Minnesota Pollution Control Agency

AP42 C1
EFD Ref. 95
(C)

February 1, 1996

Mr. Ronald E. Myers
Emission Factor and Inventory Group
Office of Air Quality Planning & Standards
US Environmental Protection Agency
Research Triangle Park, North Carolina 27711

RE: AP-42 Draft Section for Municipal Solid Waste Landfills (2.4)

Dear Mr. Myers:

The Minnesota Pollution Control Agency (MPCA) received your letter dated October 26, 1995, regarding the proposed draft section of AP-42 on air emissions from Municipal Solid Waste (MSW) landfills. In a telephone conversation on December 7, you requested comments on the draft in mid-January 1996. Specifically, you requested comments on two issues. The first issue being the non-degradable refuse content in landfills. The second issue being mercury emissions from landfills. You also solicited comments on the content of the draft AP-42 section.

Non-Degradable Refuse Content in Landfills

In the draft AP-42 section 2.4 the amount of non-degradable refuse accepted at a landfill is estimated at 20 percent. Your letter states that new data on the historical characterization of MSW suggests that the amount of non-degradable refuse accepted at a landfill may be 25 percent. The MPCA agrees that 25 percent is a more representative estimation. This is based on the results of a municipal solid waste composition study that was conducted in Minnesota during 1990 through 1992. All communities studied have some kind of recycling program in place, although recycling started as recent as 1989 in some locations. Recycling does reduce the amount of waste that is disposed, but because recycling is available for both degradable and non-degradable waste types it is not readily apparent whether the percentage of the waste stream that is non-degradable changes because of recycling practices.

The waste composition study was conducted in such a way to represent waste disposal practices throughout the state. The first part of the study evaluated waste in Minnesota counties representing "Greater Minnesota," which is all of the state excluding the seven-counties that make up the "Twin Cities Metropolitan Area." The "Twin Cities Metropolitan Area" contains between 50 to 55 percent of Minnesota's population. This area was evaluated for the second part of the study. The enclosed maps in Attachment 1 show the study areas.

520 Lafayette Rd.; St. Paul, MN 55155-4194; (612) 296-6300; Regional Offices: Duluth • Brainerd • Detroit Lakes • Marshall • Rochester

The first part of the waste composition study occurred over all four seasons of the year, from July 1990 to May 1991. The second part of the study occurred from January to November 1992, except one site which was evaluated in 1991 and early 1992. In both studies, five study sites were selected to represent different economic activities, geographic regions, and community sizes throughout "Greater Minnesota" and the "Twin Cities Metropolitan Area."

Waste sorting was conducted at each site each season for a one-week period, Monday through Friday. Although some waste sorting sites receive waste on Saturday, the small amounts did not warrant sorting on those days. The waste hauling trucks were randomly selected for waste sorting. In the "Greater Minnesota" part of the study, a total of 20 waste sorts were conducted over 100 days, from which 884 samples were analyzed. The total weight of the samples was about 143 tons, of which the average sample weighed 336 pounds. In the "Twin Cities Metropolitan Area" part of the study, a total of 19 waste sorts were conducted over 19 weeks, from which 1,170 samples were analyzed. The total weight of the samples was about 172 tons, of which the average sample weighed 307 pounds.

The two enclosed (Attachment 1) Tables, entitled "Greater Minnesota" and "Twin Cities Metropolitan Area" show the overall percentage estimates of material (by weight) in the waste streams at each site and at all sites combined. Below is a summary of the percentage of non-degradable refuse content determined from the study.

Non-Degradable Refuse Content in Minnesota Waste Stream (percent)			
Refuse Category	"Greater Minnesota"	"Twin Cities Metropolitan Area"	"Greater Minnesota" & "Twin Cities Metropolitan Area"
plastic	10.0	11.6	11.4
metal	5.0	5.0	5.0
major appliances	0.1	0.0	0.0
small electric appliances	0.4	0.8	0.8
glass	3.1	3.1	3.1
demolition/construction debris	3.7	2.8	2.9
other inorganic waste*	3.6	3.8	3.8
Total:			27

* other inorganic waste is defined as those items that do not fall into any other category and that are composed of inert materials that would not decompose when left exposed to the elements. Examples are, rocks, dirt, ceramics, porcelain, kitty litter (clay), and small fragments of inorganic material passing through the sort screen. Also included inseparable inorganic composite items not listed under consumer electronics, such as electrical components.

Mercury Emissions from Landfills

In 1993, the MPCA conducted a preliminary study of mercury concentrations in gas emitted from three large MSW landfills in Minnesota. The three landfills are equipped with gas extraction systems leading to a flare. A known sample volume of gas was taken from the pipe leading to the flare. The sampled gas was passed through two iodated carbon traps in series--the second serving as a test for break-through--and total mercury was determined. Measured mercury concentrations ranged from 0.25 micrograms per cubic meter ($\mu g/m^3$) to 4.47 $\mu g/m^3$ (Attachment 2, Table 1). However, because break-through occurred to the second carbon trap, the MPCA believes that the measurements underestimate the actual concentration to an unknown degree. Break-through occurs when the first trap in the series does not quantitatively retain mercury in the gas stream. There are several processes that may have contributed to the break-through. First, the testing was conducted in the winter resulting in condensation of water in the sample train, which may have reduced trapping efficiency. Second, although methane is not trapped by iodated carbon, there are many other organic gases present in landfill gas that are trapped by carbon that likely saturated the carbon adsorption sites, reducing trapping efficiency for mercury. Even so, this preliminary data demonstrates that mercury vapor is carried out of landfills by the methane stream.

