sludges show relatively high concentration due to bleaching process. NCASI Technical Bulletin<sup>23</sup> suggest that less than 1% of the total PCDD/Fs in sludges burned were found to be present in the combustion ashes. This report concludes that firing bleached Kraft mill sludges does not adversely impact the level of PCDD/F emissions from a wood-fired boiler. In fact, the test data suggest some positive effects from the burning of these sulfur-containing fuels as far as PCDD/F emissions are concerned. The data reported by NCASI was used by the EPA's Office of Air Quality Planning and Standards in connection with the ICCR process. Similar findings have been reported by the Canadian research by PAPRICAN. Recently, Raili and Martti<sup>24</sup> conducted an experimental investigation on PCDD/Fs emissions from a 4 MW bubbling fluidized boiler fired with wood chips, mill peat and RDF. Emissions of PCDD/F in flue gases (collected after ESP) expressed as TEQ were significantly below the emission limit 0.1 ng/m<sup>3</sup> (11% O<sub>2</sub>). The PCDD/F concentrations of fly ashes separated by an ESP were significantly below the 1 ng/g TEQ limit for agricultural soil in Germany. The fly ashes generated were analyzed using EPA TCLP (toxicity characteristic leaching procedure) and reported that all concentrations (including heavy metals) fell below boundary levels.

## **Summary and Conclusions**

In conclusion, combustion of inland wood or wood fuel with very low levels of salt (chloride content less than 0.03%) in a hogged fuel boiler, the dioxin/furans formation and emission would be low after scrubber/FF/ESP control. As long as the salt-laden wood or pulp bleaching are kept out of the mixed wood fuel, or at least kept to a minimum, the levels of PCDD/Fs emission through flue gases (after PM control devices) should be of little concern. Recent studies demonstrated that the presence of sulfur and chlorine (S/Cl) in the mixed fuels (coal, BMK sludge) would scavenge PCDD/Fs formation/emission. It can be concluded that the firing of sulfur content coal and/or BKM sludge does not seem to adversely impact the level of PCDD/F emissions from wood-fired boilers. In fact, the data often suggest some positive effects from the burning of these sulfur-containing fuels as far as PCDD/F emissions are concerned.

The available data suggest that for combustion of inland wood residue or wood fuel with very low levels of chloride content (<0.03%), the dioxin level in the ashes is of no concern. However, higher levels of chloride in the fuel mix from whatever additional source (salt water, bleached Kraft mill sludge, etc) have the potential to create higher levels of PCDD/Fs in ash. Nevertheless, the correlation between fuel chloride and combustion ash PCDD/F concentration is not fully understood. However, as long as extraneous sources of chloride such as from salt water or pulp bleaching are kept out of the wood fuel mix, or kept to a minimum, levels of dioxins and furans in the ash should also be of little or no concern.

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# Appendix F - Hog-Fuel Boiler RACT Toxicological Analysis

## Abstract

The Washington Department of Ecology Air Quality Program (Ecology) predicted the emissions and ambient concentrations of 90 chemicals (or groups of chemicals) including certain aldehydes, ketones, phenols, PAHs, phthalates, halocarbons, and other organic chemicals that would be produced by Hog-Fuel Boiler (HFB) sources meeting proposed Reasonably Available Control Technology (RACT).

Ecology estimated the concentrations of these chemicals using atmospheric dispersion modeling of the estimated emissions. The estimated concentrations were then compared to health-based standards as a hazard screening step. Acrolein and formaldehyde are the only chemicals that exceed the hazard quotient of one, and are therefore analyzed in greater detail in order to characterize the risk they pose. Acrolein, formaldehyde, and about half of the other 90 chemicals have reference health-based standards; however, such standards are not available for the other HFB chemicals identified by Ecology. To help exemplify the risks these standardless chemicals might pose, Ecology categorized them by chemical structure, and presents what is known about the toxicity of structurally related chemicals.

This appendix cites risk modeling done by USEPA to determine acrolein and formaldehyde risk distributions for a typical person in Washington. There are significant risks of adverse respiratory tract effects from acrolein exposure for some people: in particular sensitive persons (those with pre-existing respiratory illnesses such as asthma, COPD, chronic bronchitis, etc.) Acrolein is capable of causing irritation of the eyes, nose, throat, and respiratory tract in a person with typical levels of exposure in Washington, both outdoors and inside buildings. The frequency and level of exposure are highly variable. Consequently, such risks range widely across Washington. On average, major industrial sources – in which HFBs are included – are thought to account for less than 1% of the ambient acrolein concentration; therefore, implementation of the proposed HFB RACT would reduce the statewide average concentration only slightly. However, in the immediate vicinity of HFBs, the effect of implementing RACT could help reduce acrolein health hazards significantly. Formaldehyde is a probable human carcinogen, based on limited evidence in humans, and sufficient evidence in animals. The level of formaldehyde throughout much of Washington is estimated to be higher than that which could increase a person's cancer risk by  $10^{-6}$  (1 in 1,000,000). USEPA estimated that on average in Washington, 2% of formaldehyde emissions are from major sources (which include HFBs). With the implementation of HFB RACT, formaldehyde levels may be lower than they are currently but would still be excessive.

As for the HFB emission chemicals without sufficient toxicity data for setting health-based standard's, there is qualitative evidence suggesting the possibility of a variety of serious adverse health effects. Respiratory tract and eye irritation seem the most likely results of exposure to HFB emissions at the calculated concentrations. Also possible are certain types of cancer, immunosuppression, neurological effects, and effects on skin and other organs. Public health should be monitored carefully in exposed populations with the possibility that such health effects, if occurring, might be related to HFB emission exposures.

## Introduction

The Washington Department of Ecology Air Quality Program (Ecology) has identified and predicted the emissions and ambient concentrations of 90 chemicals (or groups of chemicals) that would result from the Hog-Fuel Boiler (HFB) sources meeting proposed Reasonably Available Control Technology (RACT) standards. These chemicals and their estimates are shown in Table 1.

Table 1. Emission Factor for Speciated Toxic VOC Emission Rate (Max. Ambient Conc. Based on a 200 MMBtu/hr Fuel Feed Rate)

Organic Compound	Average Emission Factor <sup>[1]</sup>	Emission Rate in g/s <sup>[2]</sup>	Worst-case max. 1-hr conc. <sup>[3]</sup>	24-hr max. avg. conc. <sup>[4]</sup>	Yearly avg. conc. <sup>[5]</sup>
	lbs/MMBtu	@ 200 MMBtu/hr	@ 9.94- μg/m <sup>3</sup>	μg/m <sup>3</sup>	μg/m <sup>3</sup>
Acenaphthene	9.10E-07	2.30E-05	2.28E-04	9.13E-05	1.83E-05
Acenaphthylene	5.00E-06	1.26E-04	1.25E-03	5.02E-04	1.00E-04
Acetaldehyde	8.30E-04	2.10E-02	2.08E-01	8.33E-02	1.67E-02
Acetone	1.90E-04	4.80E-03	4.77E-02	1.91E-02	3.81E-03
Acetophenone	3.20E-09	8.08E-08	8.03E-07	3.21E-07	6.42E-08
Acrolein	4.00E-03	1.01E-01	1.00E+00	4.01E-01	8.03E-02
Anthracene	3.00E-06	7.57E-05	7.53E-04	3.01E-04	6.02E-05
Benzaldehyde	8.50E-07	2.15E-05	2.13E-04	8.53E-05	1.71E-05
Benzene	4.20E-03	1.06E-01	1.05E+00	4.22E-01	8.43E-02
Benzo(a)anthracene	6.50E-08	1.64E-06	1.63E-05	6.52E-06	1.30E-06
Benzo(a)pyrene	2.60E-06	6.56E-05	6.52E-04	2.61E-04	5.22E-05
Benzo(b)fluoranthene	1.00E-07	2.52E-06	2.51E-05	1.00E-05	2.01E-06
Benzo(e)pyrene	2.60E-09	6.56E-08	6.52E-07	2.61E-07	5.22E-08
Benzo(g,h,i)perylene	9.30E-08	2.35E-06	2.33E-05	9.33E-06	1.87E-06
Benzo(j,k)fluoranthene	1.60E-07	4.04E-06	4.01E-05	1.61E-05	3.21E-06
Benzo(k)fluoranthene	3.60E-08	9.09E-07	9.03E-06	3.61E-06	7.23E-07
Benzoic acid	4.70E-08	1.19E-06	1.18E-05	4.72E-06	9.43E-07
bis(2-Ethylhexyl)phthalate	4.70E-08	1.19E-06	1.18E-05	4.72E-06	9.43E-07
Bromomethane	1.50E-05	3.79E-04	3.76E-03	1.51E-03	3.01E-04
2-Butanone (MEK)	5.40E-06	1.36E-04	1.35E-03	5.42E-04	1.08E-04
Carbazole	1.80E-06	4.54E-05	4.52E-04	1.81E-04	3.61E-05
Carbon tetrachloride	4.50E-05	1.14E-03	1.13E-02	4.52E-03	9.03E-04
Chlorine	7.90E-04	1.99E-02	1.98E-01	7.93E-02	1.59E-02
Chlorobenzene	3.30E-05	8.33E-04	8.28E-03	3.31E-03	6.62E-04
Chloroform	2.80E-05	7.07E-04	7.03E-03	2.81E-03	5.62E-04

Chloromethane	2.30E-05	5.81E-04	5.77E-03	2.31E-03	4.62E-04
2-Chloronaphthalene	2.40E-09	6.06E-08	6.02E-07	2.41E-07	4.82E-08
2-Chlorophenol	2.40E-08	6.06E-07	6.02E-06	2.41E-06	4.82E-07
Chrysene	3.80E-08	9.59E-07	9.53E-06	3.81E-06	7.63E-07
Crotonaldehyde	9.90E-06	2.50E-04	2.48E-03	9.94E-04	1.99E-04
Decachlorobiphenyl	2.70E-10	6.82E-09	6.77E-08	2.71E-08	5.42E-09
Dibenzo(a,h)anthracene	9.10E-09	2.30E-07	2.28E-06	9.13E-07	1.83E-07
1,2-Dibromoethene	5.50E-05	1.39E-03	1.38E-02	5.52E-03	1.10E-03
Dichlorobiphenyl	7.40E-10	1.87E-08	1.86E-07	7.43E-08	1.49E-08
1,2-Dichloroethane	2.90E-05	7.32E-04	7.28E-03	2.91E-03	5.82E-04
Dichloromethane	2.90E-04	7.32E-03	7.28E-02	2.91E-02	5.82E-03
1,2-Dichloropropane	3.30E-05	8.33E-04	8.28E-03	3.31E-03	6.62E-04
2,4-Dinitrophenol	1.80E-07	4.54E-06	4.52E-05	1.81E-05	3.61E-06
Ethylbenzene	3.10E-05	7.83E-04	7.78E-03	3.11E-03	6.22E-04
Fluoranthene	1.60E-06	4.04E-05	4.01E-04	1.61E-04	3.21E-05
Fluorene	3.40E-06	8.58E-05	8.53E-04	3.41E-04	6.82E-05
Formaldehyde	4.40E-03	1.11E-01	1.10E+00	4.42E-01	8.83E-02
Heptachlorobiphenyl	6.60E-11	1.67E-09	1.66E-08	6.62E-09	1.32E-09
Hexachlorobiphenyl	5.50E-10	1.39E-08	1.38E-07	5.52E-08	1.10E-08
Hexanal	7.00E-06	1.77E-04	1.76E-03	7.03E-04	1.41E-04
Heptachlorodibenzo-p-dioxins	2.00E-09	5.05E-08	5.02E-07	2.01E-07	4.01E-08
Heptachlorodibenzofurans	2.40E-10	6.06E-09	6.02E-08	2.41E-08	4.82E-09
Hexachlorodibenzo-p-dioxins	1.60E-06	4.04E-05	4.01E-04	1.61E-04	3.21E-05
Hexachlorodibenzofurans	2.80E-10	7.07E-09	7.03E-08	2.81E-08	5.62E-09
Hydrogen chloride	1.90E-02	4.80E-01	4.77E+00	1.91E+00	3.81E-01
Indeno(1,2,3,c,d)pyrene	8.70E-08	2.20E-06	2.18E-05	8.73E-06	1.75E-06
Isobutyraldehyde	1.20E-05	3.03E-04	3.01E-03	1.20E-03	2.41E-04
Methane	2.10E-02	5.30E-01	5.27E+00	2.11E+00	4.22E-01
2-Methylnaphthalene	1.60E-07	4.04E-06	4.01E-05	1.61E-05	3.21E-06
Monochlorobiphenyl	2.20E-10	5.55E-09	5.52E-08	2.21E-08	4.42E-09
Naphthalene	9.70E-05	2.45E-03	2.43E-02	9.74E-03	1.95E-03
2-Nitrophenol	2.40E-07	6.06E-06	6.02E-05	2.41E-05	4.82E-06
4-Nitrophenol	1.10E-07	2.78E-06	2.76E-05	1.10E-05	2.21E-06
Octachlorodibenzo-p-dioxins	6.60E-08	1.67E-06	1.66E-05	6.62E-06	1.32E-06
Octachlorodibenzofurans	8.80E-11	2.22E-09	2.21E-08	8.83E-09	1.77E-09
Pentachlorodibenzo-p-dioxins	1.50E-09	3.79E-08	3.76E-07	1.51E-07	3.01E-08
Pentachlorodibenzofurans	4.20E-10	1.06E-08	1.05E-07	4.22E-08	8.43E-09
Pentachlorobiphenyl	1.20E-09	3.03E-08	3.01E-07	1.20E-07	2.41E-08
Pentachlorophenol	5.10E-08	1.29E-06	1.28E-05	5.12E-06	1.02E-06
Perylene	5.20E-10	1.31E-08	1.30E-07	5.22E-08	1.04E-08
Phenanthrene	7.00E-06	1.77E-04	1.76E-03	7.03E-04	1.41E-04
Phenol	5.10E-05	1.29E-03	1.28E-02	5.12E-03	1.02E-03
Propanal [Propionaldehyde]	3.20E-06	8.08E-05	8.03E-04	3.21E-04	6.42E-05
Propionaldehyde [Propanal]	6.10E-05	1.54E-03	1.53E-02	6.12E-03	1.22E-03
Pyrene	3.70E-06	9.34E-05	9.28E-04	3.71E-04	7.43E-05

