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# Indirect Pathways as the Primary Source of Human Exposure to Emissions from a Minnesota Municipal Waste Combustor

Beth L. Neely[1]
Sheri Tickle Hester[2]
Mark W. Yambert[1]
David Cleverly[3]
Curtis C. Travis[1]

[1]Office of Risk Analysis
Heatlh and Safety Research Division
P.O. Box 2008; MS 6109
Oak Ridge National Laboratory*
Oak Ridge, TN 37831

[2]Integrated Laboratory Systems
P.O. Box 5713
Oak Ridge, TN 37831

[3]Office of Technology Transfer and Regulatory Support (H-8105)
U.S. Environmental Protection Agency
26 W. Martin Luther King Drive
Cincinnati, OH 45268

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## INTRODUCTION

Increasing problems of land disposal have forced many communities to actively consider incineration as a disposal alternative. With the growth of incineration arises the fundamental issue of the environmental impact of pollutants in combustor emissions. Municipal Waste Combustors (MWC) are known to release both metals and organics into the environment. In the past, most analyses of human health risk associated with atmospheric emissions from combustion sources have focused only on exposures resulting from direct inhalation. Recent studies, however, have linked elevated levels of pollutants in soils, lake sediments, and cow's milk to atmospheric transport and deposition of pollutants from combustion sources.[1] These studies indicate that deposition of atmospherically emitted pollutants could result in indirect pathways of exposure for humans. Indirect exposure pathways include ingestion of contaminated drinking water, crops, fish, or even soil, although food ingestion is the primary route of indirect exposure. The purpose of the present study is to assess the extent to which indirect exposure pathways, particularly the terrestrial food chain, pose risks to human health. This will be accomplished by applying the U.S. EPA Methodology for Assessing Health Risks Associated with Indirect Exposure to Combustor Emissions[2] to a MWC in Minnesota. This study will focus on the following toxic organic compounds and heavy metals: Benzo(a)pyrene, Dioxin, Polychlorinated Biphenyls, Hexachlorobenzene, Arsenic, Cadmium, Chromium, Lead, Mercury, and Nickel.

## ATMOSPHERIC DISPERSION MODEL METHODOLOGY

An atmospheric dispersion model was used to estimate contaminant air concentrations, transport of contaminants through the atmosphere, and deposition rates of contaminants in the vicinity of the MWC. These air concentrations and deposition rates were used as input into the U.S. EPA Indirect Exposure Methodology[3] to compute total daily intake of pollutants from food, soil, water and fish ingestion.

COMPDEP, a gaussian plume dispersion model developed for the EPA, was used to estimate atmospheric pollutant concentrations and deposition in complex terrain. To estimate particle size-dependent atmospheric pollutant concentrations at receptor locations, COMPDEP requires hourly, pre-processed meteorological data. Dry deposition was calculated based on particle size-dependent deposition velocities which were automatically calculated by the model using algorithms developed by the California Air Resources Board (CARB)[4] from the work of Sehmel.[5] However, unlike other metals that adsorb onto particles during incineration, mercury remains primarily in the vapor phase.[6] A dry deposition velocity of 0.06 cm/sec[7] was used for elemental mercury vapor and mercuric chloride. Pollutant scavenging due to wet deposition was modeled as a first order loss process using scavenging coefficients dependent on particle size and rain type and intensity.[8]

### Pollutant Emission Rates

Table I outlines pollutant emission rates that were used as input into the model and were based on the latest available measurements of metal emissions from 1990 and organic emissions from 1987:

TABLE I Pollutant Emission Rates.