Perhaps even more significant is the finding that mercury is methylated within landfills and the methyl mercury is also carried by the emitted gas. Several samples of water that condensed in the landfills' gas collection system were analyzed for total and methyl mercury (Attachment 2, Table 2). Methyl mercury concentrations in the condensate ranged from 14 to 69 nanograms per liter (ng/L) and constituted from 3 to 34 percent of total mercury.

No additional funds have been available for the MPCA to continue to further study mercury emissions from landfills. MPCA staff is unaware of any other studies available on mercury emissions from landfills.

Comments on the Content of the AP-42 Section on MSW Landfills

p. 2.4-2 2.4.3 Control Technology: The second paragraph of this section refers to the--now proposed--New Source Performance Standard (NSPS) and Emissions Guidelines (EG). The most recent revised proposed rule (August 1995) contains a default NMOC emission rate that triggers installation of control equipment of 50 Mg/yr (55 tons/yr). It should be noted that this requirement only affects landfills with a design (permitted) capacity greater than 2.5 million Mg.

2.4.4 Emissions: In this section it would be helpful to discuss the other components of landfill gas that can, and in some cases must, be quantified for regulatory purposes in addition to methane (CH_3), carbon dioxide (CO_2) and nitrogen (N_2), such as non-

methane organic compounds (NMOCs), hazardous air pollutants (HAPs), volatile organic compounds (VOCs). The relationship between NMOCs and VOCs deserves attention in the main text, as opposed to relying on the footnote of the Table on p. 2.4-11. VOCs will likely be the pollutant that determines whether a facility without active gas collection is required to obtain an air emissions permit.

Other emissions associated with the landfill should also be described, such as those from control -- combustion -- devices (carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), hydrogen chloride (HC*l*) and CO_2) and fugitive dust (PM_{10}). The AP-42 section does not address HC*l* emissions. HC*l* emissions from large landfill control systems can be significant. The Potential to Emit (PTE) estimate for a large MSW landfill in Minnesota combusting 7,750 scfm of landfill gas is 44.8 tons per year. Since this exceeds the 10 tons per year air permitting threshold for an individual HAP, the facility is classified as major under Title III. An excerpt from the permit application for the facility is attached as Attachment 3.

Readability may be improved by setting-up Section 2.4.4 as follows:

2.4.4 Emissions
- 2.4.4.1 Gas Generation Rate
- 2.4.4.2 Uncontrolled Gas Emissions from Landfill
  - 2.4.4.2.1 Methane and CO_2
  - 2.4.4.2.2 NMOC
  - 2.4.4.2.3 VOCs
  - 2.4.4.2.4 HAPs
- 2.4.4.3 Controlled Landfill Gas Emissions
  - 2.4.4.3.1 Destruction Efficiencies of Previously Uncontrolled Landfill Gases
  - 2.4.4.3.2 CO
  - 2.4.4.3.3 NOx
  - 2.4.4.3.4 SO_2
  - 2.4.4.3.5 HC*l* (a HAP created when the many chlorinated NMOCs in landfill gas are combusted)
  - 2.4.4.3.6 CO_2 (additional)

2.4.3 Control Technology. Change information in third paragraph:
Landfill gas collection... to extract landfill gas by the use of... by the increase in ~~landfill~~ pressure ~~from landfill~~ created by gas generation within the landfill to mobilize...

p. 2.4-3 2.4.4.1 Uncontrolled Emissions: The results from using the equations that begin on this page for calculating mass emission rates of various compounds from landfill gas

are 96 percent of the results obtained when using the model downloaded from the EPA's Bulletin Board Service (referenced in paragraph 1 of this Section).

In the equation, clarify that the time since initial refuse placement (t) is the sum of the number of years the landfill has accepted waste (open) and the number of years closed.

Paragraph 2 comments are in this letter under the section entitled "Non-Degradable Refuse Content in Landfills."

Paragraph 3 of this section refers to EPA Method 2E. It would be helpful to add where this method can be found.

Paragraph 4 of this section provides Lo and k values used in regulatory compliance (NSPS and EG). The recent version of the proposed NSPS has an Lo of 170 m^3/Mg and a k of 0.05/yr, it also has an equation to use for calculating emissions by section of landfill. It may be useful to include both the Lo and k values and the equation. Paragraph 4 also recommends default k values based on "normal or above normal precipitation" and "drier waste." It would be useful to state an approximate annual precipitation value.

p. 2.4-4 The second full paragraph on this page states that the regulatory default option for total NMOC concentration is 8000 ppmv. The most recent version of the proposed NSPS and EG is 4000 ppmv.

The third full paragraph on this page discusses the correction for air infiltration. Change information to:
If a site-specific total ~~NMOC~~ pollutant concentration is available (~~i.e.,~~ e.g., as measured by EPA Reference Method 25C), it must be corrected for air infiltration into the collected landfill gas sample. ~~before it can be combined with the estimated landfill gas emissions to estimate total NMOC emissions~~.

p. 2.4-5 The equation on this page should contain all applicable units:

$$UM_P = Q_P * [\ MW_P * 1\ atm / (8.205 \times 10^{-5}\ m^3\text{-atm/mol-K})(1000 g/kg)(273+T)]$$

where,

UM_P	=	uncontrolled mass emissions of pollutant, kg/yr;
Q_P	=	emission rate of P, m^3/yr;
MW_P	=	molecular weight of P, g/mol;
T	=	temperature of landfill gas, °C

p. 2.4-6 2.4.4.2 Controlled Emissions: The first paragraph provides typical collection efficiencies that range from 60 to 85 percent, with an average of 75 percent most commonly assumed. It is not clear if the collection efficiency assumed may vary based on if the landfill is fully lined. If so, it would be helpful if this section provided one range of collection efficiencies for unlined landfills, and another range for lined landfills. Info. not available.