Styrene	1.90E-03	4.80E-02	4.77E-01	1.91E-01	3.81E-02
2,3,7,8-Tetrachlorodibenzo-p-dioxin	8.60E-12	2.17E-10	2.16E-09	8.63E-10	1.73E-10
Tetrachlorodibenzo-p-dioxins	4.70E-10	1.19E-08	1.18E-07	4.72E-08	9.43E-09
2,3,7,8-Tetrachlorodibenzofuran	9.00E-11	2.27E-09	2.26E-08	9.03E-09	1.81E-09
Tetrachlorodibenzofurans	7.50E-10	1.89E-08	1.88E-07	7.53E-08	1.51E-08
Tetrachlorobiphenyl	2.50E-09	6.31E-08	6.27E-07	2.51E-07	5.02E-08
Tetrachloroethene	3.80E-05	9.59E-04	9.53E-03	3.81E-03	7.63E-04
o-Tolualdehyde	7.20E-06	1.82E-04	1.81E-03	7.23E-04	1.45E-04
p-Tolualdehyde	1.10E-05	2.78E-04	2.76E-03	1.10E-03	2.21E-04
Toluene	9.20E-04	2.32E-02	2.31E-01	9.23E-02	1.85E-02
Trichlorobiphenyl	2.60E-09	6.56E-08	6.52E-07	2.61E-07	5.22E-08
1,1,1-Trichloroethane	3.10E-05	7.83E-04	7.78E-03	3.11E-03	6.22E-04
Trichloroethene	3.00E-05	7.57E-04	7.53E-03	3.01E-03	6.02E-04
Trichlorofluoromethane	4.10E-05	1.03E-03	1.03E-02	4.11E-03	8.23E-04
2,4,6-Trichlorophenol	2.20E-08	5.55E-07	5.52E-06	2.21E-06	4.42E-07
Vinyl Chloride	1.80E-05	4.54E-04	4.52E-03	1.81E-03	3.61E-04
o-Xylene	2.50E-05	6.31E-04	6.27E-03	2.51E-03	5.02E-04
Total organic compounds (TOC)	0.06	1.51E+00	1.51E+01	6.02E+00	1.20E+00
Volatile organic compounds	0.038	9.59E-01	9.53E+00	3.81E+00	7.63E-01
Nitrous Oxide (N <sub>2</sub> O)	0.013	3.28E-01	3.26E+00	1.30E+00	2.61E-01
Carbon Dioxide (CO <sub>2</sub> )	195	4.92E+03	4.89E+04	1.96E+04	3.91E+03

[<sup>1</sup>] Emission factors from AP-42 (assuming no control for TAPs and the emission factors are the worst-case scenario as far the TAPs are concerned).

[<sup>2</sup>] Emission rates in (g/s) for a 200 MMBtu/hr hog fuel feed rate (an average size model boiler in the state).

[<sup>3</sup>] The maximum 1-hr concentrations based on the SCREEN model for several facilities (at Daisawa, the max. conc. is 9.94- $\mu\text{g}/\text{m}^3$ ). The Emission rate data were multiplied by a factor of by 9.94 to obtain the max. 1-hr conc. in  $\mu\text{g}/\text{m}^3$  for all TAPs.

[<sup>4</sup>] Max. 24-hr concentration in  $\mu\text{g}/\text{m}^3$  (the worst-case max. 1-hr conc. data were multiplied by a factor of 0.4).

[<sup>5</sup>] Yearly average concentration in  $\mu\text{g}/\text{m}^3$  (the 24-hr max. av. conc. data were multiplied by a factor of 0.08).

## What about metals?

A variety of metals, ranging from antimony to zinc, have been reported in wood-fired boiler emissions, particularly if the wood-waste fuel is contaminated with certain toxic metals. Various metals present potential health risks such as respiratory cancers, kidney damage, neurological effects, and developmental decrements, depending on the amounts of the various metals present. Similarly, a wide range of health effects is associated with exposure to airborne metal compounds and dusts. For example, airborne arsenic and chromium compounds are associated with lung

cancer in humans exposed in a variety of occupational settings. Both metals are classified as “A” or “*known human carcinogens*” by USEPA.<sup>58</sup> Non-cancerous health effects are also reported with a number of metals. For example, exposure to lead has been shown to cause a number of health effects in humans, particularly in young children. Because it is not readily excreted, lead can adversely affect the kidneys, liver, and other organs. Even at low doses, lead exposure is associated with damage to the nervous systems of fetuses and young children, resulting in learning deficits and lowered IQ. Recent studies also show that lead may be a factor in high blood pressure and subsequent heart disease.

Metals are notably absent from the list of substances considered here in Table 1. This is because the amounts emitted from hog fuel boilers are expected to be too variable for reliable prediction and generally small compared to organic chemical emissions.

## Hazard Screening

Among the 90 chemicals, 31 had established ASILs, and another 15 had health-based standards set by some other authority. There were 45 chemicals without any available health-based standards. Thus, in order to complete a hazard screening, the concentrations resulting from estimated emissions of 46 out of 90 chemicals could be compared to health-based standards. Ecology did not compare the “Worst-case max. 1-hr concs.” to any health-based standards. The results of the hazard screenings, using other concentration averaging durations, are summarized in Tables 2, 3, and 4.

Table 2. Hazard Quotient Exceeded

HFB Chemical	Toxicity Criterion ( $\mu\text{g}/\text{m}^3$ )	Averaging Time	Criterion Source	Predicted conc. / Criterion
Acrolein	0.02	24-hr	ASIL	20.073
Formaldehyde	0.077	annual	ASIL	1.147

As shown in Table 2, the risks from acrolein and formaldehyde emitted by HFB may or may not be within acceptable levels, even with BACT in place. However, as shown in Table 3, hazard quotients are less than one for several other chemicals emitted by HFB with RACT.

Table 3. Hazard Quotient Not Exceeded

HFB Chemical	CAS	Toxicity Criterion ( $\mu\text{g}/\text{m}^3$ )	Averaging Time	Criterion Source	Predicted conc./ Criterion
<b>Aldehydes</b>					
Acetaldehyde	000075-07-0	0.45	annual	ASIL	0.037
Crotonaldehyde	004170-30-3	20	24-hr	ASIL	0.000

**Other Gasses**

Chlorine	007782-50-5	5	24-hr	ASIL	0.016
Hydrogen chloride	007647-01-0	7	24-hr	ASIL	0.272
Nitrous Oxide (N <sub>2</sub> O)	010024-97-2	18.004	annual	TLV/5000 <sup>[1]</sup>	0.014

**Halocarbons**

1,1,1-Trichloroethane	000071-55-6	6400	24-hr	ASIL	0.000
1,2-Dichloroethane	000107-06-2	0.038	annual	ASIL	0.015
1,2-Dichloropropane	000078-87-5	4	24-hr	ASIL	0.001
Bromomethane	000074-83-9	5	24-hr	ASIL	0.000
Carbon tetrachloride	000056-23-5	0.067	annual	ASIL	0.013
Chlorobenzene	000108-90-7	150	24-hr	ASIL	0.000
Chloroform	000067-66-3	0.043	annual	ASIL	0.013
Chloromethane	000074-87-3	340	24-hr	ASIL	0.000
Dichloromethane	000075-09-2	0.56	annual	ASIL	0.010
Tetrachloroethene	000127-18-4	1.1	annual	ASIL	0.001
Trichloroethylene	000079-01-6	0.59	annual	ASIL	0.001
Trichlorofluoromethane	000075-69-4	19000	24-hr	ASIL	0.000
Vinyl Chloride	000075-01-4	0.012	annual	ASIL	0.030

**Dioxins and Furans**

2,3,7,8-Tetrachlorodibenzo-p-dioxin	051207-31-9	2.63E-06	annual	OEHHA E-5 <sup>[2]</sup>	0.001
2,3,7,8-Tetrachlorodibenzofuran	001746-01-6	3E-08	annual	ASIL	0.006
Hexachlorodibenzo-p-dioxins	019408-74-3	0.0004	annual	OEHHA E-5 <sup>[2]</sup>	0.080
Octachlorodibenzo-p-dioxin	003268-87-9	0.000263	annual	OEHHA E-5 <sup>[2]</sup>	0.005
Octachlorodibenzofuran	039001-02-0	0.000263	annual	OEHHA E-5 <sup>[2]</sup>	0.000

**Ketones**

2-Butanone (MEK)	000078-93-3	1	24-hr	ASIL	0.000
Acetone	000067-64-1	5.9	24-hr	ASIL	0.000
Acetophenone	000098-86-2	2.00E-05	annual	IRIS RfC <sup>[3]</sup>	0.000

**Phenols**

2,4,6-Trichlorophenol	000088-06-2	0.00032	annual	ASIL	0.000
2-Chlorophenol	000095-57-8	0.018	annual	OEHHA REL <sup>[4]</sup>	0.000
Pentachlorophenol	000087-86-5	0.00033	annual	ASIL	0.000
Phenol	000108-95-2	0.063	24-hr	ASIL	0.000

**PAHs**

Benzo(a)anthracene	000056-55-3	9.09E-05	annual	OEHHA E-5 <sup>[2]</sup>	0.000
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Benzo(a)pyrene	000050-32-8	4.8E-07	annual	ASIL	0.109
Benzo(b)fluoranthene	000205-99-2	9.09E-05	annual	OEHHA E-5 <sup>[2]</sup>	0.000
Benzo(k)fluoranthene	000207-08-9	9.09E-05	annual	OEHHA E-5 <sup>[2]</sup>	0.000
Chrysene	000218-01-9	0.000909	annual	OEHHA E-5 <sup>[2]</sup>	0.000
Dibenz(a,h)anthracene	000053-70-3	1.14E-05	annual	IRIS E-5	0.000
Indeno(1,2,3,c,d)pyrene	000193-39-5	9.09E-05	annual	OEHHA E-5 <sup>[2]</sup>	0.000
Naphthalene	000091-20-3	0.17	24-hr	ASIL	0.000

#### Other Aromatics

Benzene	000071-43-2	0.00012	annual	ASIL	0.703
Ethylbenzene	000100-41-4	1	24-hr	ASIL	<0.001
o-Xylene	000095-47-6	0.7	annual	OEHHA REL <sup>[4]</sup>	<0.001
Styrene	000100-42-5	1	24-hr	ASIL	<0.001
Toluene	000108-88-3	0.4	24-hr	ASIL	<0.001

#### Phthalates

Bis(2-Ethylhexyl)phthalate	000117-81-7	0.0025	annual	ASIL	<0.001
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[1] The American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) divided by a factor of 5000 in order to adjust workplace exposure limits, developed for healthy workers having repeated 40- hour work week exposures to a continuous general population exposure.

[2] The E<sup>-5</sup> (1/100,000) excess risk level exposure concentration, based on State of California Inhalation Unit Risk ( $\mu\text{g}/\text{m}^3$ )<sup>-1</sup>, published in the *Technical Support Document for Describing Available Cancer Potency Factors* (OEHHA, 1999).

[3] The USEPA integrated risk information system (IRIS) reference concentration (RfC).

[4] The State of California reference exposure limit (REL), published in the *Chronic Reference Exposure Levels and Target Organs* list adopted by OEHHA March 4, 2002 (<http://www.arb.ca.gov/toxics/healthval/chronic.pdf>).