| Pollutant | Emissions (g/sec) |
|---|---|
| Benzo(a)pyrene (B[a]P) | 3.95 x 10-05 |
| Dioxin (TCDD) | 8.50 x 10-10 |
| Polychlorinated Biphenyls (PCBs) | 2.45 x 10-05 |
| Hexachlorobenzene (HCB) | 1.10 x 10-05 |
| Arsenic (As) | 5.27 x 10-05 |
| Cadmium (Cd) | 3.47 x 10-06 |
| Chromium (Cr) | 1.13 x 10-05 |
| Lead (Pb) | 3.61 x 10-05 |
| Mercury ($HgCl_2$ or $Hg^0$) | 4.93 x 10-04 |

| | |
|---|---|
| Nickel (Ni) | 1.13 x 10-05 |

Most mercury in the environment is generally assumed to be elemental ($Hg^0$) vapor.[9] However, recent studies by Bergstrom[10] show that the majority of the mercury in incinerator gases may be of the mercuric chloride ($HgCl_2$) type. Since no conclusive data regarding the speciation of mercury present in the study incinerator's emissions were available, two model runs were made for mercury in order to determine a possible range of exposure: the first assumed that all emitted mercury was elemental, while the second assumed it was the highly soluble mercuric chloride type. In each case, all mercury was assumed to be in the vapor phase. Since the model results showed no significant differences between elemental mercury and mercuric chloride, we assumed that emissions from this particular MWC were in the form of mercuric chloride.

## Results

Tables II, III, and IV summarize each chemical's dry deposition rates, wet deposition rates, and average annual air concentrations as predicted by the COMPDEP model. Values for the average and maximum scenarios are included.

TABLE II COMPDEP Predicted Average Annual Air Concentrations (ug/m$^3$).

| | AVERAGE | MAXIMUM |
|---|---|---|
| B[a]P | 3.90x10-07 | 4.36x10-05 |
| TCDD | 8.38x10-12 | 9.38x10-10 |
| PCBs | 2.42x10-07 | 2.70x10-05 |
| HCB | 1.09x10-07 | 1.21x10-05 |
| As | 5.02x10-07 | 5.82x10-05 |
| Cd | 3.24x10-08 | 3.84x10-06 |
| Cr | 1.03x10-07 | 1.25x10-05 |
| Pb | 3.56x10-07 | 3.98x10-05 |
| $HgCl_2$ | 4.80x10-06 | 5.16x10-04 |
| Ni | 1.03x10-07 | 1.25x10-05 |

TABLE III COMPDEP Predicted Dry Deposition Rates (g/m$^2$/year).

| | AVERAGE | MAXIMUM |
|---|---|---|
| B[a]P | 1.44x10-08 | 2.68x10-06 |
| TCDD | 3.12x10-13 | 5.74x10-11 |
| PCBs | 8.96x10-09 | 1.66x10-06 |
| HCB | 4.02x10-09 | 7.45x10-07 |
| As | 3.34x10-08 | 6.54x10-06 |
| Cd | 2.84x10-09 | 5.64x10-07 |
| Cr | 1.09x10-08 | 2.20x10-06 |
| Pb | 1.27x10-08 | 2.34x10-06 |
| $HgCl_2$ | 9.06x10-08 | 9.72x10-06 |
| Ni | 1.09x10-08 | 2.20x10-06 |

TABLE IV COMPDEP Predicted Wet Deposition Rates (g/m$^2$/year).

| | AVERAGE | MAXIMUM |
|---|---|---|
| B[a]P | 1.83x10-08 | 5.78x10-05 |
| TCDD | 3.96x10-13 | 1.24x10-09 |
| PCBs | 1.14x10-08 | 3.58x10-05 |
| HCB | 5.13x10-09 | 1.61x10-05 |
| As | 2.46x10-08 | 9.78x10-05 |
| Cd | 1.61x10-09 | 7.34x10-06 |
| Cr | 5.26x10-08 | 2.66x10-05 |
| Pb | 1.68x10-08 | 5.18x10-05 |
| $HgCl_2$ | 1.13x10-07 | 7.62x10-03 |
| Ni | 5.26x10-08 | 2.66x10-05 |

## INDIRECT EXPOSURE METHODOLOGY

The U.S. EPA Indirect Exposure Methodology[11] was used to predict human exposure to MWC emissions by calculating human daily pollutant intake via indirect exposure pathways such as the food chain, and ingestion of soil, drinking water, and fish. The U.S. EPA methodology[12] assumes that pollutant intake from the terrestrial food chain can occur via ingestion of contaminated plants, such as leafy vegetables, root vegetables, garden fruits, legumes, potatoes, and animal forage and grains, or animal tissue, such as beef, beef liver, lamb, pork, poultry, milk, and eggs. Plants may become contaminated through either root uptake, direct deposition to exposed plant surfaces, or air-to-plant transfer of pollutants in the vapor phase. Pollutants may bioaccumulate in animals due to ingestion of contaminated plants, or by direct ingestion of contaminated soils.