The second paragraph states that control efficiencies for the combustion of CH_4, NMOCs and some speciated organics with differing control devices are presented in Table 2.4-3. It should be explained that these control efficiencies are based on tested data. It should be mentioned that a 98 percent control efficiency is assumed in the NSPS for an open flare (combustion of NMOC) if designed in accordance to the Code of Federal Regulations at 40 CFR pt. 60.18.

p. 2.4-9 to 11 Table 2.4-1 Uncontrolled Landfill Gas Concentrations: It would be helpful to identify and add footnotes for those compounds that are non-VOCs, and refer to the relationship between VOCs and NMOCs. It would be also useful to include a short explanation about how the Table was derived so the user of the information can better understand how best to apply the data. The explanation could be in the section on Uncontrolled Emissions and could include how the particular pollutants were selected (e.g. the list does not exhaust all speciated organics in landfill gas, but are the only compounds for which data was collected according to literature and database research), and the basis of the default concentrations. It would be helpful to note whether landfills should look at other potential components in landfill gas, or whether the only significant emissions to consider are on the AP-42 list.

Change information in footnote to Table 2.4-2 as shown:
** For NSPS/Emission Guideline..., the default VOC content at co-disposal sites = 82 percent by weight (~~167~~ 1997 ppmv as hexane); at No or Unknown sites = 28 percent by weight (~~1997~~ 167 ppmv as hexane).

p. 2.4-12 Table 2.4-3 Control Efficiencies for Landfill Gas Constituents: This Table should contain a destruction efficiency for VOCs. The Table lists fairly wide ranges of destruction efficiencies for the various types of control device. Given that the emission factor rating is low for these estimates, would it be defensible to recommend one destruction efficiency for each type of device? That would greatly simplify emission calculations and provide a figure to use for pollutants (e.g., individual HAPs) that aren't included in the Table. It appears that 98 percent could safely be assumed for a gas turbine, while internal combustion engine destruction efficiency could be set at approximately 85 percent.

If you have any questions in regard to the analysis of mercury emissions from landfills, call Ed Swain, of my staff, at 612/296-7800. Refer any other questions to Margaret McCourtney, of my staff, at 612/297-7894.

Sincerely,

J. David Thornton
Program Development & Air Analysis Section
Air Quality Division

JDT:lmg

cc: Margaret McCourtney, Air Quality Division
Ed Swain, Air Quality Division
John Seltz, Air Quality Division
Carol Andrews, Air Quality Division
Brian Holtrop, Air Quality Divsion
Marty Osborn, Ground Water & Solid Waste Division

Enclosures

Figure III-3. Location of the Twin Cities seven-county Metro Area and the five sorting sites in Greater Minnesota.