There are several chemicals known to be emitted from HFBs but for which screening concentration criteria are not available. We did not complete the hazard screening step for these chemicals, but did categorize them by chemical structure, as shown in Table 4, to help characterize the risks they might pose based on what is known of the toxicity of structurally related chemicals.

Table 4. Insufficient Toxicity Data For Hazard Quotient Analysis

Aldehydes	CAS	PAHs	CAS
Benzaldehyde	000100-52-7	2-Chloronaphthalene	000091-58-7
Hexanal	000066-25-1	2-Methylnaphthalene	000091-57-6
Isobutyraldehyde	000078-84-2	Acenaphthene	000083-32-9
Propionaldehyde (Propanal)	000123-38-6	Acenaphthylene	000208-96-8
o-Tolualdehyde	000529-20-4	Anthracene	000120-12-7
p-Tolualdehyde	000104-87-0	Benzo(e)pyrene	000192-97-2
		Benzo(g,h,i)perylene	000191-24-2

<b>Aromatics</b>		Benzo(j,k)fluoranthene	000206-44-0
Benzoic acid	000065-85-0	Carbazole	000086-74-8
<b>Dioxins and Furans</b>		Fluoranthene	000206-44-0
Heptachlorodibenzofurans	038998-75-3	Fluorene	000086-73-7
Heptachlorodibenzo-p-dioxins	037871-00-4	Perylene	000198-55-0
Hexachlorodibenzofurans	055684-94-1	Phenanthrene	000085-01-8
Pentachlorodibenzofurans	030402-15-4	Pyrene	000129-00-0
Pentachlorodibenzo-p-dioxins	036088-22-9	<b>Other Gasses</b>	
Tetrachlorodibenzo-p-dioxin	041903-57-5	Carbon Dioxide	000124-38-9
Tetrachlorodibenzourans	030402-14-3	Methane	000074-82-8
<b>PCBs</b>		<b>Halocarbons</b>	
Decachlorobiphenyl	002051-24-3	1,2-Dibromoethene	000540-49-8
Dichlorobiphenyl	002050-68-2	<b>Nitrophenols</b>	
Heptachlorobiphenyl	028655-71-2	2,4-Dinitrophenol	000051-28-5
Hexachlorobiphenyl	026601-64-9	2-Nitrophenol	000088-75-5
Pentachlorobiphenyl	025429-29-2	4-Nitrophenol	000100-02-7
Tetrachlorobiphenyl	026914-33-0		

The various health effects of chemicals in these categories (in Table 4) are summarized in Table 5.

Table 5. Potential Health Effects

Pollutant	Health Effects
<b>Aldehydes</b>	Respiratory cancers (nasal and laryngeal), nasal irritation.  Several aldehydes have been reported from wood-fired boilers, including benzaldehyde, formaldehyde, and acetaldehyde. Health effects associated with inhalation of acetaldehyde include nasal and laryngeal cancers in laboratory animals. Because the human data on acetaldehyde exposure is limited and inconclusive, acetaldehyde is rated a B2, or probable human carcinogen. Non-carcinogenic effects such as irritation of the nasal epithelium and trachea were also found in lab animals exposed via inhalation. <sup>59</sup> Similar health effects have been reported for formaldehyde with somewhat stronger carcinogenicity evidence reported in humans. Rats and mice exposed long-term to airborne formaldehyde showed significant increases in nasal squamous cell carcinomas. Since nine epidemiological studies in humans have shown statistically significant increases in respiratory cancers, formaldehyde is classified as a B1, or probable human carcinogen, by USEPA. <sup>60</sup>

<sup>59</sup> USEPA 1999. Integrated Risk Information System. *Toxicological file for acetaldehyde*.

<sup>60</sup> USEPA, 1999. Integrated Risk Information System. *Toxicological file for formaldehyde*.



**Aromatics**  
Benzoic acid

Benzoic acid is probably not toxic at these or lower concentrations.

**Dioxins and  
Furans**

Skin, liver, and thyroid toxicity, suppression of immunity, cancer, developmental and birth defects, endocrine effects.

This group of chemicals may be produced when chlorine contaminated wood wastes are burned, as occurs when logs have been submerged in seawater before processing. Dioxins and furans are classified as B2 or probable human carcinogens by USEPA (USEPA, 1994). However, more recent analyses by the Centers for Disease Control and the International Agency for Research on Cancer (IARC) have upgraded dioxin from a *probable* to a *known* human carcinogen.<sup>61</sup> Dioxins are also associated with a number of non-carcinogenic health effects including neurological, immunological, and developmental impairment. In addition, dioxins and furans tend to biomagnify in the environment. As a result, even relatively low emission levels can result in high exposure levels for individuals that are higher in the food chain.<sup>62</sup>

**Gasses**  
Carbon dioxide  
Methane

At these levels, the greenhouse gasses, carbon dioxide and methane, do not pose a significant risk of asphyxiation.

**Halocarbons**  
(Other chlorinated  
compounds like  
1,2-Dibromoethene)

Many of halogenated hydrocarbons have the ability to form toxic contaminants upon chemical reaction and are persistent when released into the environment. All halogenated solvents produce central nervous system depression upon inhalation exposure; in addition, some have demonstrated carcinogenic properties (chloroform: liver; methylene chloride: lung), and are associated with hepatotoxicity, nephrotoxicity, vasodilation, hypotension, respiratory irritation, reproductive toxicity, and immunosuppression.<sup>63</sup> Halogenated hydrocarbons are greenhouse gasses and are known to cause ozone depletion.

**Nitrophenols**

After repeated exposure by inhalation to 4-nitrophenol, the formation of methaemoglobin (causing reduced oxygen carrying ability of blood) has been shown to be the most critical effect. 2-nitrophenol is similar in toxicity but less potent. Other apparent toxic effects of mononitrophenols have not been related to exposure level and so are less certain.<sup>64</sup>

Oral ingestion by humans of doses of dinitrophenol (DNP) as low as 1000-

<sup>61</sup> ATSDR, 1998. *Toxicological Profile for Chlorinated Dibenzo(p)dioxins*. PB/99/1 21 998/AS.

<sup>62</sup> USEPA, 1994. *Dioxin Re-assessment*. EPA/600/BP-92/001. Review Draft.

<sup>63</sup> Barceloux, D.G. 1992. *Halogenated Solvents*. Hazardous Materials Toxicology, Clinical Principles of Environmental Health, J. B. Sullivan, Jr., and G. R. Krieger, Editors; Williams and Wilkins, Baltimore, Maryland, pp. 732-747

<sup>64</sup> Anon. 2000. *Mononitrophenols*. Concise International Chemical Assessment Document.

<sup>65</sup> ATSDR. 1995. *Public Health Statement for Dinitrophenols*  
<http://www.atsdr.cdc.gov/toxprofiles/phs64.html>

µg/kg body weight /day has caused weight loss, increased heart rate, breathing rate, and body temperature. Some people who took doses of DNP for various periods experienced numbness in their hands and feet, cellular immunosuppression, skin reactions, or cataracts. Inhalation, ingestion, or skin contact by humans with large amounts of DNP has caused death.<sup>65</sup>

#### **PAHs**

Cancer, suppression of immunity, reproductive and developmental impairments.

No harmful effects have been proven in humans, although animal studies have shown adverse effects on the reproductive cycle, skin, and immune system. The U.S. Department of Health and Human Services has determined that some PAHs may reasonably be expected to be carcinogens.<sup>66</sup>

Plants and animals accumulate PAHs, and the concentration in these organisms may be much greater than the concentration in surrounding air, water, or soil.

#### **PCBs**

Cancer, skin conditions, suppression of immunity, low birth weight and developmental delays, possibly liver, stomach and thyroid damage, anemia, behavioral alterations, and impaired reproduction.

Studies in humans provide supportive evidence for potential carcinogenic and non-carcinogenic effects. PCBs have been shown to cause cancer and a number of serious non-cancer health effects in animals. In addition, health effects may include effects on the nervous system, endocrine systems, blood pressure, eyes, and skin.<sup>67</sup>

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## **Assessment**

The chemicals listed in Table 4 may or may not be emitted from HFBs in quantities sufficient to harm public health of the environment. Information regarding existing background concentrations for many of these was not found, and information regarding their toxic potencies was not adequate to quantitatively estimate the excess cancer risk or non-cancer health hazards they may pose.

Most of the chemicals emitted from HFBs are probably associated with particulate matter (PM). Exposure to PM is associated with increased mortality rates, and increased incidence and severity of respiratory diseases (asthma, COPD, chronic bronchitis, etc.).

In the absence of better information, a reasonable assumption is that exposure to these chemicals will increase the risks of particular health effects to some degree, the magnitude of which cannot be determined at this time.

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<sup>66</sup> ATSDR, 1995. Toxicological Profile for Polycyclic Aromatic Hydrocarbons (PAHs)  
<http://www.atsdr.cdc.gov/toxprofiles/tp69.html>

<sup>67</sup> USEPA 2002. Health Effects of Polychlorinated Biphenyls (PCBs)  
<http://www.epa.gov/opptintr/pcb/effects.html#Other>

## Evaluation of Chemicals Exceeding Hazard Quotients

The remainder of HFB RACT toxicological analysis consists of sources, ambient concentrations, exposure and limited health effects risk assessments of acrolein and formaldehyde at the estimated concentrations.

The adverse health effect risks are expressed in two ways:

1. Risk to a hypothetical average person (expressed as the excess probability of cancer per 70-year lifetime time). The level of concern is exceeded where persons with average exposure have above 1 in 100,000 cancer risk from inhalation of some specific chemical; and
2. Proportionate health hazard (non-cancer) beyond a health-based standard. The level of concern is exceeded where the hazard quotient (exposure concentration ÷ its a health-based standard) is equal to or greater than one.

Potential cancer and non-cancer health effect risks are considered separately in this assessment because the nature of their associated uncertainties is substantially different. However, the HFB RACT control strategies should serve to reduce both categories of health risks.

Information from the USEPA's 1996 NATA<sup>68</sup> including modeling of population risk with information on population size, demographics, and behavior was used to supplement this report. Beyond this, the range of exposures and individual sensitivities to HFB emission exposures is not explored in this report.

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<sup>68</sup> USEPA. 2002. National-Scale Air Toxics Assessment for 1996. Office of Air Quality Planning and Standards. EPA-453/R-01-003

## Acrolein

$\text{H}_2\text{C}=\text{CHCHO}$  CAS Registry Number: 107-02-8 Conversion Factor: 1 ppm = 2.29-mg/m<sup>3</sup>

Acrolein is a colorless or yellowish, flammable liquid with an unpleasant, extremely pungent odor (Sax, 1989). It is a federal hazardous air pollutant.<sup>69</sup> Ecology identified it as a Class B toxic air pollutant under 173-460-160 WAC in 1991.

### 1. Sources

Acrolein is emitted from sources where it is manufactured and used as a chemical intermediate in addition to HFB emissions. It is also found in wildfire and prescribed fire emissions, diesel, gasoline, and turbine engine exhausts, and in structure fires. Further, it is a photooxidation product of various hydrocarbons including 1,3-butadiene.

Acrolein is a registered aquatic-use pesticide in Washington. It is registered as an algicide and herbicide for control of algae and waterborne weeds in irrigation canals by the State of Washington Department of Ecology, Water Quality Program.

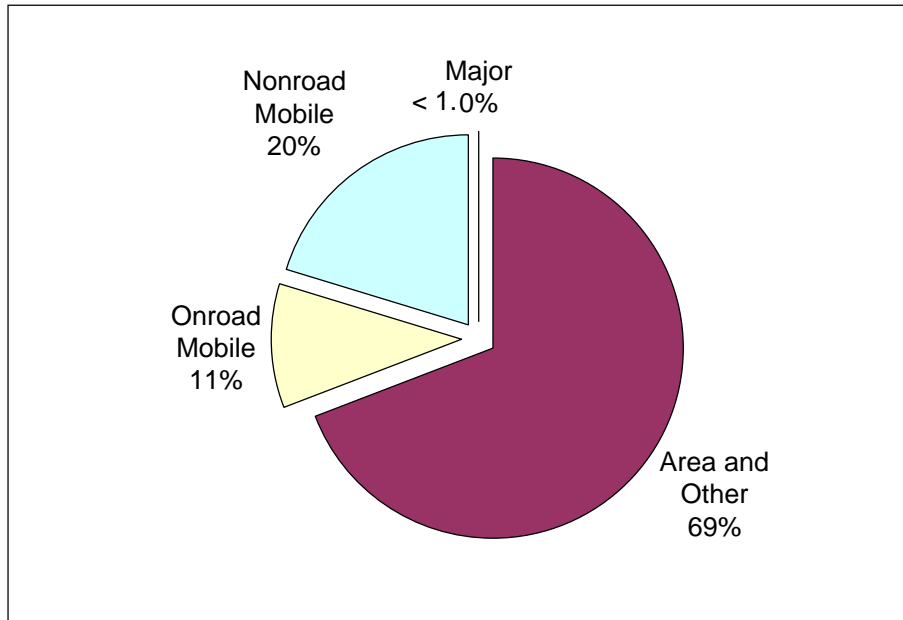
County-by-county source category contributions (from major, area and other, on-road mobile, non-road mobile, and estimated background sources) for 33 hazardous air pollutants, including acrolein and formaldehyde, were estimated by USEPA.<sup>70</sup> The statewide source category contributions, excluding background sources, are shown in Figure 1.