Exposure due to ingestion of contaminated soil was calculated assuming pollutants deposit onto local soil at a constant rate and are then consumed either inadvertently or intentionally. Pollutants are not necessarily soil incorporated and may be concentrated in the uppermost soil layer. Deposited contaminant was assumed to be distributed within the uppermost 1 cm of soil, and ingested soil was assumed to originate from the same 1 cm layer. Loss of soil pollutants may be attributed to leaching, degradation, and revolatilization.

Contaminant intake from drinking water and fish ingestion is related to contaminant concentration in local water bodies. Contaminants enter local water bodies through direct deposition and by deposition onto local watersheds due to subsequent soil runoff. Drinking water ingestion was calculated directly from water concentrations while intake from fish ingestion assumes a certain fraction of the pollutants bioaccumulate in fish.

In addition to these indirect exposure pathways, direct exposure due to inhalation was also calculated for the purpose of comparison.

## INDIRECT EXPOSURE FROM ORGANICS AND METALS EMITTED FROM MWCs

All available data, including chemical- and site-specific parameters were input into the U.S. EPA Methodology[13] to determine human daily pollutant intake via indirect exposure pathways. Based on average daily intake values for ingestion and inhalation, results of the ten pollutants analyzed are presented for the average exposure scenario, and the cancer risks and toxic hazard index risks have been calculated.

### Total Daily Intake

Total daily intake (the sum of inhalation exposure and indirect pathway exposures) was computed for the study MWC. Results indicated that total intake is dominated by the indirect pathways, which include plant, animal, soil, drinking water, and fish ingestion. Indirect pathways contribute more than 96.5% of total exposure for all organics (see Table V). The contribution of indirect pathways for metals is somewhat lower due to low uptake of metals in fish. Therefore, indirect pathways never account for less than 74% of human daily pollutant intake which illustrates the importance of considering indirect exposure pathways when assessing potential risks to humans from MWCs.

TABLE V Percentages of total daily pollutant intake from indirect pathways.

| | Average Scenario | Maximum Scenario |
|---|---|---|
| B[a]P | 96.76% | 99.92% |
| TCDD | 96.47% | 99.06% |
| PCB | 99.67% | 99.99% |
| HCB | 98.66% | 99.96% |
| As | 74.44% | 98.72% |
| Cd | 91.14% | 99.66% |
| Cr | 76.93% | 97.65% |
| Pb | 65.13% | 97.64% |
| $HgCl_2$ | 88.42% | 99.98% |
| Ni | 96.34% | 99.88% |

## Cancer Risks

The cancer risks for each pollutant emitted from the incinerator were calculated by multiplying the daily intake values by the cancer potency factor (CPF). This process converts estimated daily intakes averaged over a lifetime of exposure directly to incremental risk of an individual developing cancer. Table VI lists the excess risk levels associated with carcinogens emitted from the MWC.

TABLE VI Excess risks associated with carcinogens.
Based on average exposure scenario daily pollutant intake.
(Intake = mg/kg/day, CPF = $(mg/kg/day)^{-1}$)