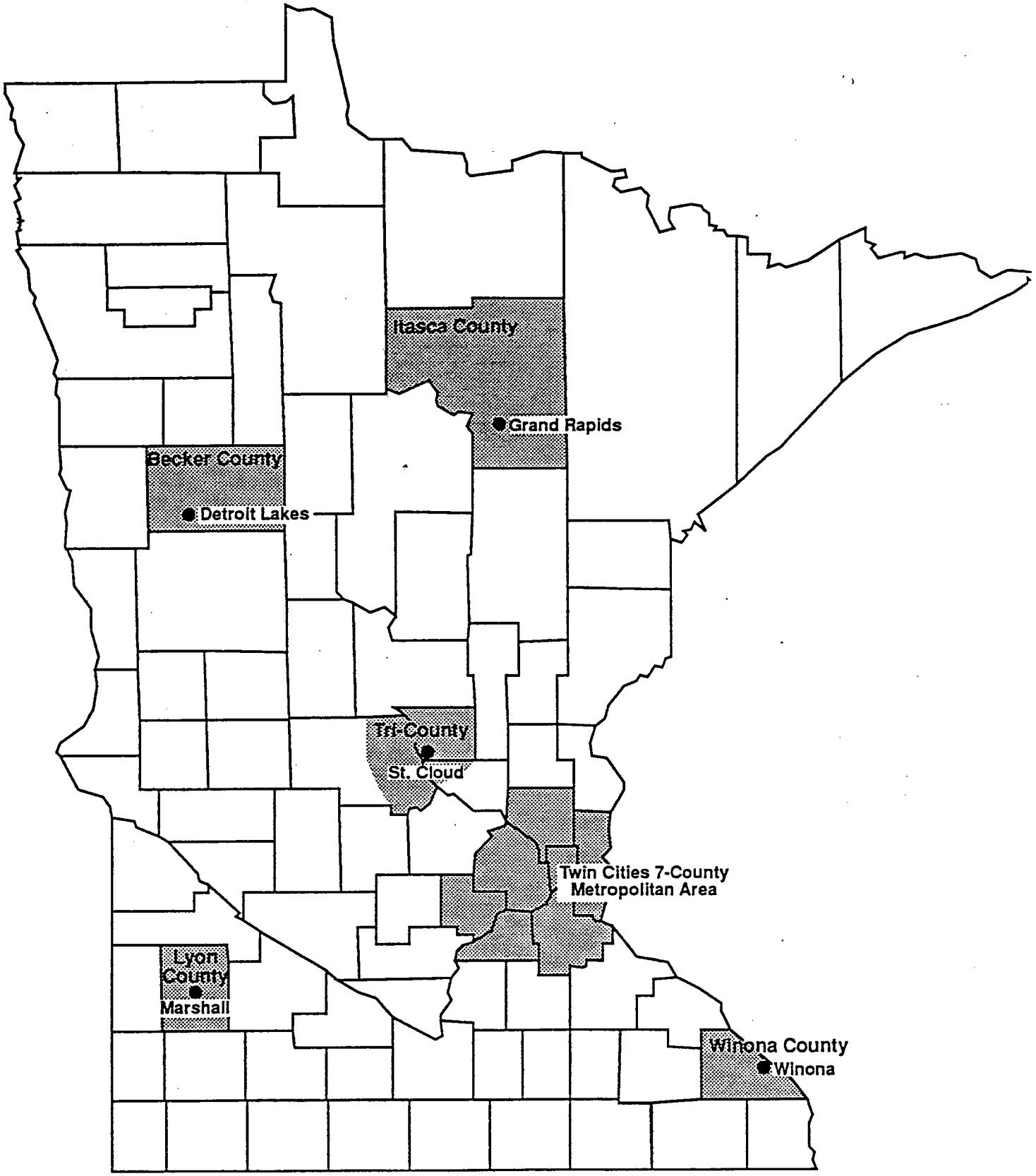

Figure III-4. Location of the five Metro Area sorting sites.

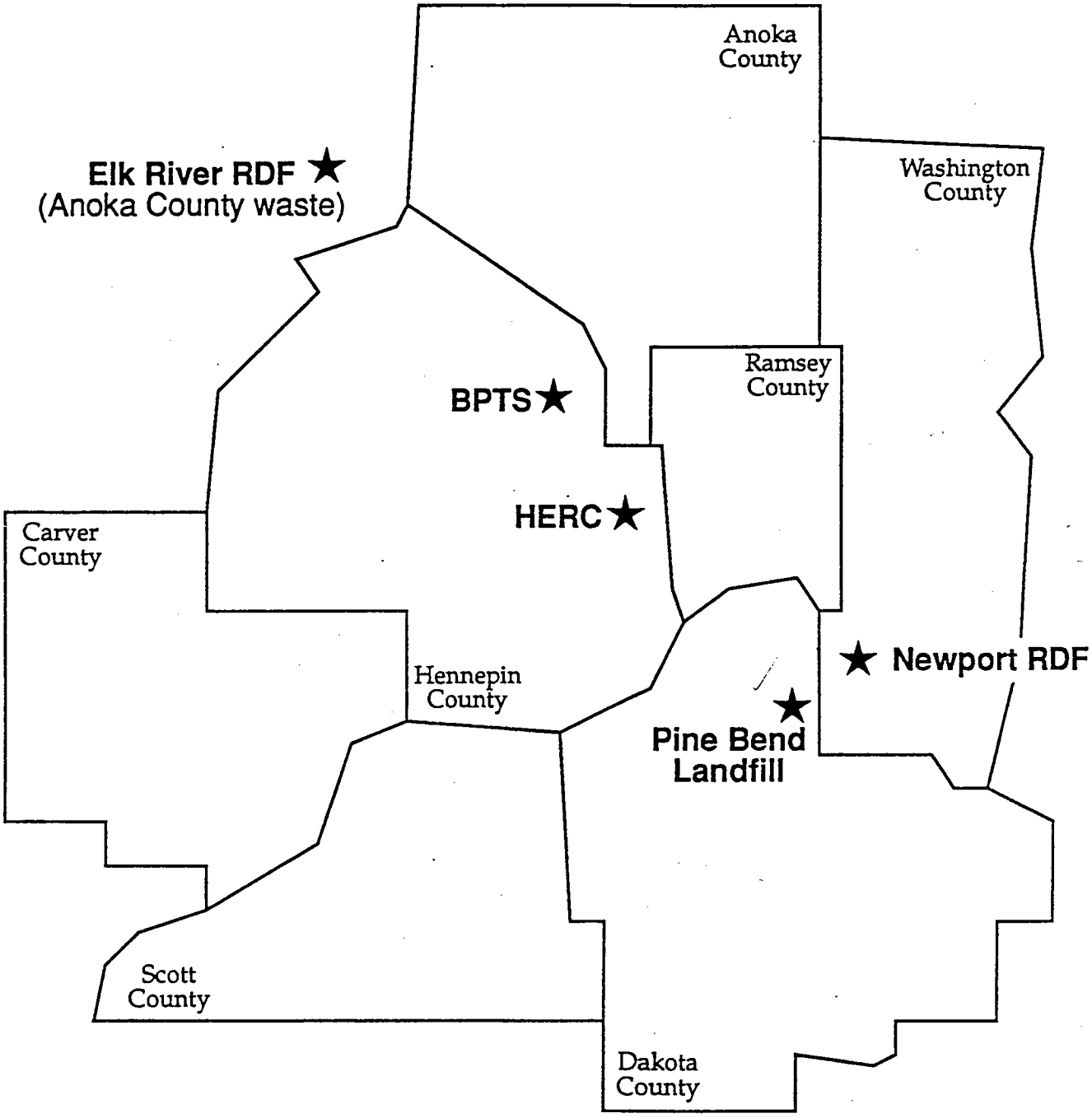

Table I-1. Overall percentage estimates of material in MSW (by weight) during the one-year study period at each site and at all sites combined.