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<sup>69</sup> Clean Air Act Section 112(b) HAP list. 40 CFR 63.50-56

<sup>70</sup> USEPA. 2002. National-Scale Air Toxics Assessment for 1996. Office of Air Quality Planning and Standards. EPA-453/R-01-003

Figure 1. Acrolein source categories across Washington (percent of total)



Based on 1996 emission estimates published in NATA (USEPA, 2002)

## 2. Emissions

Based on the average of a recent emissions inventory by Ecology and other data reported in the NATA for 1996,<sup>71</sup> the total emissions of acrolein from all mobile, major, area and other sources in Washington are estimated to be about 828 tons per year, as shown in Tables 6 and 7.

Table 6. Acrolein emissions in Washington

Source	Tons per year emitted
Open Burning: Forest and Wildfires	426.00
Open Burning: Prescribed Burnings	127.99
All Off-highway Vehicle: Diesel	104.84
All Aircraft Types and Operations	35.31
Light Duty Gasoline Vehicles (LDGV)	33.38
Heavy Duty Diesel Vehicles (HDDV)	20.50
Structure Fires	20.30
Light Duty Gasoline Trucks 1 & 2 (LDGT)	16.77
Heavy Duty Gasoline Vehicles (HDGV)	15.96
All Off-highway Vehicle: Gasoline, 2-Stroke	11.86
All Off-highway Vehicle: Gasoline, 4-Stroke	10.50
<i>Total</i>	<i>823.42</i>

<sup>71</sup> *ibid*

Table 7. Source category emissions of acrolein in Washington during 1996.

Source category	Tons per year emitted
Major	0.57
Area and Other	575
On-road Mobile	87.8
Non-road Mobile*	169
<i>Total</i>	<i>833</i>

\*Non-road mobile sources include off-road vehicles, boats, ships, and trains, aircraft, construction equipment and similar motorized sources.

### 3. Natural Occurrence

Acrolein is reported to be a common product of a variety of microbial and vegetative processes.<sup>72</sup>

### 4. Atmospheric Persistence

The dominant atmospheric loss process for acrolein is by reaction with the hydroxyl radical. Based on this reaction, the atmospheric half-life and lifetime of acrolein is estimated to be 12 hours and 17 hours, respectively.<sup>73</sup>

### 5. Ambient Concentrations

The USEPA compiled information from 1961 to 1980 for two urban locations that reported a range of acrolein concentrations from 8.2 to 24.6- $\mu\text{g}/\text{m}^3$  or 3.6 to 10.7 ppb, with a mean concentration of 14.3- $\mu\text{g}/\text{m}^3$ , or 6.2-ppb.<sup>74</sup>

Acrolein exposure concentrations predicted by the USEPA in the NATA are shown in Table 8.

Table 8. Model estimated annual (1996) average ambient concentration ( $\mu\text{g}/\text{m}^3$ ) of acrolein including secondarily formed acrolein.

County	Percentile Distribution of Ambient Concentrations Across Census Tracts							
	5th	10th	25th	Median	Average	75th	90th	95th
Adams	2.80E-03	2.80E-03	3.15E-03	1.23E-02	9.87E-03	1.49E-02	1.62E-02	1.62E-02
Asotin	1.93E-02	1.93E-02	3.85E-02	4.82E-02	4.46E-02	5.66E-02	5.71E-02	5.71E-02
Benton	7.41E-03	2.15E-02	3.34E-02	3.85E-02	3.72E-02	4.58E-02	5.45E-02	5.64E-02
Chelan	1.46E-02	3.12E-02	5.67E-02	7.38E-02	8.62E-02	1.22E-01	1.34E-01	1.72E-01
Clallam	1.36E-02	1.78E-02	3.42E-02	5.43E-02	6.60E-02	7.92E-02	1.25E-01	2.01E-01
Clark	1.00E-01	1.06E-01	1.14E-01	1.36E-01	1.44E-01	1.62E-01	1.81E-01	2.35E-01
Columbia	1.26E-02	1.26E-02	1.26E-02	1.33E-02	1.33E-02	1.40E-02	1.40E-02	1.40E-02
Cowlitz	3.86E-02	6.22E-02	7.77E-02	8.84E-02	8.64E-02	9.93E-02	1.12E-01	1.12E-01
Douglas	1.26E-02	1.26E-02	4.88E-02	9.46E-02	7.99E-02	1.12E-01	1.16E-01	1.16E-01
Ferry	1.81E-02	1.81E-02	1.81E-02	1.90E-02	2.26E-02	3.08E-02	3.08E-02	3.08E-02

<sup>72</sup> California Air Resources Board - ARB/SSD/SES - Toxic Air Contaminant Identification, List Summaries – Acrolein, September 1997. <http://www.arb.ca.gov/toxics/tac/factshts/acrolein.pdf>.

<sup>73</sup> *ibid.*

<sup>74</sup> *ibid.*

Franklin	5.02E-03	5.02E-03	1.88E-02	6.36E-02	8.81E-02	1.78E-01	1.86E-01	1.86E-01
Garfield	2.60E-02	2.60E-02	2.60E-02	2.72E-02	2.72E-02	2.83E-02	2.83E-02	2.83E-02
Grant	5.70E-03	5.99E-03	8.52E-03	1.54E-02	1.55E-02	1.99E-02	2.76E-02	2.78E-02
Grays Harbor	2.21E-02	2.34E-02	3.45E-02	6.55E-02	7.01E-02	9.71E-02	1.32E-01	1.43E-01
Island	2.98E-02	3.07E-02	3.37E-02	3.81E-02	3.99E-02	4.70E-02	5.18E-02	5.30E-02
Jefferson	2.00E-02	2.00E-02	2.44E-02	3.01E-02	2.90E-02	3.25E-02	3.89E-02	3.89E-02
King	7.23E-02	7.61E-02	9.03E-02	1.06E-01	1.20E-01	1.30E-01	1.64E-01	2.34E-01
Kitsap	5.11E-02	5.35E-02	6.21E-02	6.60E-02	6.46E-02	6.97E-02	7.28E-02	7.48E-02
Kittitas	2.67E-02	2.67E-02	3.09E-02	5.48E-02	7.23E-02	1.15E-01	1.15E-01	1.15E-01
Klickitat	1.42E-02	1.42E-02	1.42E-02	3.88E-02	3.20E-02	4.31E-02	4.31E-02	4.31E-02
Lewis	2.80E-02	3.03E-02	3.95E-02	6.42E-02	5.94E-02	7.20E-02	9.06E-02	1.04E-01
Lincoln	1.38E-03	1.38E-03	2.65E-03	7.08E-03	1.23E-02	2.19E-02	3.36E-02	3.36E-02
Mason	4.73E-02	5.66E-02	5.78E-02	6.85E-02	8.23E-02	1.14E-01	1.21E-01	1.39E-01
Okanogan	1.26E-02	1.78E-02	2.41E-02	3.32E-02	3.81E-02	4.36E-02	7.01E-02	7.68E-02
Pacific	1.42E-02	1.42E-02	2.55E-02	2.87E-02	3.55E-02	3.67E-02	6.95E-02	6.95E-02
Pend Oreille	2.25E-02	2.25E-02	2.93E-02	4.75E-02	4.20E-02	4.85E-02	6.23E-02	6.23E-02
Pierce	6.91E-02	8.08E-02	9.18E-02	1.07E-01	1.06E-01	1.22E-01	1.36E-01	1.43E-01
San Juan	9.27E-03	9.27E-03	1.13E-02	1.80E-02	2.08E-02	2.17E-02	4.67E-02	4.67E-02
Skagit	2.61E-02	3.07E-02	3.29E-02	6.17E-02	5.91E-02	8.07E-02	9.65E-02	9.96E-02
Skamania	2.81E-02	2.81E-02	6.33E-02	6.64E-02	6.59E-02	7.81E-02	9.35E-02	9.35E-02
Snohomish	5.48E-02	6.24E-02	7.17E-02	7.80E-02	7.67E-02	8.43E-02	8.91E-02	9.24E-02
Spokane	3.32E-02	3.93E-02	4.32E-02	4.64E-02	4.85E-02	5.02E-02	5.62E-02	6.23E-02
Stevens	2.31E-02	2.35E-02	2.77E-02	3.46E-02	8.79E-02	9.81E-02	2.48E-01	4.35E-01
Thurston	6.10E-02	6.18E-02	7.02E-02	8.13E-02	8.56E-02	1.02E-01	1.10E-01	1.24E-01
Wahkiakum	5.93E-02	5.93E-02	5.93E-02	5.93E-02	5.93E-02	5.93E-02	5.93E-02	5.93E-02
Walla Walla	6.52E-03	1.43E-02	2.95E-02	3.89E-02	3.83E-02	4.59E-02	6.27E-02	7.88E-02
Whatcom	1.57E-02	1.65E-02	2.96E-02	6.91E-02	6.36E-02	9.03E-02	1.21E-01	1.22E-01
Whitman	5.69E-03	8.25E-03	1.82E-02	2.85E-02	3.12E-02	4.17E-02	5.55E-02	5.75E-02
Yakima	3.17E-02	3.70E-02	4.70E-02	7.31E-02	6.94E-02	8.81E-02	9.87E-02	1.10E-01
<i>Statewide</i>	2.20E-02	3.17E-02	4.99E-02	8.06E-02	8.59E-02	1.09E-01	1.36E-01	1.61E-01
<i>All Urban Counties</i>	3.19E-02	4.14E-02	6.17E-02	8.63E-02	9.24E-02	1.13E-01	1.39E-01	1.67E-01
<i>All Rural Counties</i>	1.05E-02	1.42E-02	2.60E-02	4.56E-02	5.54E-02	7.37E-02	1.06E-01	1.16E-01

The estimated risk to a hypothetical nearly maximally exposed individual (in the 95th percentile) across census tracts at ambient concentrations is provided in the far right-hand column. Risks to individuals with lower exposures (in lesser percentiles) are also shown in Table 8. It is noteworthy that the Science Advisory Board criticized the method used by USEPA to predict ambient acrolein concentrations, pointing out that ASPEN does not adequately account for secondary formation of acrolein. In the same report, SAB also questioned the results of the HAPEM4 model used by USEPA to predict the range of human exposures. SAB suggested that the ranges of exposures possible within affected populations were probably not fully expressed.<sup>75</sup> Thus it is possible that acrolein exposures are in fact greater on average than those predicted in Table 8, and that the exposure ranges span a wider range of concentrations.

The concentration in the census tract in each county estimated to have the median acrolein exposure level was mapped by USEPA in NATA as shown in Figure 2.

