Acknowledgments

RCN 670-017-52-02

MEXICO EMISSIONS INVENTORY PROGRAM
ADVANCED TRAINING WORKBOOK

FINAL

Prepared for:

Western Governors' Association
Denver, Colorado

and

Binational Advisory Committee

Prepared by:

Radian International LLC
10389 Old Placerville Road
Sacramento, CA 95827

September 1997

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LIST OF ACRONYMS

AFR   air to fuel ratio

AST   aboveground storage tank

bbl   barrels

Btu   British thermal unit

C   Celsius

C_8H_{18} octane

CE   control efficiency

CFC   chlorofluorocarbon

cfm   cubic feet per minute

CI   compression ignition

CO   carbon monoxide

CO_2 carbon dioxide

DRE   destruction removal efficiency

EC   elemental carbon

F   Fahrenheit

FAER   fuel/air equivalence ratio

ft   foot

ft^3 cubic foot

g   gram

gal   gallon

GIS   geographic information system

LIST OF ACRONYMS (CONTINUED)

H_2O	water
hr	hour
HVLP	high volume/low pressure
IC	internal combustion
J	joule
kcal	kilocalorie
kg	kilogram
kW	kilowatt
lb	pound
LPG	liquefied petroleum gas
m	meter
m^3	cubic meter
MEK	methyl ethyl ketone
mg	milligram
Mg	megagram (i.e. 10^6 g = 1 metric ton)
ml	milliliter
MMBtu	10^6 British thermal units
mmHg	millimeters of mercury
MMscf	10^6 standard cubic feet
mol	mole
MW	molecular weight
n	number of moles

LIST OF ACRONYMS (CONTINUED)

N_2	nitrogen
ng	nanogram
NMHC	non-methane hydrocarbon
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
O_2	oxygen
OC	organic carbon
P	pressure
PEMEX	Petróleos Mexicanos
PM	particulate matter
$PM_{2.5}$	particulate matter of aerodynamic diameter of 2.5 microns or less
PM_{10}	particulate matter of aerodynamic diameter of 10 microns or less
ppmv	parts per million - volume
psi	pounds per square inch
psia	pounds per square inch - absolute
psig	pounds per square inch - gage
PSM	particle size multiplier
R	ideal gas constant
R	Rankine
ROG	reactive organic gas
RVP	Reid vapor pressure
scf	standard cubic feet

LIST OF ACRONYMS (CONTINUED)

scfm   standard cubic feet per minute

SI   spark ignition

sm^3 standard cubic meter

SO_x sulfur oxides

T   temperature

TOG   total organic gas

TSP   total suspended particulate

U.S.   United States

U.S. EPA   United States Environmental Protection Agency

V   volume

VKT   vehicle kilometers traveled

wt%   weight percent

yr   year

μg   microgram

μm   micrometer (micron)

Introduction

Purpose and Scope

The purpose of this workbook is to provide example problems that illustrate various emission estimating techniques used during an emissions inventory development effort. In addition, several potential difficulties are also examined. It is intended that the material presented in this workbook will both help facilitate training programs and be used as a resource document during the development of emission estimates by various states and municipalities.

This workbook contains realistic examples. Each example has been carefully written to explain in detail the basis for each illustrated emission estimating technique, as well as any inherent assumptions. Special emphasis has been placed on explaining the thought process and decisions that may be required in applying the illustrated technique. The material presented in this workbook will demonstrate the use of specific engineering principles and will illustrate the application of engineering judgment and problem-solving techniques to the development of emission estimates in Mexico.

Challenges of Estimating Emissions ("Beyond the Cookbook")

With sufficient information, the calculation of the estimated emissions from any source is generally a straightforward mathematical exercise. An analogy can be made that many emission calculation techniques are as straightforward as recipes in a cookbook. When conducting an actual emissions inventory, however, there are often individual sources or entire source categories for which the development of emissions estimates is not so simple. To use the cookbook analogy, there are sources and source categories for which there are no simple recipes in the cookbook.