	SITES					
SORTING CATEGORIES	Winona (%)	Itasca (%)	Lyon (%)	Tri-Co (%)	Becker (%)	TOTAL (%)
Newsprint	2.3	4.8	4.4	4.4	4.1	4.0
High Grade Paper	2.3	3.1	3.3	5.2	2.3	3.8
Corrugated/Kraft Paper	12.7	7.4	11.4	8.1	9.2	9.5
Magazines	1.9	3.1	2.8	2.8	2.2	2.6
Other Paper	21.3	21.6	20.5	20.0	15.3	20.0
Total percentage: Paper	**40.5**	**40.0**	**42.4**	**40.5**	**33.1**	**39.8**
High Density Polyethylene - HDPE	0.4	0.9	0.6	0.7	0.9	0.7
Plastic Film	5.8	4.4	6.4	4.6	4.6	5.0
Polyethylene Terephthalate - PET	0.1	0.3	0.4	0.4	0.5	0.3
Polystyrene	0.5	1.1	0.8	1.1	0.9	0.9
Other Plastic	4.9	2.2	2.5	2.8	1.9	3.1
Total percentage: Plastic	**11.8**	**8.9**	**10.7**	**9.5**	**8.8**	**10.0**
Aluminum Beverage Containers	0.2	0.5	0.6	0.5	0.6	0.5
Other Aluminum	0.3	0.4	0.2	0.3	0.3	0.3
Ferrous Food Cans	0.6	1.9	1.2	1.3	1.6	1.3
Other Ferrous	4.0	2.4	1.5	2.3	2.3	2.6
Other Non-Ferrous	0.2	0.4	0.3	0.2	0.5	0.3
Total percentage: Metal	**5.4**	**5.7**	**3.8**	**4.8**	**5.3**	**5.0**
Glass Food/Beverage Containers	1.1	4.2	2.4	2.4	3.5	2.4
Other Glass	0.6	0.7	0.6	0.8	0.7	0.7
Total percentage: Glass	**1.7**	**4.9**	**3.0**	**3.2**	**4.2**	**3.1**
Small Yard Waste	1.2	2.5	3.2	4.1	6.1	3.4
Large Yard Waste	0.1	0.2	0.0	0.3	0.2	0.2
Total percentage: Yard Waste	**1.2**	**2.7**	**3.2**	**4.4**	**6.2**	**3.6**
Food Waste	12.8	17.3	15.9	11.7	25.2	14.5
Wood Waste	8.5	1.6	5.1	6.7	2.8	5.9
Tires	0.0	0.0	0.1	0.0	0.0	0.0
Adult and Infant Diapers	2.0	3.1	2.5	2.6	3.3	2.6
Textiles	4.9	2.5	2.0	3.7	2.3	3.5
Other Organic Waste	3.5	5.6	4.6	2.5	2.5	3.3
Major Appliances	0.1	0.0	0.0	0.1	0.0	0.1
Small Electric Appliances	0.3	0.7	0.7	0.3	0.3	0.4
Demolition/Construction Debris	4.9	1.1	1.1	4.7	1.7	3.7
Hazardous Waste	0.5	1.0	0.7	0.9	0.6	0.8
Oil Filters	0.1	0.2	0.4	0.2	0.4	0.2
Other Inorganic Waste	1.8	4.9	3.9	4.2	3.1	3.6

Table I-1. Overall percentage estimates of material in MSW (by weight) during the 16-month study period at each site and at all sites combined.

	SITES					
SORTING CATEGORIES	Anoka (%)	Newport (%)	Pine Bend (%)	BPTS (%)	HERC (%)	TOTAL (%)
Newsprint	4.7	3.4	4.0	3.5	4.8	4.0
High Grade Paper	2.8	4.7	3.5	4.1	5.6	4.5
Corrugated/Kraft Paper	7.5	9.4	11.1	6.8	8.5	8.7
Magazines	2.6	2.7	1.9	3.0	3.8	2.9
Other Paper	19.4	19.3	17.2	21.5	21.5	20.0
Total percentage: Paper	**36.9**	**39.6**	**37.6**	**38.9**	**44.3**	**40.1**
High Density Polyethylene - HDPE	1.0	0.6	0.6	0.7	0.6	0.7
Plastic Film	4.2	4.5	4.7	4.3	5.4	4.7
Polyethylene Terephthalate - PET	0.4	0.2	0.2	0.3	0.3	0.3
Polystyrene	1.2	0.9	1.4	1.0	1.3	1.1
Other Plastic	4.1	5.7	4.6	5.0	4.1	4.8
Total percentage: Plastic	**10.9**	**12.0**	**11.6**	**11.2**	**11.6**	**11.6**
Aluminum Beverage Containers	0.7	0.4	0.5	0.5	0.6	0.5
Other Aluminum	0.3	0.4	0.3	0.4	0.4	0.4
Ferrous Food Cans	0.9	0.9	0.9	0.8	0.8	0.9
Other Ferrous	3.4	2.5	2.4	2.8	3.0	2.8
Other Non-Ferrous	0.5	0.3	0.5	0.4	0.7	0.5
Total percentage: Metal	**5.8**	**4.6**	**4.6**	**4.9**	**5.4**	**5.0**
Glass Food/Beverage Containers	2.3	1.6	1.8	2.0	2.4	2.0
Other Glass	1.3	0.8	1.0	1.3	1.2	1.1
Total percentage: Glass	**3.6**	**2.4**	**2.8**	**3.3**	**3.6**	**3.1**
Small Yard Waste	3.8	3.1	1.7	3.7	1.3	2.7
Large Yard Waste	0.1	0.3	0.1	0.0	0.1	0.1
Total percentage: Yard Waste	**4.0**	**3.4**	**1.8**	**3.7**	**1.4**	**2.8**
Food Waste	13.0	14.3	11.6	12.8	12.7	13.2
Wood Waste	5.6	7.6	12.4	5.7	3.8	6.6
Tires	0.0	0.1	0.1	0.0	0.1	0.1
Adult and Infant Diapers	3.1	2.3	2.3	2.7	2.0	2.4
Textiles	3.2	2.5	2.6	3.2	3.6	3.0
Other Organic Waste	3.7	3.4	3.3	4.2	4.2	3.8
Major Appliances	0.0	0.0	0.0	0.0	0.1	0.0
Small Electric Appliances	0.7	0.8	0.5	0.5	1.2	0.8
Demolition/Construction Debris	3.1	2.6	3.2	3.4	2.5	2.8
Hazardous Waste	0.4	0.5	0.4	0.5	0.8	0.5
Empty Hazardous Waste Containers	0.5	0.1	0.4	0.5	0.3	0.3
Oil Filters	0.2	0.1	0.1	0.1	0.2	0.1
Other Inorganic Waste	5.3	3.7	4.6	4.3	2.4	3.8