<sup>75</sup> Science Advisory Board. 2001. NATA – Evaluating the National-Scale Air Toxics Assessment 1996 Data – An SAB Advisory. EPA-SAB-EC-ADV-02-001. Accessed at [www.epa.gov/sab/pdf/ecadv02001.pdf](http://www.epa.gov/sab/pdf/ecadv02001.pdf)

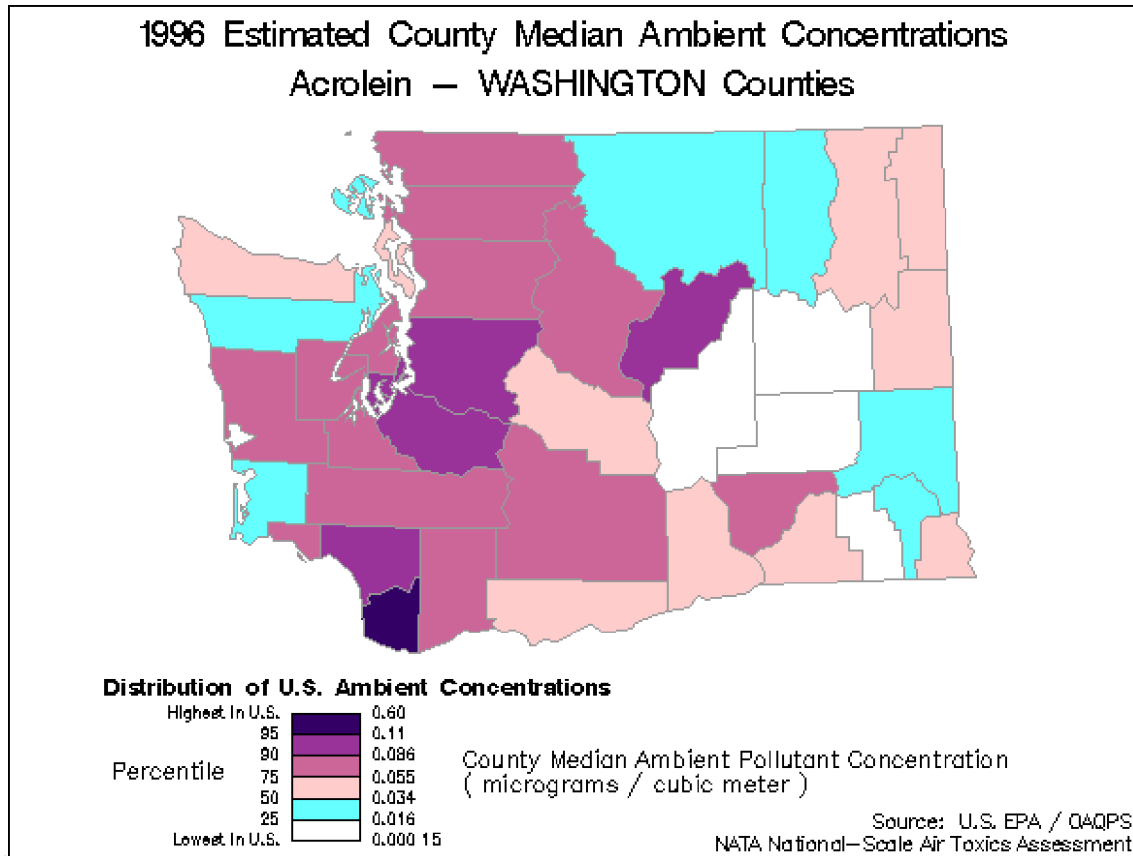


Figure 2. Estimated acrolein concentrations in census tracts with median exposure level in each county.



USEPA estimates that these concentrations lead to a hazard distribution, across Washington counties, as indicated in Figure 3.

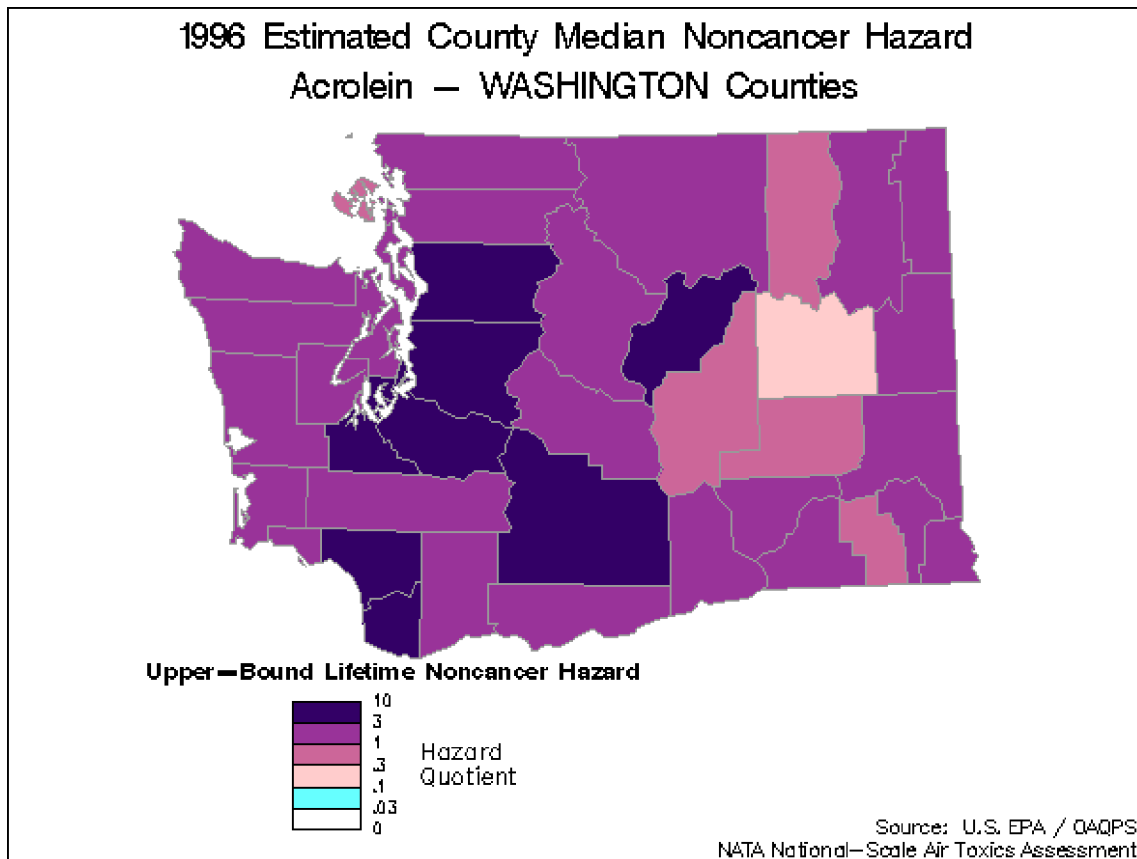


Figure 3. Estimated acrolein hazard distribution in census tracts with median exposure level in each county.

## 6. Indoor Sources and Concentrations

The major sources of acrolein in the indoor environment are cigarettes and wood smoke.<sup>76</sup>

## 7. Health Effects

Inhalation and ingestion are the probable routes of human exposure to acrolein.<sup>77</sup>

<sup>76</sup> Washington Dept. of Health. *Indoor Air Quality Primer*, Environmental Health Programs, Office of Toxic Substances. January 1999.

<sup>77</sup> Hazardous Substances Data Bank. Acrolein. 02/13/2002. Accessed at <http://toxnet.nlm.nih.gov/>

#### Non-Cancer:

Inhalation exposure causes irritation of the eyes, nose, throat, and respiratory tract.<sup>78</sup> In severe cases, pulmonary edema may occur. Birth defects have only been observed in animal studies where acrolein was injected directly into the embryonic tissue.<sup>79</sup>

The USEPA has established a Reference Concentration (RfC) of 0.02- $\mu\text{g}/\text{m}^3$  for acrolein. They estimate that inhalation of this concentration or less, over a lifetime, would not likely result in the occurrence of chronic, non-cancer effects. They have not established an oral Reference Dose (RfD) for acrolein. However, they calculated a provisional RfD of 0.02 milligrams per kilogram per day. The USEPA estimates that consumption of this dose or less, over a lifetime, would not likely result in the occurrence of chronic, non-cancer effects.<sup>80</sup>

The California Office of Environmental Health Hazard Assessment lists an acute Reference Exposure Level (REL) of 0.19- $\mu\text{g}/\text{m}^3$ <sup>81</sup> and a chronic REL of 0.06- $\mu\text{g}/\text{m}^3$  for acrolein.<sup>82</sup> Functions of the respiratory system are considered the most sensitive to acute and chronic acrolein toxicity.

#### Cancer:

No information is available on the carcinogenic effects of acrolein in humans. An increased incidence of adrenocortical tumors in female rats exposed to acrolein in drinking water was reported in one study. The USEPA has placed acrolein in Class C: Possible human carcinogen.<sup>83</sup> The International Agency for Research on Cancer has placed acrolein in Group 3: Unclassifiable as to carcinogenicity to humans.<sup>84</sup>

### 8. Assessment

The predicted peak 24-hr average concentration of acrolein exceeds the ASIL screening criterion and the USEPA RfC (both 0.02- $\mu\text{g}/\text{m}^3$ ) by more than 20-fold. Additionally, due to mobile, area and other (non-major) source emissions, the level of acrolein throughout much of the outdoor air in Washington is estimated to exceed this concentration. The USEPA estimate of the statewide annual average acrolein concentration in 1996 was 0.0859- $\mu\text{g}/\text{m}^3$ . Therefore, days comprising the highest concentrations during 1996 may have averaged 0.4295- $\mu\text{g}/\text{m}^3$ , based on a factor of five for daily extremes during a typical year.

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<sup>78</sup> *ibid.*

<sup>79</sup> USEPA.1994. Integrated Risk Information System (IRIS), Acrolein. *Accessed at* <http://toxnet.nlm.nih.gov>

<sup>80</sup> *ibid.*

<sup>81</sup> Office of Environmental Health Hazard Assessment. 1999. Acute Toxicity Summary, Acrolein *Accessed at* [http://www.oehha.ca.gov/air/acute\\_rels/pdf/107028A.pdf](http://www.oehha.ca.gov/air/acute_rels/pdf/107028A.pdf)

<sup>82</sup> Office of Environmental Health Hazard Assessment. 2000. Chronic Toxicity Summary, Acrolein *Accessed at* [http://www.oehha.ca.gov/air/chronic\\_rels/pdf/107028.pdf](http://www.oehha.ca.gov/air/chronic_rels/pdf/107028.pdf)

<sup>83</sup> USEPA.1994. Integrated Risk Information System (IRIS). Acrolein. *Accessed at* <http://toxnet.nlm.nih.gov>

<sup>84</sup> IARC. 1995 Dry Cleaning, Some Chlorinated Solvents and Other Industrial Chemicals. Summary of Data Reported and Evaluation. Acrolein. Vol.: 63 (1995) (p. 337) *Accessed at* <http://193.51.164.11/htdocs/monographs/vol63/acrolein.htm>

For a typical person in Washington, both outdoors and inside buildings at these levels of exposure, acrolein is capable of causing irritation of the eyes, nose, throat, and respiratory tract. There are significant risks of adverse respiratory tract effects for some people, in particular sensitive persons (those with pre-existing respiratory illnesses such as asthma, COPD, chronic bronchitis, etc.) The risk of such effects is dependant on the frequency and level of exposure, which are highly variable. Consequently, there is a wide range of risks for Washington's residents.

On average, major industrial sources – in which HFBs are categorically included – are thought to account for less than 1% of the ambient acrolein concentration; therefore, implementation of the proposed HFB RACT would reduce the statewide average concentration only slightly. However, in the immediate vicinity of HFBs, the effect of implementing new controls could help reduce acrolein health hazards significantly.

## Formaldehyde

HCHO    CAS Registry Number: 50-00-0    Conversion Factor: 1 ppm = 1.23 mg/m<sup>3</sup>

The odor of formaldehyde is irritating and pungent. It is very reactive, combines with many substances, and polymerizes easily.<sup>85</sup> Formaldehyde is a federal hazardous air pollutant.<sup>86</sup> In 1991, the WDOE AQP identified it as a Class "A" toxic air pollutant under 173-460-150 WAC.

### 1. Sources

Formaldehyde is both directly emitted into the atmosphere, as shown in Figure 4, and formed in the atmosphere as a result of photochemical oxidation of reactive organic gases with ozone and nitrogen oxides. Photochemical oxidation is the largest source of formaldehyde concentrations in Washington's ambient air. Formaldehyde is also a product of incomplete combustion.<sup>87</sup> It is present in vehicular exhaust.<sup>88</sup>

In addition to HFBs, other sources of formaldehyde include catalytic cracking and fuel combustion at refineries. In addition, ceramics and glass production use fuel combustion sources such as boilers, furnaces, incinerators, and engines in the manufacturing processes which generate formaldehyde. Formaldehyde is used in urea-formaldehyde and phenol formaldehyde resins, and copper plating solutions. Formaldehyde-based resins are used in pressed wood, grocery bags, and waxed paper. Detergents, cosmetics, and other domestic chemicals (shampoos and conditioners)

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<sup>85</sup> Anon. 1996. The Merck Index: An Encyclopedia of Chemicals, Drugs, and Biologicals. 12<sup>th</sup> Edition. S. Budavari, ed., Merck & Co., Inc. Whitehouse Station, NJ.