The most commonly encountered problem in any emissions inventory project is that of incomplete information (data gaps). When there are data gaps, the task of estimating

emissions becomes more complex and the application of engineering judgment and various problem-solving skills is required. In this workbook, Example 3 (Residential Fuel Combustion) was developed specifically to illustrate some of the techniques that are typically used to fill data gaps. Example 3 is a detailed discussion of the methodology used to fill the significant data gaps that were encountered during the development of an air toxics emission inventory for Nogales, Sonora.

Four of the more common methods for filling data gaps are:

- Derive needed information from available data;

- Develop reasonable alternative approaches to estimate emissions;

- Apply assumptions and bounding estimates to the problem; and

- Collect additional data.

Example 3 illustrates the decision process that was used to select the most appropriate of these methods to fill the data gaps encountered in Nogales. Some of the other examples in this workbook also illustrate the techniques that can be used to fill data gaps (see Examples 2a and 7).

In addition to data gaps, other difficulties commonly encountered when conducting an emissions inventory include:

- Selecting the appropriate emission estimation technique for each source, including selecting emission factors;

- Ensuring reasonable accuracy in the data used to prepare the estimate, including selecting information from conflicting data sources; and

- Verifying that the calculated emissions are a realistic estimation of the true emissions from the source. If the calculated emissions are not realistic or if there is no reasonable basis for comparison, then estimating the level of uncertainty in the estimates is necessary.

To achieve the most reasonable and realistic estimate of emissions, one must identify and characterize all of the possible emission types and sources, select the appropriate estimating techniques, develop an understanding of the selected techniques, make any necessary assumptions, and gather or otherwise develop the necessary data for the calculations. Once the necessary information is at hand, the emission estimates must be prepared and thoroughly documented. In addition, critical to the overall quality of any technical project such as the development of emissions estimates is the consistent use of peer review. Reviewers typically are people who are familiar with the specific emission source and are experienced in the field of emission estimation. Each decision, assumption, and calculation should be thoroughly reviewed in order to ensure accuracy and reasonableness in the final estimates.

Like any other major engineering project or scientific research project, there are often many interesting and challenging problems to solve during an emissions inventory development effort. Several of the more common problems have been examined in the examples that are presented in this workbook. As explained in this section and illustrated in the remainder of this workbook, the problems most commonly encountered in developing emission estimates do not always have simple solutions. Those who prepare the emissions estimates will benefit from a more complete understanding of the principles and assumptions inherent in each of the techniques that are illustrated in this workbook. This workbook consists of the following seven examples:

- Example 1 - Stationary internal combustion engines;

- Example 2 - External combustion boilers;

- Example 3 - Residential heating (biomass combustion);

- Example 4 - Gasoline distribution system;

- Example 5 - Solvent evaporation sources;

- Example 6 - Use of point source test data; and

- Example 7 - Particulate matter.

Some of these examples contain multiple parts. In addition, supplemental information is also provided for several examples.

Where possible, examples are calculated using metric units; U.S. units are used elsewhere. A collection of conversion factors and material properties is presented in Appendix A. Also, a listing of other example problems found in the Mexico Emissions Inventory Program Manuals series is provided in Appendix B.

Finally, all examples presented in this workbook represent hypothetical situations. The examples demonstrate various useful calculation methodologies. However, activity data contained within these examples should <u>not</u> be used in real-life situations; instead, actual data should be collected.

<center>**Example 1**

Stationary Internal Combustion Engines</center>

Stationary internal combustion (IC) engines are significant sources of emissions in urban areas. They are used in a wide range of applications and include engines based on reciprocating and rotary motion. The primary fuels for reciprocating type engines are gasoline, diesel fuel oil, and natural gas. They are used in applications such as generators and pumps. Examples of rotary motion IC engines include gas turbines used for electric power generation and in various process industries, and natural gas-fired pipeline compressor engines and turbines. This problem focuses on reciprocating gasoline- and diesel-powered IC engine emissions.

Problem Statement

Estimate the annual uncontrolled emissions of TOG (total organic gas), CO (carbon monoxide), NO_x (nitrogen oxides), PM_{10} (particulate matter of aerodynamic diameter of 10 microns or less), and SO_x (sulfur oxides) from diesel powered engines.