Attachment 2

Mercury in MSW Landfill Gas in Minnesota

Table 1
Total Mercury in Landfill Gas
(sampled May 1993)

Landfill Name	Sample I.D. No.	Flow Rate (cc/min)	Total Minutes	Volume (Liters)	Hg found, ng/trap front	Hg found, ng/trap back	Total Hg ($\mu g/m^3$)
Pine Bend	M10	505	290	146	215 227	18	1.62
Pine Bend	M11	505	290	146	157 108 107	3	0.85
Anoka	M12	500	180	90	151	11	1.77
Anoka	M14	250	180	45	92	1	2.00
Anoka	"spike" (1000 ng)	500	60	30	730 729	7	64% recovery
Anoka	M13	254	60	15.2	76 62	2	4.47
Flying Cloud	M15	500	162	81	21	1.9	0.246
Flying Cloud	M16	250	162	40.5	21 14	0	0.358
	"blank"				1 2	---	---

Table 2
Mercury in Condensate from Landfill Gas Collection System

Sample I.D. No.	Mercury Concentrations (µg/L) total	Mercury Concentrations (µg/L) methyl	Methyl Mercury (percent of total)
A FGB-086	1.68 1.73	0.069	4
A FGB-081	1.67	0.058 0.056	3
B FGB-089	0.167	0.014	8
B FGB-096	0.080	0.027	34
"blank"	0.020	0.003	
	percent	percent	
"spike recovery"	102	89	

See page 3 of 5 for HCl calculations

The fourth column of Table 2 lists the maximum emission increases for each air pollutant at the Pine Bend Landfill caused by either of the two proposed operating scenarios. The basis for the proposed operating emissions outlined in Table 2 are defined in more detail in Attachments PE-01 and PE-03. The existing flare emission rates in the first column of Table 2 are calculated similarly to the proposed flare emission rates as shown in Attachment PE-01. For each emitting unit, proposed or existing, the landfill gas makeup used for the emissions calculations is given in this attachment, Section 2. The potential to emit of each unit in the proposed system is summarized in Section 3.

2. Landfill Gas Composition

2.1 Expected Landfill Gas Composition

The methane concentration in landfill gas typically ranges from 40% to 60% by volume. Overall, the composition of the gas extracted from a landfill may vary between different landfills and at the same landfill over time. Landfill gas primarily consists of methane and carbon dioxide with other trace compounds accounting for less than 1% of the total gas volume. However, nitrogen and oxygen can also be present in extracted landfill gas due to the air infiltration through the landfill surface. A breakdown of the expected range of component concentrations for the gas extracted from the Pine Bend Landfill is listed in Table 3.

Table 3. Range of landfill gas compositions and expected composition for the gas extracted from the Pine Bend Landfill.

Compound	Range	Expected
Methane	40 to 60 %	50 %
Carbon Dioxide	40 to 50 %	40 %
Nitrogen	0 to 10 %	9 %
Oxygen	0 to 5 %	1 %
Trace Compounds	< 1 %	< 1 %

2.2 Organic Compound Worst-Case Concentrations

The gas to be extracted from the Pine Bend Landfill is expected to consist of 50% methane (CH_4), 40% carbon dioxide (CO_2), 9% nitrogen (N_2) and 1% oxygen (O_2). Trace landfill gas constituents are expected to make up less than 1% of the total gas volume. A summary worst-case concentrations for all possible constituents expected in the Pine Bend Landfill gas is given in Table 4. These concentrations are based on numerous gas samples collected at other Browning-Ferris landfills of similar design throughout the country. For each compound, gas sample results from the numerous landfill sites were assumed to follow a normal distribution. From these distributions, the concentration corresponding to the upper bound of the 95% confidence level was calculated for each compound. These concentrations, listed in Table 4, are assumed to be representative of a worst-case composition.

2. Combustion Equation

The inlet landfill gas, for the purposes of calculating the products of combustion and the exhaust gas flowrate, is assumed to be a mixture of 50% methane (CH_4), 40% carbon dioxide (CO_2), 9% nitrogen (N_2), and 1% oxygen (O_2). Concentrations of the other landfill gas constituents are negligible with regards to the combustion process. Nitrogen and oxygen presence in the landfill gas is assumed to account for the possible infiltration of ambient air into the gas extraction system through the surface of the landfill.

The methane is assumed to be completely oxidized in the flare combustion. In addition, based on manufacturer tests of enclosed landfill flares, the content of exhaust oxygen is assumed to be 11.2%. Under these assumptions, the combustion of the landfill gas can be represented by the following equation.

$$50\,CH_4 + 40\,CO_2 + 9\,N_2 + O_2 + 236.03\,(3.76\,N_2 + O_2) = 90\,CO_2 + 100\,H_2O + 896.49\,N_2 + 137.03\,O_2$$

At a volumetric flow rate of 1,390 scfm, the molar flow rate of landfill gas into the flare can be calculated as follows.

$$\left(1{,}390\,\frac{sft^3}{min}\right)\left(60\,\frac{min}{hr}\right)\left[\frac{1\text{ atm}}{\left(0.7302\,\frac{atm\ ft^3}{lbmole\ °R}\right)(519.67\ °R)}\right] = 219.78\,\frac{lbmole\ fuel}{hr}$$