<sup>86</sup> Clean Air Act, Section 112(b) HAP list. 40 CFR 63.50-56

<sup>87</sup> Control of Emissions of Hazardous Air Pollutants from Mobile Sources; Final Rule. Federal Register: March 29, 2001 (Vol. 66, No. 61) pp.17229-17273. Part II Environmental Protection Agency. 40 CFR Parts 80 and 86. Accessed at <http://www.epa.gov/fedrgstr/EPA-AIR/2001/March/Day-29/a37.htm>

<sup>88</sup> Pope A., L. Driver, R. Billings, D. Wilson. 2002. The Development of the 1996 National Toxics Inventory. Accessed at <http://www.epa.gov/ttn/chief/nti/ntipap1.pdf>

contain formaldehyde as an antimicrobial agent. Formaldehyde is also used in fumigants, soil disinfectants, embalming fluid, and in leather tanning.<sup>89</sup>

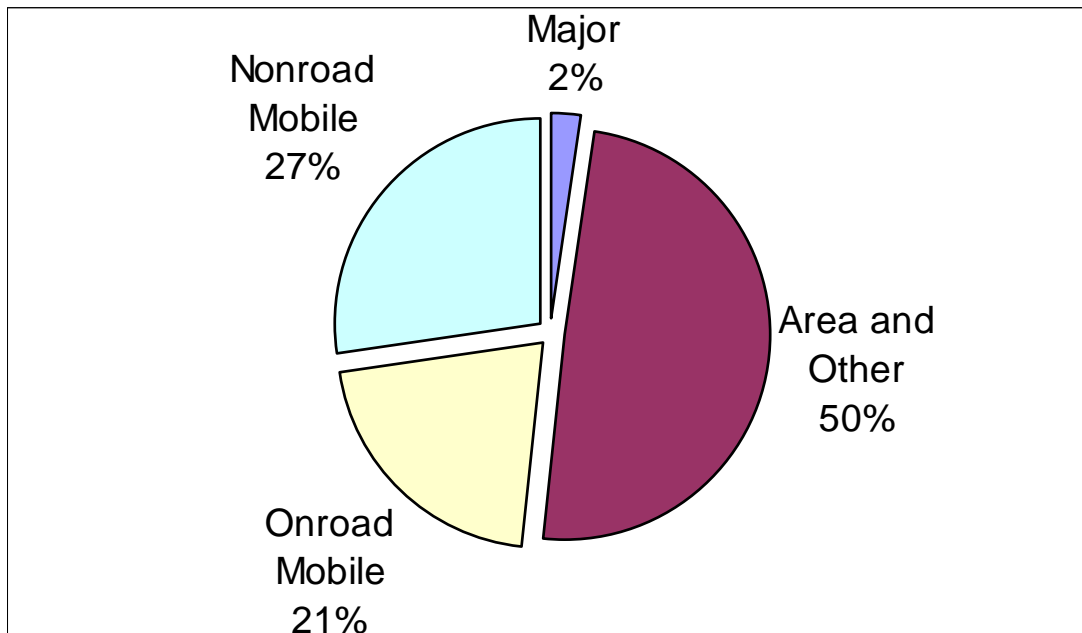


Figure 4. Formaldehyde source categories across Washington (percent of total).

## 2. Emissions

Based on a recent emissions inventory by WDOE AQP and based on data reported in the NATA for 1996<sup>90</sup>, the total emissions of formaldehyde from all mobile, major, area and other sources in Washington are estimated to be about 6885 tons per year, as shown in Tables 9 and 10.

<sup>89</sup> U.S. Department of Labor, Occupational Safety & Health Administration. 1992. Properties, Manufacture, and Uses of Formaldehyde (III). *Assessed at* [http://www.osha-slc.gov/pls/oshaweb/owadisp.show\\_document?p\\_table=PREAMBLES&p\\_id=923](http://www.osha-slc.gov/pls/oshaweb/owadisp.show_document?p_table=PREAMBLES&p_id=923)

<sup>90</sup> USEPA. 2002. National-Scale Air Toxics Assessment for 1996. Office of Air Quality Planning and Standards. EPA-453/R-01-003

Table 9. Formaldehyde emissions in Washington

Source	Tons per year emitted
Open Burning: Forest and Wildfires	2590
All Off-highway Vehicle: Diesel	1364
Open Burning: Prescribed Burnings	779
Light Duty Gasoline Vehicles (LDGV)	453
Light Duty Gasoline Trucks 1 & 2 (LDGT)	442
Heavy Duty Diesel Vehicles (HDDV)	348
All Aircraft Types and Operations	242
Heavy Duty Gasoline Vehicles (HDGV)	195
All Off-highway Vehicle: Gasoline, 4-Stroke	192
Point	176
<i>Total</i>	<i>6781</i>

Table 10. Source category emissions of formaldehyde in Washington during 1996.

Source category	Tons per year emitted
Major	150
Area and Other	3470
On-road Mobile	1470
Non-road Mobile*	1900
<i>Total</i>	<i>6990</i>

\*Non-road mobile sources include off-road vehicles, boats, ships, trains, aircraft, construction equipment, and similar non-road motorized sources.

### 3. Natural Occurrence

Natural emission of formaldehyde include forest fires, animal wastes, microbial products of biological systems, and plants. It can also be formed in seawater by photochemical processes.<sup>91</sup>

### 4. Atmospheric Persistence

Photolysis of formaldehyde is calculated to dominate over the gas-phase reaction with hydroxyl radicals as a tropospheric removal process, with a photolysis lifetime for formaldehyde of about four hours. Formaldehyde is also formed in the atmosphere from the photooxidation of most other organic compounds; and hence, it is being removed and formed at the same time. Rain or fog can shorten the atmospheric lifetime of formaldehyde.<sup>92</sup>

<sup>91</sup> ATSDR. 1999 Toxicological Profile for Formaldehyde. Chapter 5. Potential for Human Exposure. Assessed at <http://www.atsdr.cdc.gov/toxprofiles/tp111-c5.pdf>

<sup>92</sup> *ibid.*

## 5. Ambient Concentrations

Formaldehyde has been routinely monitored by Ecology at two or more sites in the Seattle area since January 2000. The different sites in the network have had a range of mean concentrations of formaldehyde from 0.8 to 1.4 parts per billion (ppb) or 0.98 to 1.72- $\mu\text{g}/\text{m}^3$ .

These concentrations are close to the ones predicted with the ASPEN model used in the 1996 NATA.<sup>93</sup> The range of formaldehyde exposure concentrations across census tracts in each Washington county predicted by the USEPA in the NATA<sup>94</sup> are shown in Table 11.

Table 11. Estimated annual average ambient concentrations ( $\mu\text{g}/\text{m}^3$ ) for formaldehyde (includes secondarily formed formaldehyde).

County	Percentile Distribution of Ambient Concentrations Across Census Tracts							
	5th	10th	25th	Median	Average	75th	90th	95th
Adams	2.69E-01	2.69E-01	2.73E-01	3.47E-01	3.27E-01	3.70E-01	3.75E-01	3.75E-01
Asotin	3.78E-01	3.78E-01	5.16E-01	5.90E-01	5.63E-01	6.16E-01	6.90E-01	6.90E-01
Benton	3.30E-01	4.01E-01	4.61E-01	4.93E-01	5.03E-01	5.66E-01	6.20E-01	6.38E-01
Chelan	3.15E-01	3.88E-01	4.94E-01	5.84E-01	6.60E-01	8.24E-01	9.32E-01	1.16E+00
Clallam	3.22E-01	3.43E-01	4.36E-01	5.59E-01	6.41E-01	8.03E-01	1.05E+00	1.31E+00
Clark	1.04E+00	1.13E+00	1.24E+00	1.43E+00	1.50E+00	1.72E+00	1.81E+00	2.23E+00
Columbia	3.15E-01	3.15E-01	3.15E-01	3.18E-01	3.18E-01	3.22E-01	3.22E-01	3.22E-01
Cowlitz	4.75E-01	5.84E-01	7.12E-01	7.74E-01	7.66E-01	8.64E-01	9.02E-01	9.28E-01
Douglas	3.03E-01	3.03E-01	4.62E-01	6.67E-01	6.07E-01	7.58E-01	7.84E-01	7.84E-01
Ferry	3.25E-01	3.25E-01	3.25E-01	3.29E-01	3.48E-01	3.89E-01	3.89E-01	3.89E-01
Franklin	3.02E-01	3.02E-01	3.83E-01	5.84E-01	7.53E-01	1.25E+00	1.33E+00	1.33E+00
Garfield	3.92E-01	3.92E-01	3.92E-01	4.04E-01	4.04E-01	4.17E-01	4.17E-01	4.17E-01
Grant	2.87E-01	2.87E-01	2.95E-01	3.47E-01	3.51E-01	3.97E-01	4.33E-01	4.65E-01
Grays Harbor	3.51E-01	3.64E-01	4.16E-01	5.92E-01	6.31E-01	7.62E-01	1.07E+00	1.09E+00
Island	4.74E-01	4.75E-01	5.17E-01	5.48E-01	5.65E-01	6.20E-01	6.65E-01	6.74E-01
Jefferson	3.79E-01	3.79E-01	3.93E-01	4.37E-01	4.51E-01	4.87E-01	5.58E-01	5.58E-01
King	8.36E-01	8.79E-01	9.86E-01	1.12E+00	1.21E+00	1.31E+00	1.52E+00	1.84E+00
Kitsap	6.56E-01	6.84E-01	7.84E-01	8.48E-01	8.30E-01	8.97E-01	9.28E-01	9.52E-01
Kittitas	3.65E-01	3.65E-01	3.96E-01	4.91E-01	6.63E-01	9.76E-01	9.76E-01	9.76E-01
Klickitat	3.14E-01	3.14E-01	3.14E-01	4.24E-01	3.93E-01	4.41E-01	4.41E-01	4.41E-01
Lewis	3.78E-01	4.00E-01	4.56E-01	5.99E-01	5.83E-01	6.63E-01	7.64E-01	9.06E-01
Lincoln	2.62E-01	2.62E-01	2.68E-01	2.94E-01	3.37E-01	4.06E-01	4.98E-01	4.98E-01
Mason	4.94E-01	5.62E-01	6.13E-01	7.07E-01	7.86E-01	9.57E-01	1.10E+00	1.29E+00
Okanogan	3.05E-01	3.26E-01	3.53E-01	3.98E-01	4.23E-01	4.35E-01	5.96E-01	6.56E-01
Pacific	3.22E-01	3.22E-01	3.69E-01	3.88E-01	4.30E-01	4.48E-01	6.09E-01	6.09E-01
Pend Oreille	3.48E-01	3.48E-01	3.87E-01	4.91E-01	4.63E-01	5.06E-01	5.83E-01	5.83E-01
Pierce	7.17E-01	8.13E-01	9.04E-01	1.03E+00	1.04E+00	1.17E+00	1.28E+00	1.32E+00
San Juan	3.19E-01	3.19E-01	3.20E-01	3.75E-01	3.93E-01	3.98E-01	5.71E-01	5.71E-01

<sup>93</sup> USEPA. 2002. National-Scale Air Toxics Assessment for 1996. Office of Air Quality Planning and Standards. EPA-453/R-01-003

<sup>94</sup> *ibid.*

Skagit	4.26E-01	4.32E-01	4.86E-01	6.11E-01	6.26E-01	7.45E-01	8.49E-01	8.71E-01
Skamania	3.79E-01	3.79E-01	5.81E-01	6.25E-01	5.95E-01	6.72E-01	7.20E-01	7.20E-01
Snohomish	6.21E-01	7.14E-01	8.00E-01	8.44E-01	8.33E-01	9.08E-01	9.39E-01	9.54E-01
Spokane	4.80E-01	5.44E-01	5.84E-01	6.11E-01	6.24E-01	6.46E-01	6.90E-01	7.44E-01
Stevens	3.48E-01	3.50E-01	3.77E-01	4.36E-01	7.48E-01	7.74E-01	1.78E+00	2.88E+00
Thurston	6.09E-01	6.26E-01	7.22E-01	7.99E-01	8.16E-01	9.19E-01	1.00E+00	1.10E+00
Wahkiakum	5.48E-01	5.48E-01	5.48E-01	5.48E-01	5.48E-01	5.48E-01	5.48E-01	5.48E-01
Walla Walla	3.05E-01	3.38E-01	4.30E-01	4.74E-01	4.78E-01	5.22E-01	6.30E-01	7.23E-01
Whatcom	3.53E-01	3.62E-01	4.26E-01	6.61E-01	6.53E-01	7.82E-01	9.66E-01	1.01E+00
Whitman	3.02E-01	3.14E-01	3.74E-01	4.53E-01	4.62E-01	5.49E-01	6.28E-01	6.55E-01
Yakima	4.62E-01	4.63E-01	4.96E-01	6.83E-01	6.86E-01	7.98E-01	8.74E-01	9.85E-01
Statewide	3.71E-01	4.39E-01	6.10E-01	8.52E-01	8.90E-01	1.09E+00	1.33E+00	1.53E+00
All Urban Counties	4.68E-01	5.44E-01	6.71E-01	9.11E-01	9.58E-01	1.14E+00	1.37E+00	1.57E+00
All Rural Counties	3.06E-01	3.29E-01	3.87E-01	4.91E-01	5.74E-01	6.86E-01	8.70E-01	9.85E-01

It is noteworthy that the Science Advisory Board criticized the method used by USEPA to predict ambient formaldehyde concentrations (as with acrolein), pointing out that ASPEN does not adequately account for secondary formation of formaldehyde.<sup>95</sup> Thus it is possible that formaldehyde exposures are in fact greater on average than those predicted in Table 11.