| | Ingestion Intake | CPF[14] | Ingestion Risk | Inhalation Intake | CPF[15] | Inhalation Risk | Total Cancer Risk |
|---|---|---|---|---|---|---|---|
| B[a]P | 3.33x10-09 | 11.5 | 3.83x10-08 | 1.11x10-10 | 6.10 | 6.77x10-10 | 3.90x10-08 |
| TCDD | 6.55x10-14 | 1.6x10+05 | 1.05x10-08 | 2.40x10-15 | 1.6x10+05[a] | 3.84x10-10 | 1.09x10-08 |
| PCB | 2.07x10-08 | 4.34 | 9.00x10-08 | 6.87x10-11 | 4.34[b] | 2.98x10-10 | 9.03x10-08 |
| HCB | 2.30x10-09 | 1.7 | 3.91x10-09 | 3.12x10-11 | 1.7[a] | 5.30x10-11 | 3.96x10-09 |
| As | 1.34x10-08 | 15.0 | 6.26x10-09 | 1.43x10-10 | 50.0 | 7.17x10-09 | 1.34x10-08 |
| Cd | 9.52x10-11 | N/A | N/A | 9.26x10-12 | 6.1 | 5.65x10-11 | 5.65x10-11 |
| Cr | 9.81x10-11 | N/A | N/A | 2.94x10-11 | 41.0 | 1.21x10-09 | 1.21x10-09 |
| Pb | 1.90x10-10 | N/A | N/A | 1.02x10-10 | N/A | N/A | N/A |
| $HgCl^2$ | 1.05x10-08 | N/A | N/A | 1.37x10-09 | N/A | N/A | N/A |
| Ni | 7.75x10-10 | N/A[b] | N/A | 2.94x10-11 | 0.84[b] | 2.47x10-11 | 2.47x10-11 |

[a] U.S. EPA. IRIS, 1990.[16]

[b] Strenge and Peterson, 1989.[17]

## Toxic Risks

Risks due to systemic toxicological effects were calculated for the pollutants emitted from the incinerator by dividing the daily intake values by the reference dose (RfD) values (see Table VII). The RfD is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without adverse noncarcinogenic health effects during a lifetime.

The Hazard Quotient is the ratio of an exposure level over a specified time period (e.g., lifetime) to the Rfd. If the exposure level exceeds the Rfd threshold (i.e., if the Hazard Quotient = >1), then adverse health effects may occur.

The Hazard Index is designed to assess the overall potential for noncarcinogenic effects posed by exposure via more than one pathway. The Hazard Index is the sum of the Hazard Quotients; a Hazard Index that exceeds one (>1) indicates the possibility that adverse health effects may occur.

TABLE VII Risks associated with threshold-acting toxicants.
Based on average exposure scenario daily pollutant intake.
(Intake = mg/kg/day, RfD = mg/kg/day)

| | Ingestion Intake | RfD[18] | Hazard Quotient | Inhalation Intake | RfD[19] | Hazard Quotient | Hazard Index |
|---|---|---|---|---|---|---|---|
| B[a]P | 3.33x10-09 | N/A | N/A | 1.11x10-10 | N/A | N/A | N/A |
| TCDD | 6.55x10-14 | N/A | N/A | 2.40x10-15 | N/A | N/A | N/A |
| PCB | 2.07x10-08 | N/A | N/A | 6.87x10-11 | N/A | N/A | N/A |
| HCB | 2.30x10-09 | 0.0008[a] | 2.88x10-06 | 3.12x10-11 | 0.0008[b] | 3.9x10-08 | 2.92x10-06 |
| As | 4.18x10-10 | 0.001[a] | 4.18x10-07 | 1.43x10-10 | N/A | N/A | 4.18x10-07 |
| Cd | 9.52x10-11 | 0.0003 | 3.17x10-07 | 9.26x10-12 | N/A | 0.0[b] | 3.17x10-07 |
| Cr | 9.81x10-11 | 0.005 | 1.96x10-08 | 2.94x10-11 | 0.005 | 5.88x10-09 | 2.55x10-08 |
| Pb | 1.90x10-10 | 0.0014 | 1.36x10-07 | 1.02x10-10 | 0.0004 | 2.55x10-07 | 3.91x10-07 |
| $HgCl^2$ | 1.05x10-08 | 0.0003 | 4.0x10-05 | 1.37x10-09 | 0.00005 | 3.0x10-05 | 7.0x10-05 |
| Ni | 7.75x10-10 | 0.01 | 7.75x10-08 | 2.94x10-11 | N/A | 0.0[b] | 7.75x10-08 |