Based on the combustion equation, the ratio of the exhaust gas molar flowrate to the inlet landfill gas (fuel) molar flowrate can be calculated as follows.

$$\frac{(90 + 100 + 896.49 + 137.03)}{100} = 12.235\,\frac{lbmole\ exhaust}{lbmole\ fuel}$$

For this and all other calculations, natural gas processing industry standard conditions of 60°F (519.67°R) and 1 atm have been used. With knowledge of the exhaust gas to fuel gas flow ratio, the molar flowrate of exhaust gas out of the flare can then be calculated as follows.

$$\left(12.235\,\frac{lbmole\ exhaust}{lbmole\ fuel}\right)\left(219.78\,\frac{lbmole\ fuel}{hr}\right) = 2{,}689\,\frac{lbmole\ exhaust}{hr}$$

3. Organic Constituent Emission Rates

The individual landfill gas constituent flow rates listed in Table 2-1 are calculated based on the fuel gas molar flow rate. The calculation for each constituent is similar. For illustration, the inlet mass flow rate of benzene, with a landfill gas concentration of 4,170 ppb, is calculated as follows.

$$\left(\frac{4.170\ lbmole\ benzene}{1 \times 10^6\ lbmole\ fuel}\right)\left(78.11\,\frac{lb\ benzene}{lbmole\ benzene}\right)\left(219.78\,\frac{lbmole\ fuel}{hr}\right) = 0.072\,\frac{lb}{hr}\ benzene$$

Organic compound exhaust gas emission rates shown in Table 2-1 are based on a flare overall destruction efficiency of 98%. A complete and reliable compilation of landfill gas destruction

efficiencies for open flares is not yet available, but based on the landfill gas flow rate and heating value, during stable combustion operations, a 98% overall destruction rate should be attainable.[1,2] A sample calculation for benzene is shown for illustration.

$$\left(0.072\frac{\text{lb benzene}}{\text{hr}}\right)(1 - 0.98) = 0.0014\frac{\text{lb}}{\text{hr}}\ \text{benzene}$$

4. Nitrogen Oxides and Carbon Monoxide Emission Rates

The calculation of nitrogen oxides (NO_x) and carbon monoxide (CO) emissions are based on conservative emission factors related to the heat released during combustion. This heat of combustion, assuming a heating value of methane of 909.8 Btu/scf, can be calculated as follows.

$$\left(1{,}390\frac{\text{sft}^3}{\text{min}}\right)\left(0.5\frac{\text{ft}^3\ CH_4}{\text{ft}^3}\right)\left(\frac{909.8\ \text{Btu}}{\text{ft}^3\ CH_4}\right)\left(60\frac{\text{min}}{\text{hr}}\right)\left(\frac{1\ \text{MMBtu}}{10^6\ \text{Btu}}\right) = 37.94\frac{\text{MMBtu}}{\text{hr}}$$

Based on EPA AP-42 guidance for industrial flares, a conservative NO_x emission factor of 0.10 lb/MMBtu and a CO emission factor of 0.40 lb/MMBtu are used to estimate the NO_x and CO emission rates as follows.[3]

$$\left(0.1\frac{\text{lb NO}_x}{\text{MMBtu}}\right)\left(37.94\frac{\text{MMBtu}}{\text{hr}}\right) = 3.79\ \frac{\text{lb}}{\text{hr}}\ NO_x$$

$$\left(0.4\frac{\text{lb CO}}{\text{MMBtu}}\right)\left(37.94\frac{\text{MMBtu}}{\text{hr}}\right) = 15.18\ \frac{\text{lb}}{\text{hr}}\ CO$$

5. Hydrogen Chloride and Chlorine Emission Rates

Hydrogen chloride (HCl) and chlorine (Cl_2) emissions from the auxiliary flare are estimated by assuming that approximately 99% of the chlorine molecules oxidized from chlorinated compounds in the landfill gas during combustion are converted to HCl. The remaining 1% would convert to Cl_2. The number of chlorine atoms available from each compound is calculated based on an overall destruction efficiency of 98% for chlorinated compounds. This calculation is illustrated as follows for perchloroethylene, which has a landfill gas concentration of 27,290 ppb.

$$\left(\frac{27{,}290\ \text{lbmole}}{10^9\ \text{lbmole fuel}}\right)(0.98)\left(\frac{\text{lbmole fuel}}{12.235\ \text{lbmole exhaust}}\right)\left(\frac{4\ \text{lbmole Cl}}{\text{lbmole}}\right)\left(\frac{1\ \text{ppb}}{\frac{1\ \text{lbmole}}{10^9\ \text{lbmole exhaust}}}\right) = 8{,}743.3\ \text{ppb Cl}$$

---

[1] U.S. Environmental Protection Agency, Office of Air and Radiation and Office of Air Quality Planning and Standards, *Compilation of Air Pollution Emission Factors, Volume I: Stationary Point and Area Sources*, EPA 450/2-78/027R, Research Triangle Park, NC, September 1991, Section 11.5.

[2] Engineering-Science, *A Report on Flare Efficiency Study*, Prepared for Chemical Manufacturers Association, Washington, D.C., September 1982.

[3] Ibid, Ref. 1.

Thus, 8,743.3 ppb of chlorine atoms are available from perchloroethylene to convert to either HCl or Cl_2 during combustion. The total concentration of chlorine atoms available from all chlorinated compounds is calculated in Table 2-2.

Table 2-2. Total concentration of chlorine atoms oxidized from chlorinated compounds during combustion available to react and form HCl and Cl_2.