Available Information

Number of engines:	6
Power rating:	20 kilowatts (kW) per engine
Hours of operation:	12 hours per day, 365 days per year
Average engine load factor:	45%
Fuel type:	Diesel
Fuel usage rate:	5 liters/hour of operation
Heating value of diesel:	4×10^7 joules (J)/liter (19,300 British thermal units [Btu]/lb)
Controlled/uncontrolled emissions:	Uncontrolled

Note: The diesel heating value in joules/liter was converted from the value of 19,300 Btu/lb obtained from the United States Environmental Protection Agency's (U.S. EPA) Compilation of Air Pollution Emission Factors (AP-42) (U.S. EPA, 1995a) Table 3.3-2 as follows:

$$\text{Heating value} \left(\frac{J}{\text{liter}} \right) = \left(19{,}300 \ \frac{\text{Btu}}{\text{lb}} \right) \left(7.428 \ \frac{\text{lb}}{\text{gal}} \right) \left(\frac{1 \ \text{gal}}{3.78 \ \text{liters}} \right) \left(\frac{1055 \ J}{\text{Btu}} \right)$$

$$\text{Heating value} = 4.0 \times 10^7 \ \frac{J}{\text{liter}}$$

Methodology - Power Output Based Emission Factor Method

Emissions are calculated using "brake-specific" emission factors (mass of emissions/power-time) and several types of activity data. The required activity data are engine operation time, power rating, and the engine load factor (power actually used divided by power available). This methodology is represented mathematically with the following equation.

$$\text{Emissions}_p = \sum_{e \, = \, 1}^{N} P_e \times LF_e \times T_e \times EF_p$$

where:
	Emissions_p	=	Mass of emission of pollutant p (kg);
	N	=	Number of engines;
	P_e	=	Average rated power of engine e (kW);
	LF_e	=	Typical engine load factor of engine e (%);
	T_e	=	Time period of engine operation for engine e (hours); and
	EF_p	=	Emission factor for pollutant p (kg/kW-hr).

Although this example provides all required activity data, the collection of activity data may be an involved process. Typically, equipment information will be collected in equipment inventories. If information is unavailable through equipment inventories, the equipment manufacturers should be contacted. Alternatively, information from similar equipment may be used if no other data are available. U.S. EPA's *Nonroad Engine and Vehicle Emissions Study* (U.S. EPA, 1991a) also provides various typical physical characteristics for IC engines that can be used when specific engine information is unavailable.

The main source of emission factors for stationary internal combustion sources is AP-42, Chapter 3. The emission factors for industrial diesel engines are presented below in Table 1-1.

Table 1-1

Emission Factors for Uncontrolled Diesel Industrial Engines

Pollutant	Emission Factor (g/kW-hr)	Emission Factor (ng/J)
Exhaust TOG	1.50	152
Evaporative TOG	0.00	0.00
Crankcase TOG	0.03	2.71
Refueling TOG	0.00	0.00
Total TOG[a]	1.53	154.71
CO	4.06	410
NO_x	18.8	1,896
PM_{10}	1.34	135
SO_x	1.25	126

Source: AP-42, Table 3.3-1

[a] Total TOG consists of exhaust, evaporative, crankcase, and refueling TOG.

Calculations - Annual Uncontrolled Emissions Using Power Output Based Emission Factors

$$E_{TOG} = (6)(20 \text{ kW})(0.45)\left(\frac{12 \text{ hr}}{\text{day}}\right)\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{1.53 \text{ g}}{\text{kW–hr}}\right)$$

$$= 362 \text{ kg/yr} = 0.36 \text{ Mg/yr}$$

$$E_{CO} = (6)(20 \text{ kW})(0.45)\left(\frac{12 \text{ hr}}{\text{day}}\right)\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{4.06 \text{ g}}{\text{kW–hr}}\right)$$

$$= 960 \text{ kg/yr} = 0.96 \text{ Mg/yr}$$

$$E_{NOx} = (6)(20 \text{ kW})(0.45)\left(\frac{12 \text{ hr}}{\text{day}}\right)\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{18.8 \text{ g}}{\text{kW–hr}}\right)$$