The concentration in the census tract in each county estimated to have the median formaldehyde exposure level may be mapped as shown in Figure 5.

<sup>95</sup> Science Advisory Board. 2001. NATA – Evaluating the National-Scale Air Toxics Assessment 1996 Data – An SAB Advisory. EPA-SAB-EC-ADV-02-001. Accessed at [www.epa.gov/sab/pdf/ecadv02001.pdf](http://www.epa.gov/sab/pdf/ecadv02001.pdf)

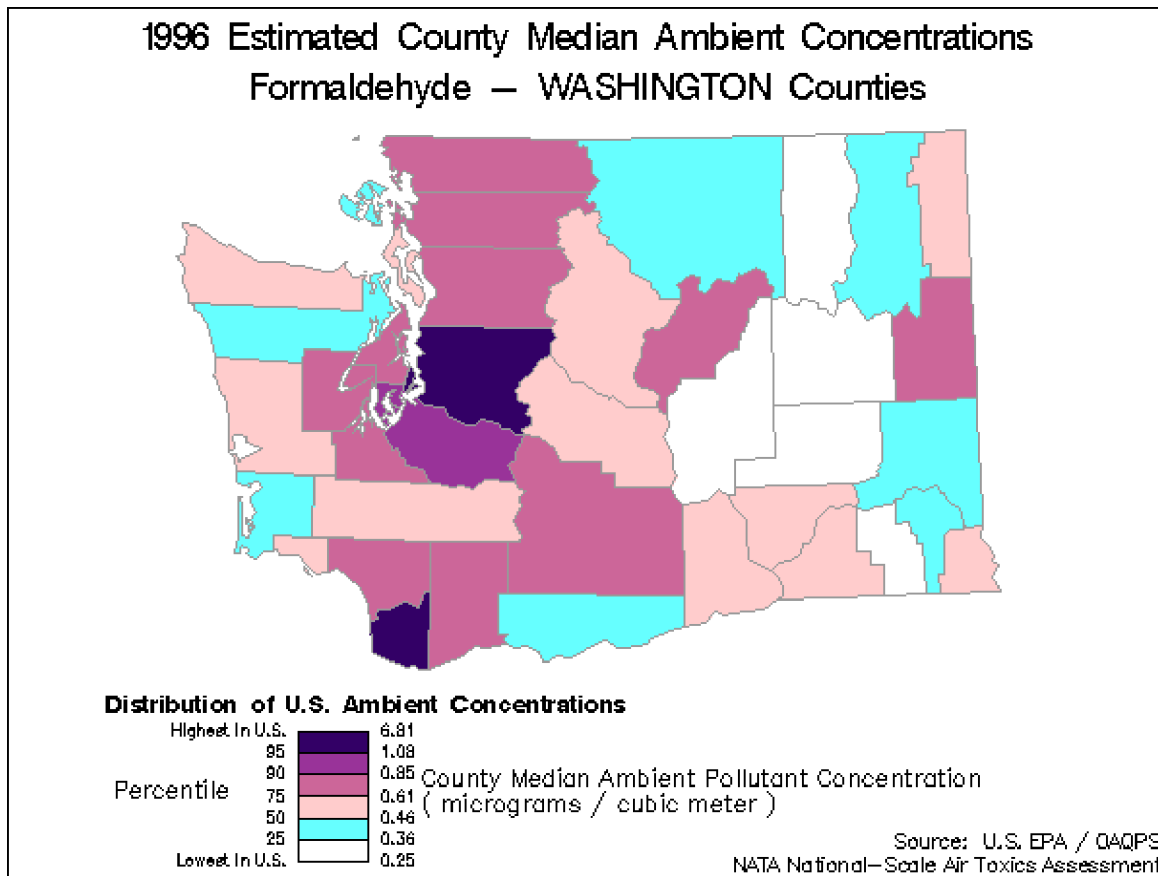


Figure 5. Estimated formaldehyde concentrations in census tracts with median exposure level in each county.

USEPA estimated that the concentrations shown in Figure 5 lead to a proportionate median cancer risk and — even though USEPA has not established an inhalation RfC for formaldehyde — non-cancer hazard distributions across Washington counties as indicated in Figures 6 and 7.



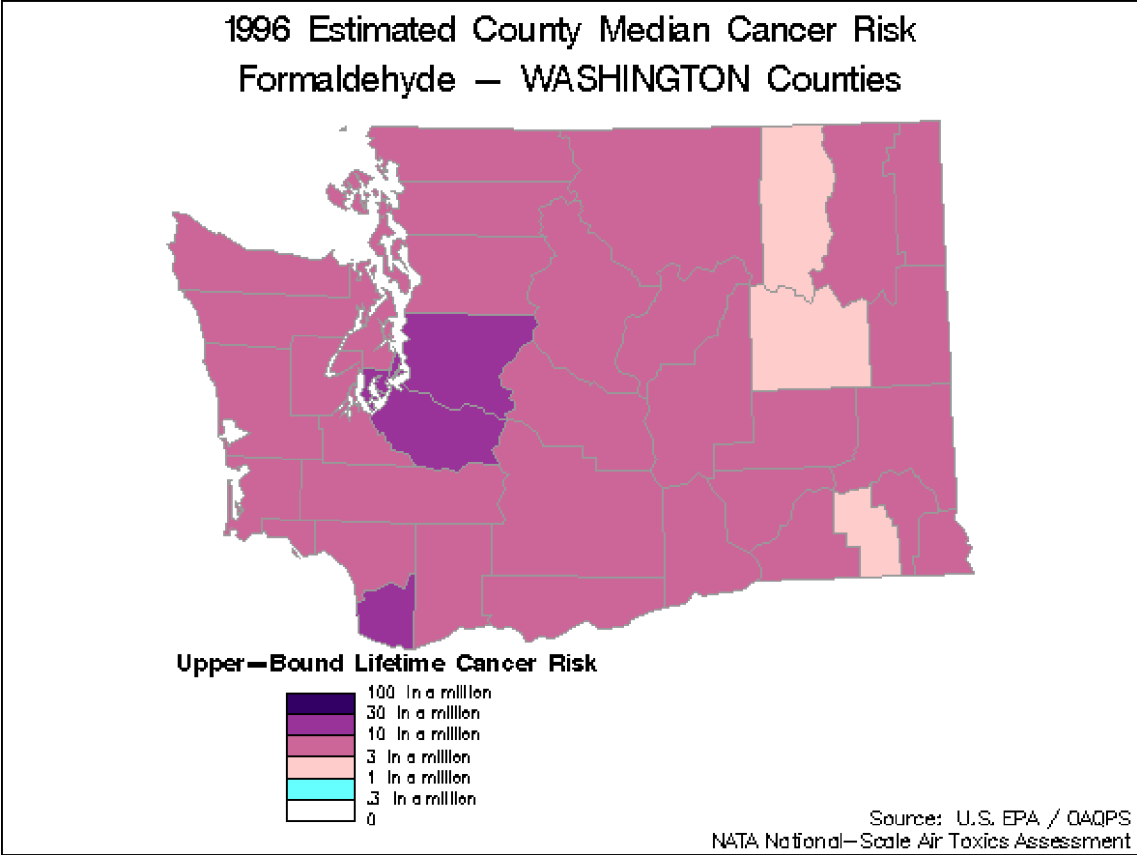


Figure 6. Estimated formaldehyde cancer risk distribution in census tracts with median exposure level in each county.

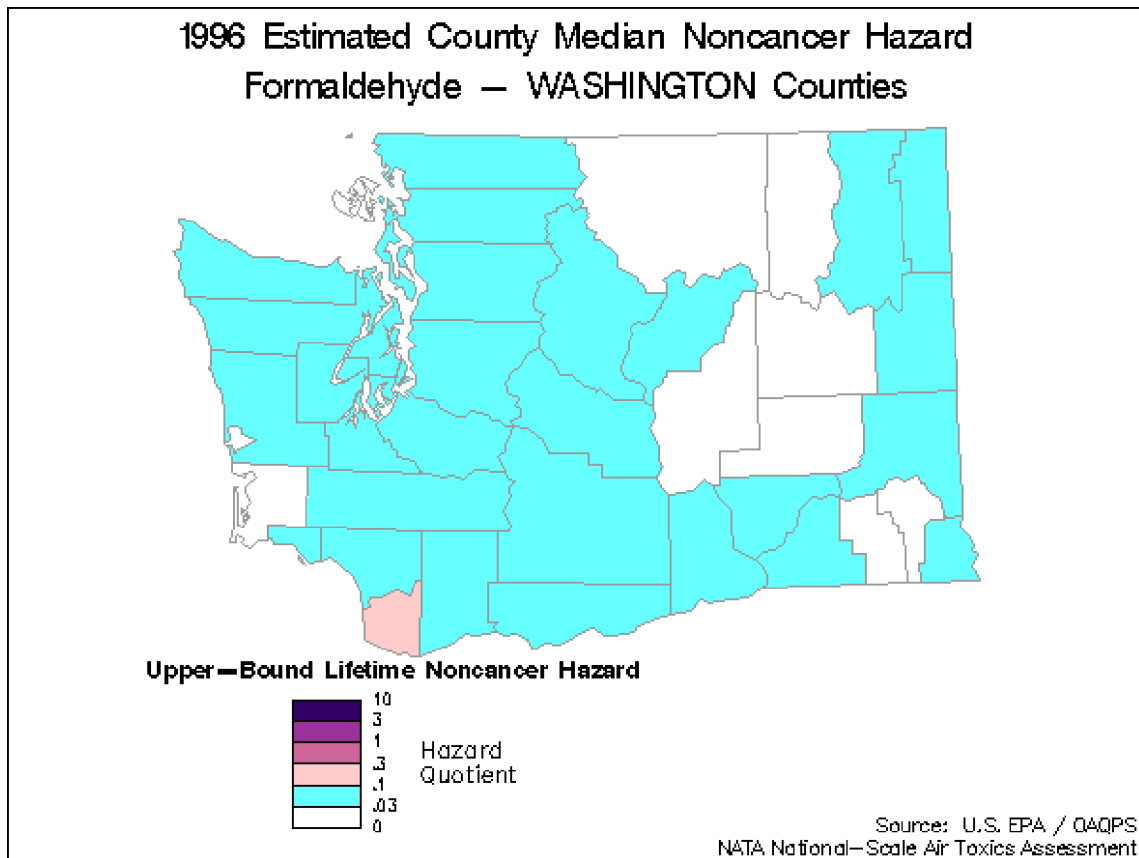


Figure 7. Estimated formaldehyde hazard distribution in census tracts with median exposure level in each county.

The modeling done by USEPA to determine this risk distribution shown in Figure 7 incorporated estimates of formaldehyde exposures in different locations outdoors, inside motor vehicles and indoors, for people of all ages having a range of different daily activity patterns<sup>96</sup>, in order to obtain a range of realistic exposures. For an average person, indoor exposures are greater than outdoor exposures because concentrations of formaldehyde are typically higher in indoor air and because most people spends the majority of their time indoors. In a review of NATA, SAB questioned the results of the HAPEM4 model used by USEPA to predict the range of human exposures. SAB suggested that the ranges of exposures to formaldehyde and other HAPs possible within affected populations were probably not fully expressed.<sup>97</sup>

In terms of possible health effects, in the vicinity of a HFB, outdoor exposure alone may be significant. Further, under normal circumstances, the concentration of formaldehyde in structures in the vicinity of a HFB would be proportionately higher as well.