Chlorinated Compounds in Landfill Gas	Landfill Gas Concentration (ppb)	Chlorine Atoms in Compound	Chlorine Available to React (ppb)
Chlorobenzene	846	1	67.8
Vinyl Chloride	10,222	1	818.7
Chloroform	56	1	4.5
1,1- Dichloroethane	9,068	2	1452.6
1,2- Dichloroethane	1,837	2	294.3
1,1- Dichloroethylene	561	2	89.9
1,2- Dichloroethylene	15,840	2	2537.5
Trichloroethylene	6,028	3	1448.5
Perchloroethylene	27,290	4	8743.3
Carbon Tetrachloride	44	4	14.1
Methylene Chloride	33,774	1	2705.2
1,1,1- Trichloroethane	3,042	3	731.0
		TOTAL:	18,907

Based on a total concentration of chlorine atoms of 18,907 ppb and by assuming that 99% of the chlorine atoms will convert to HCl, the HCl emission rates can be calculated as follows.

$$\left(\frac{18{,}907 \text{ lbmole Cl}}{10^9 \text{ lbmole exhaust}}\right)(0.99)\left(\frac{2{,}689 \text{ lbmole exhaust}}{\text{hr}}\right)\left(\frac{1 \text{ lbmole HCl}}{1 \text{ lbmole Cl}}\right)\left(\frac{36.46 \text{ lb HCl}}{\text{lbmole HCl}}\right) = 1.84\frac{\text{lb HCl}}{\text{hr}}$$

Assuming that the remaining 1% of available chlorine atoms oxidized in the combustion process will convert to Cl_2, the Cl_2 emission rate can be calculated in a similar fashion.

6. Sulfur Oxides Emission Rates

Similar to the calculation of HCl and Cl_2 emission rates, the emission rates of sulfur dioxide (SO_2) and sulfur trioxide (SO_3) from the auxiliary flare are based on the number of available sulfur atoms released from sulfur-containing compounds in the landfill gas during combustion. An assumption is made that 97% of the sulfur atoms will be converted to SO_2 and that the remaining 3% of available sulfur atoms will convert to SO_3. Using carbon disulfide as an example, the concentration of sulfur atoms oxidized from an individual sulfur containing compound during combustion that will be available to convert to SO_2 and SO_3 is calculated as follows.

$$\left(\frac{456 \text{ lbmole } CS_2}{10^9 \text{ lbmole fuel}}\right)(0.98)\left(\frac{\text{lbmole fuel}}{12.235 \text{ lbmole exhaust}}\right)\left(\frac{2 \text{ lbmole S}}{\text{lbmole } CS_2}\right)\left(\frac{1 \text{ ppb S}}{\frac{1 \text{ lbmole S}}{10^9 \text{ lbmole exhaust}}}\right) = 73.0 \text{ ppb S}$$

The total concentration of sulfur atoms in the combustion process, found by adding the available sulfur atoms from each compound, is calculated in Table 2-3.

Table 2-3. Total concentration of sulfur atoms oxidized from sulfur containing compounds during combustion available to react and form SO_2 and SO_3.

Sulfur Containing Compounds in Landfill Gas	Landfill Gas Concentration (ppb)	Sulfur Atoms in Compound	Sulfur Available to React (ppb)
Methyl Mercaptan	2,308	1	184.9
Ethyl Mercaptan	315	1	25.2
Dimethyl Sulfide	9,614	1	770.0
Dimethyl Disulfide	395	2	63.3
Carbonyl Sulfide	364	1	29.2
Carbon Disulfide	456	2	73.0
Hydrogen Sulfide	42,867	1	3433.5
		TOTAL:	4,579

Based on a total concentration of sulfur atoms of 4,579 ppb and by assuming that 97% of the sulfur atoms will convert to SO_2, the SO_2 emission rate can be calculated as follows.

$$\left(\frac{4{,}579 \text{ lbmole S}}{10^9 \text{ lbmole exhaust}}\right)(0.97)\left(\frac{2{,}689 \text{ lbmole exhaust}}{\text{hr}}\right)\left(\frac{1 \text{ lbmole } SO_2}{1 \text{ lbmole S}}\right)\left(\frac{64.06 \text{ lb } SO_2}{\text{lbmole } SO_2}\right) = 0.765 \frac{\text{lb } SO_2}{\text{hr}}$$

Assuming that the remaining 3% of available sulfur atoms oxidized in the combustion process will convert to SO_3, the SO_3 emission rate can be calculated in a similar fashion.

7. Particulate Matter Emission Rates

The landfill gas extraction system is designed to eliminate the possibility of particulate matter being entrained in the inlet gas flow. The extracted gas is routed through a knock-out pot upstream of the primary flare. No additional fugitive dust emissions will be generated as a result of the combustion operation. Despite these measures, a conservative emission factor of 0.07 grains per standard cubic foot (gr/scf) is used to estimate the maximum potential particulate emissions from the proposed flare. At a landfill gas flow rate of 1,390 scfm, the particulate matter emission rate can be calculated as follows.

$$\left(\frac{0.07 \text{ grains PM}}{\text{SCF}}\right)\left(\frac{1{,}390 \text{ sft}^3}{\text{min}}\right)\left(\frac{1 \text{ lb PM}}{7{,}000 \text{ grains PM}}\right)\left(\frac{60 \text{ min}}{1 \text{ hr}}\right) = 0.834 \frac{\text{lb PM}}{\text{hr}}$$

PE-02 - Natural Gas 10-100 MBtu/hr
$PM_a + PM_b$ Calc. = 0.0000137 lb/scf

$(.0000137 \frac{lb}{scf})(1390 \frac{scf}{min})(60 \frac{min}{hr}) = 1.14 \frac{lb\ PM}{hr}$

close enough — threshold = 3.42 lb/hr for PM10