[a] U.S. EPA. IRIS, 1990.[20]

[b] Strenge and Peterson, 1989.[21]

## Discussion

Based on an average exposure scenario daily pollutant intake, none of the pollutants studied have excess risks greater than $1.0 \times 10^{-6}$ or lifetime exposure levels that exceed the Rfd (i.e., the Hazard Index = <1). Therefore, risk estimates indicate that exposure to these pollutants is not expected to result in any adverse health effects. However, since questions have arisen regarding mercury releases from MWCs, we investigated the contribution of the Minnesota incinerator to local mercury concentrations.

## AMBIENT MERCURY CONCENTRATIONS NEAR THE MWC

Based on the U.S. EPA Indirect Exposure Methodology for Assessing Health Risks Associated with Indirect Exposure to Combustor Emissions (1990), we predicted average mercury concentrations in precipitation, wet deposition, water, and air and compared them to direct measurements of mercury concentrations made in 1988[22] near the MWC. Measured concentrations of mercury at 10 km from the MWC were 3.0 ng/m$^3$ in air and 22 ng/l in precipitation (corresponding to an annual wet deposition rate of 14.0 ug/m$^2$/yr).[23] In addition, water samples taken from the water body adjacent to the incinerator yielded water concentrations ranging from 4.5 ng/l upstream to 12 ng/l downstream of the facility.[24] Mercury found upstream from the incinerator was attributed to wet and dry deposition and other upstream sources, while the increase in mercury concentrations found downstream was attributed to mercury contained in liquid effluent discharged from the facility.[25] Table VIII summarizes mercury concentrations in various media measured near the incinerator as well as values predicted from this analysis.

TABLE VIII Measured and predicted mercury concentrations.

| Medium | Measurement Location | Total Hg in the media[c] | Hg from MWC emissions[a] |
|---|---|---|---|
| Air | 10 km NE | 3.0 ng/m$^3$ | 0.0048 ng/m$^3$ |
| Precipitation (wet deposition) | 10 km NE | 14.0 ug/m$^2$/yr[b] | 0.113 ug/m$^2$/yr |
| Water | Upstream | 4.5 ng/l | 0.0083 ng/l |
| | Downstream | 12.0 ng/l | 17.2 ng/l |
| Fish | Upstream | background average .36 ug/g | 3.86x10-5 ug/g |
| | Downstream | background average .36 ug/g | 0.08 ug/g |

[a] Based on predicted area-weighted average values.

[b] Based on a measured concentration of 22 ng/l.

[c] Measured values reflect concentrations during a period in which incinerator emissions were 1.8 times those modeled.

### Air Concentrations

Glass et al. (1990) measured 3.0 ng/m$^3$ of mercury in air 10 km from the incinerator. This number is similar to other reported background values which range from 2.4 to 7.0 ng/m$^3$.[26] The average predicted atmospheric mercury concentrations due to incinerator emissions account for only 0.2% of the measured value. The area-weighted average mercury air concentration around the incinerator (0.0048 ng/m$^3$) is significantly less than its measured value (3.0 ng/m$^3$). It thus appears that emissions of mercury from the incinerator do not contribute significantly to the overall atmospheric mercury concentration in the surrounding area.

### Precipitation

The area-averaged wet deposition rate of mercury predicted for the study area, 0.113 ug/m$^2$/yr, accounts for less than 1% of measured wet deposition, 14.0 ug/m$^2$/yr (measured 10 km from the incinerator).[27] In the study area taken as a whole, the incinerator does not appear to be a major contributor of mercury contamination via wet deposition, although values at isolated points near the incinerator can be as much as 500 times observed values at 10 km.