## 6. Indoor Sources and Concentrations

<sup>96</sup> USEPA, 2000. *Hazardous Air Pollutant Exposure Model – Version 4*.  
<http://www.epa.gov/ttnatw01/nata/appendix-b.pdf>

<sup>97</sup> Science Advisory Board. 2001. NATA – Evaluating the National-Scale Air Toxics Assessment 1996 Data – An SAB Advisory. EPA-SAB-EC-ADV-02-001. Accessed at [www.epa.gov/sab/pdf/ecadv02001.pdf](http://www.epa.gov/sab/pdf/ecadv02001.pdf)

Over time, formaldehyde off-gases from pressed wood products (particle board, plywood, and fiberboard), and indoor levels are expected to remain higher than outdoor levels due to off-gassing by new materials brought into the home (many building materials, consumer products, and fabrics emit formaldehyde). Other indoor combustion sources such as wood and gas stoves, kerosene heaters, and cigarettes contribute intermittently to indoor formaldehyde levels, if present.<sup>98</sup>

The results of surveys of randomly selected residences in California indicate that formaldehyde concentrations inside residences can range from less than 10 ppb ( $12.3\text{-}\mu\text{g}/\text{m}^3$ ) to almost 500 ppb ( $615\text{-}\mu\text{g}/\text{m}^3$ ). Mean concentrations were 24 ppb for office and public buildings, 50 ppb for conventional homes, and 72 ppb for mobile homes.<sup>99</sup> Formaldehyde concentrations inside vehicles have been found to be similar to concentrations measured outdoors.<sup>100</sup>

## 7. Health Effects

Inhalation is a probable route of human exposure to formaldehyde.<sup>101</sup>

### Non-Cancer:

Vapors are highly irritating to the eye and respiratory tract. Acute effects include nausea, headaches, and difficulty breathing. Formaldehyde can also induce or exacerbate asthma. Chronic exposure is associated with respiratory symptoms and eye, nose, and throat irritation. Repeated exposure of skin to the liquid causes irritation and allergic dermatitis.<sup>102</sup>

The USEPA has not established an RfC for formaldehyde but the oral RfD is 0.2 milligrams per kilogram per day based on a decrease in bodyweight gain and effects on the stomach in rats. The USEPA estimates that consumption of this dose or less, over a lifetime, would not result in the occurrence of chronic, non-cancer effects.<sup>103</sup>

An acute non-cancer REL of  $94\text{-}\mu\text{g}/\text{m}^3$  and a chronic non-cancer REL of  $3.0\text{-}\mu\text{g}/\text{m}^3$  are listed for formaldehyde in California's OEHHA guidelines. The toxicological endpoints considered for chronic toxicity are irritation of the eye and respiratory system.<sup>104,105</sup>

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<sup>98</sup> Manuel J. 1999. A healthy home environment? *Environ Health Perspect.* 107(7):A352-7.

<sup>99</sup> CARB (<http://www.arb.ca.gov/toxics/tac/factshts/formald.pdf>)

<sup>100</sup> *ibid.*

<sup>101</sup> Hazardous Substances Data Bank. *Formaldehyde*, 08/06/2002. <http://toxnet.nlm.nih.gov/>

<sup>102</sup> U.S. Consumer Product Safety Commission, Office of Information and Public Affairs. 1983. *CPSC Still Concerned About Formaldehyde Health Risks*. Washington, D.C. Accessed at <http://www.cpsc.gov/cpscpub/prerel/prhtml83/83054.html>

<sup>103</sup> USEPA. 1991. Integrated Risk Information System (IRIS). *Formaldehyde*. Accessed at <http://www.epa.gov/iris/subst/0419.htm>

<sup>104</sup> Office of Environmental Health Hazard Assessment. 2000. Acute Toxicity Summary, Formaldehyde Accessed at [http://www.oehha.ca.gov/air/acute\\_rels/pdf/50000.pdf](http://www.oehha.ca.gov/air/acute_rels/pdf/50000.pdf)

<sup>105</sup> Office of Environmental Health Hazard Assessment. 1999. Chronic Toxicity Summary, Formaldehyde. Accessed at [http://www.oehha.ca.gov/air/chronic\\_rels/pdf/50000.pdf](http://www.oehha.ca.gov/air/chronic_rels/pdf/50000.pdf)

An increased incidence of menstrual disorders and pregnancy problems were observed in women working with urea-formaldehyde resins. However, possible confounding factors were not evaluated in this study. A study of hospital equipment sterilization workers did not report an association between formaldehyde exposure and spontaneous abortions.<sup>106</sup> Exposure of experimental animals to formaldehyde does not appear to result in teratogenic (birth defects) or reproductive effects of significance.<sup>107</sup>

#### Cancer:

According to the USEPA, limited human studies have reported an association between formaldehyde exposure and lung and nasopharyngeal cancer. The USEPA has classified formaldehyde in Group B1: Probable human carcinogen, with an inhalation unit risk of  $1.3 \times 10^{-5}$  per  $(\mu\text{g}/\text{m}^3)$ . The USEPA estimates that if an individual were to breathe air containing formaldehyde at  $0.08\text{-}\mu\text{g}/\text{m}^3$ , over a lifetime, that person would theoretically have no more than a 1 in 1 million increased chance of developing cancer.<sup>108</sup> The International Agency for Research on Cancer has classified formaldehyde in Group 2A: Probable human carcinogen based on limited evidence in humans and adequate evidence in animals.<sup>109</sup> The State of California has determined under Proposition 65 and AB 1807 that formaldehyde is a carcinogen. Formaldehyde is carcinogenic in rodents, producing squamous cell carcinomas in the nasal passages of male and female rats and male mice.<sup>110</sup> The inhalation potency factor being used as a basis for regulatory action in California is  $6 \times 10^{-6} (\mu\text{g}/\text{m}^3)^{-1}$ . In other words, the potential excess cancer risk for a person exposed over a lifetime to  $1\text{-}\mu\text{g}/\text{m}^3$  of formaldehyde is estimated to be no greater than 6 in 1 million.<sup>111</sup>

## 8. Assessment

The predicted annual average concentration of formaldehyde ( $0.0883\text{-}\mu\text{g}/\text{m}^3$ ) that would exist in the vicinity of HFBs as a result of their emissions alone (without other sources also contributing) exceeds the ASIL screening criterion ( $0.077\text{-}\mu\text{g}/\text{m}^3$ ) by nearly 15%. However, the USEPA formaldehyde inhalation unit risk estimate is  $1.3\text{E-}5 (\mu\text{g}/\text{m}^3)^{-1}$ ; and therefore, the air concentration at an excess risk level of  $10^{-5}$  (1 in 100,000) is estimated to be  $0.8\text{-}\mu\text{g}/\text{m}^3$ . Due to mobile, area, and other (non-major) source emissions, the level of formaldehyde throughout much of Washington is estimated to be higher than the level estimated to result in an excess cancer risk  $10^{-6}$  (1 in 1,000,000) because the USEPA estimate of the preexisting statewide annual average formaldehyde

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<sup>106</sup> USEPA. *Health and Environmental Effects Profile for Formaldehyde*. EPA/600/x-85/362.

Environmental Criteria and Assessment Office, Office of Health and Environmental Assessment, Office of Research and Development, Cincinnati, OH. 1988.

<sup>107</sup> California Air Resources Board. 1992. Final Report on the Identification of Formaldehyde as a Toxic Air Contaminant. Stationary Source Division. Sacramento, California

<sup>108</sup> USEPA. 1991. Integrated Risk Information System (IRIS). *Formaldehyde*. Accessed at <http://www.epa.gov/iris/subst/0419.htm>

<sup>109</sup> IARC. 1995 Formaldehyde. 5. Summary of Data Reported and Evaluation. Vol.: 62 (1995) (p. 217) Accessed at <http://www-cie.iarc.fr/htdocs/monographs/vol62/formal.html>

<sup>110</sup> *ibid.*

<sup>111</sup> Office of Environmental Health Hazard Assessment (OEHHA). November 1, 1994. Memorandum: California Cancer Potency Factors - Update. Standards and Criteria Work Group. Sacramento, California.

concentration during 1996 was 0.852- $\mu\text{g}/\text{m}^3$ . Therefore, the cancer risk from formaldehyde would be about 10-fold higher in the vicinity of HFBs than locations with similar air pollution, but lacking nearby HFB emissions. The USEPA NATA reports that ambient outdoor concentrations of formaldehyde exceed this level for the majority of people living in Clark, King, and Pierce counties.<sup>112</sup>

USEPA estimated that on average in Washington, 2% of formaldehyde emissions are from major sources (which include HFBs); therefore, their ambient concentration estimates of formaldehyde included HFB emissions. Limited monitoring data appear to confirm that these estimates are in the correct range. Thus, Ecology is confident that formaldehyde exposure presents a significant health risk to the majority of Washington's residents. With the implementation of HFB RACT, formaldehyde levels may be lower than they are currently but would still be excessive. Ambient concentrations of formaldehyde are above the cancer risk level of 1 per 1,000,000.

In terms of adverse health effects other than cancer, for a person in Washington with average exposure, combined indoor and outdoor levels are not predicted to result in exposure concentrations capable of respiratory symptoms. There is little possibility that a health hazards such as respiratory symptoms; eye, nose, and throat irritation; difficulty breathing; induction and/or exacerbation of asthma; also possibly headache and nausea, are occurring as a result of formaldehyde alone are occurring among people with average exposure. However, among people with much higher than average exposures, and particularly among more physically sensitive people, especially those with pre-existing respiratory illnesses, there is significant risk of such effects resulting from formaldehyde exposure. As noted, the probability and severity of these effects depends on the short-term frequency and level of exposure, and upon individual sensitivity, which are highly variable. Therefore, there is a wide range of formaldehyde-associated health risks for Washington's residents.

Major industrial sources are thought to account for less than 2% of the ambient formaldehyde concentration, so implementation of the proposed HFB RACT would reduce the statewide average concentration only slightly. However, in the immediate vicinity of HFBs, the effect of implementing new controls could help reduce formaldehyde health hazards by perhaps 10%.

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<sup>112</sup> USEPA. 2002. National-Scale Air Toxics Assessment for 1996. Office of Air Quality Planning and Standards. EPA-453/R-01-003

## Discussion

### Acrolein —

The five Washington counties with the highest major source contributions of acrolein are San Juan, Whatcom, Pacific, Skagit, and Wahkiakum. However, even in these counties, the relative contribution to ambient acrolein levels by the major sources is insignificant compared to sources in the mobile, area and other categories. The ambient concentrations of acrolein, including HFB emissions, that were estimated USEPA in the NATA present a substantial health risk. With HFB RACT, acrolein levels may be lower than these estimates but still excessive.

### Formaldehyde —

The five Washington counties with the highest major source contributions of formaldehyde are Mason, Pierce, Skagit, Snohomish, Whatcom, and Cowlitz. Nonetheless, the sources included in the “major” category account for 5% or less of the total ambient formaldehyde concentration. Compared to formaldehyde sources in the mobile, area, and other categories, major sources, which include HFBs, are relatively small throughout the state. Because of these contributions, ambient concentrations of formaldehyde are above the risk level goal 1 in 1,000,000 excess cancer risk (in Clark, King, and Pierce counties). Therefore, Ecology believes some excess risk from formaldehyde will continue to exist with RACT.

Formaldehyde is believed to be less potent in terms of its ability to induce non-cancer adverse health effects. Because of this, the average exposure concentrations for people in each of Washington’s counties are estimated to be lower than the level of concern (H.Q. < 1 for non-cancer health hazards).

### Other Chemicals —

With insufficient data on the existing concentrations and toxic potency of certain other HFB emissions (aldehydes, chlorinated dioxins and furans, 1,2-dibromomethane, nitrophenols, PAHs, and PCBs), there are unknown levels of potential risk. However, along with acrolein and formaldehyde, their potential effects may be summarized as in the Table 12.

Table 12. Potential effects of HFB organic chemical emissions summary

	Acrolein	Formaldehyde	Aldehydes	Chlorinated Dioxins and Furans	Halocarbons	Nitrophenols	PAHs	PCBs
Respiratory cancers		x	x					
Other cancers				x	x		x	x
Respiratory symptoms, eye, nose, and throat irritation	x	x	x		x			
Difficulty breathing	x	x						
Induction and/or exacerbation of asthma		x						
Suppression of immunity				x	x		x	x
Neurological effects				x	x	x		x
Skin toxicity				x		x	x	x
Liver toxicity				x	x			x
Kidney toxicity					x			
Thyroid toxicity				x				x
Stomach toxicity								x
Eye toxicity		x						x
Cataracts						x		
Developmental defects				x			x	x
Reproductive toxicity					x		x	x
Birth defects				x				x
Endocrine effects				x				x
Changes in blood pressure					x			x
Increased heart rate, breathing rate, and body temperature						x		
Anemia					x			
Methaemoglobin						x		
Headache		x						
Nausea		x						
Weight loss				x		x		x

## Conclusions

Some evidence in humans and greater evidence in animal studies suggests a variety of serious adverse health effects may result from exposure to some of the chemicals originating from HFB emissions and other sources. Respiratory tract and eye irritation seem the most likely results of exposure to HFB emissions at the calculated concentrations. Also possible are a variety of cancers, immunosuppression, neurological effects, and effects on skin and other organs, developmental and reproductive effects, endocrine modulation, effects on the heart, effects on blood chemistry, and several nonspecific adverse health effects. The different health effects of these chemicals may be interrelated, as alterations in one system may have significant implications for the other systems of the body.

Additional efforts to reduce acrolein emissions should be made. Also, public health should be monitored carefully in exposed populations with the possibility of these effects in mind. The state should do more to track environmental risks. The state budget should include funding for a program to identify cancer clusters and non-cancer health effect clusters. In such a plan, researchers would work with the Health Department officials to look for areas of the state that have high exposure to pollution and other risk factors. That data would be combined with data from the state cancer registry to find and investigate neighborhoods with higher cancer and specific non-cancer-disease rates.