### Water Concentrations

Mercury contamination in local water bodies is assumed to issue from two sources: atmospheric emissions from the MWC and the facility's liquid effluent. As with atmospheric concentration and wet deposition, on an average weighted basis atmospheric emissions appear to contribute only a small fraction to the total mercury found in local waters. Yet measured concentrations[28] in the vicinity of the incinerator indicate that mercury contamination is significantly less in areas upstream from the facility (4.5 ng/l) than downstream (12.0 ng/l). Upstream mercury concentrations are assumed to be primarily from atmospheric deposition, while downstream mercury concentrations are assumed to be from both atmospheric deposition and plant effluent. The predicted mercury concentration due to incinerator emissions in the adjacent water body range is 0.0083 ng/l, which is about 0.2% of the 4.5 ng/l concentration measured upstream[29] and 0.07% of the 12.0 ng/l concentration measured downstream[30]. While the contribution from MWC atmospheric emissions is negligible, high levels of mercury contained in the facility's liquid effluent significantly affect the mercury concentration downstream from the facility.

The discharge rate of mercury from the facility's wastewater treatment plant into the river is approximately 40 g/day and may be calculated by multiplying the facility's effluent flow rate (132.6 million liters per day) by the mean total effluent mercury concentration (300 ng/l).[31] By diluting these mercury effluent emissions by the river flow rate (40 g/day ÷ 36.5 $m^3/s$)[32] we predicted a 12.7 ng/l mercury concentration increase downstream of the facility. Assuming the 4.5 ng/l concentration measured upstream represents background, the total predicted mercury concentration downstream from the facility is 17.2 ng/l, which is close to the measured downstream concentration of 12 ng/l. The plant effluent can thus be assumed to be a major contributor to the mercury concentration downstream from the facility.

Previously, high concentrations of mercury in this wastewater were due largely to the release of water used in the scrubber pollution control system to remove pollutants from the incinerator stack exhaust gases. Efforts are underway at the facility to reduce the amount of mercury contained in the wastewater. The most recent permit issued to the facility states that concentrations of mercury in plant effluent are not to exceed 5.0 g/day. Assuming this criterion is met, future mercury concentrations downstream from the facility should only increase from 4.5 ng/l to about 6.0 ng/l, instead of the current increase from 4.5 ng/l to 12 ng/l (assuming the drop in mercury concentration discharge rate from 40 g/day to 5 g/day). The facility's overall contribution to the mercury concentrations in the adjacent water body would thus drop from around 60% to about 25%.

### Fish Concentrations

Fish ingestion is one of the primary pathways of human exposure to mercury from incineration. Like water, mercury contamination in fish is assumed to issue from two sources: atmospheric emissions from the MWC and the facility's liquid effluent. The predicted average mercury concentration in fish due to atmospheric emissions is $3.86 \times 10^{-5}$ ug/g, which is about .01% of the .36 ug/g average background measured concentration near the incinerator.[33] Thus atmospheric emissions of mercury from the incinerator do not appear to contribute significantly to the overall mercury concentration in fish.

However, liquid effluents from the incinerator contribute to an increased mercury concentration downstream from the facility. Based on measured data, the incinerator effluent increases mercury concentration in water by 63%. Theoretically, this results in a predicted mercury concentration of 0.08 ug/g in fish in the immediate vicinity (downstream) of the incinerator.

## CONCLUSION

The purpose of this study was to assess the extent to which indirect exposure pathways, particularly the terrestrial food chain, pose risks to human health. By applying the U.S. EPA methodology for assessing health risks associated with indirect exposure to combustor emissions (1990) to a MWC in Minnesota, we analyzed both direct and indirect exposure pathways for ten pollutants and concluded that indirect exposure pathways account for 65-99% of total daily pollutant intake. At this particular MWC, risk estimates based on average exposure scenario daily pollutant intake were below acceptable levels for all pollutants analyzed.

Furthermore, on an average basis, predicted values of atmospheric mercury emissions to be generated by the MWC are less than measured background concentrations in the environment; thus atmospheric emissions from the MWC do not contribute significantly to the overall atmospheric concentration in the surrounding area. Although atmospheric incinerator emissions are not considered to be a major source of mercury pollutant in this particular study area, high background levels of mercury measured in both fish and water bodies downstream from the facility may be attributed to mercury contamination contained in the facility's effluent.

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