$$= 4,447 \text{ kg/yr} = 4.45 \text{ Mg/yr}$$

$$E_{PM_{10}} = (6)(20 \text{ kW})(0.45)\left(\frac{12 \text{ hr}}{\text{day}}\right)\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{1.34 \text{ g}}{\text{kW–hr}}\right)$$

$$= 317 \text{ kg/yr} = 0.32 \text{ Mg/yr}$$

$$E_{SOx} = (6)(20 \text{ kW})(0.45)\left(\frac{12 \text{ hr}}{\text{day}}\right)\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{1.25 \text{ g}}{\text{kW–hr}}\right)$$

$$= 296 \text{ kg/yr} = 0.30 \text{ Mg/yr}$$

Alternative Methodology - Fuel Input Based Emission Factor Method

If the physical characteristics of engines are unavailable, an alternative method of estimating emissions can be used that is based upon fuel usage. Fuel input based emission factors can be found in AP-42 and other emission factor sources. Power output emission factors are a "bottom-up" estimation approach that includes considerable equipment-specific information. Fuel input emission factors are a "top-down" estimation approach that tends to miss equipment-specific details. The power output emission factors are the preferred methodology; however, data limitations may indicate that fuel input emission factors should be used.

Emissions are calculated using fuel input based emission factors (mass of emissions/energy content of fuel) and several types of activity data. The required activity data are

engine operation time, fuel usage rate, and the heating value of fuel. This methodology is represented mathematically with the following equation.

$$\text{Emissions}_p = \sum_{e=1}^{N} \text{FUR}_e \times T_e \times H \times \text{EF}_p$$

where:
	Emissions_p	=	Mass of emission of pollutant p (kg);
	N	=	Number of engines;
	FUR_e	=	Fuel usage of engine e (liters/hour);
	T_e	=	Time period of engine operation for engine e (hours);
	H	=	Heating value of fuel (J/liter); and
	EF_p	=	Emission factor for pollutant p (ng/J).

Fuel input based emission factors can also be found in AP-42, Chapter 3. These emission factors were presentd earlier in this example.

Calculations - Annual Uncontrolled Emissions Using Fuel Input Based Emission Factors

$$E_{TOG} = (6) \left(\frac{5 \text{ liters}}{\text{hour}} \right) \left(\frac{12 \text{ hours}}{\text{day}} \right) \left(\frac{365 \text{ days}}{\text{year}} \right) \left(4.0 \times 10^7 \frac{J}{\text{liter}} \right) \left(154.71 \frac{\text{ng}}{J} \right) \left(\frac{1 \text{ kg}}{10^{12} \text{ ng}} \right)$$

$$= 813 \text{ kg/yr} = 0.81 \text{ Mg/yr}$$

$$E_{CO} = (6) \left(\frac{5 \text{ liters}}{\text{hour}} \right) \left(\frac{12 \text{ hours}}{\text{day}} \right) \left(\frac{365 \text{ days}}{\text{year}} \right) \left(4.0 \times 10^7 \frac{J}{\text{liter}} \right) \left(410 \frac{\text{ng}}{J} \right) \left(\frac{1 \text{ kg}}{10^{12} \text{ ng}} \right)$$

$$= 2,155 \text{ kg/yr} = 2.16 \text{ Mg/yr}$$

$$E_{NOx} = (6) \left(\frac{5 \text{ liters}}{\text{hour}} \right) \left(\frac{12 \text{ hours}}{\text{day}} \right) \left(\frac{365 \text{ days}}{\text{year}} \right) \left(4.0 \times 10^7 \frac{J}{\text{liter}} \right) \left(1,896 \frac{\text{ng}}{J} \right) \left(\frac{1 \text{ kg}}{10^{12} \text{ ng}} \right)$$

$$= 9,965 \text{ kg/yr} = 9.97 \text{ Mg/yr}$$

$$E_{PM_{10}} = (6) \left(\frac{5 \text{ liters}}{\text{hour}} \right) \left(\frac{12 \text{ hours}}{\text{day}} \right) \left(\frac{365 \text{ days}}{\text{year}} \right) \left(4.0 \times 10^7 \frac{J}{\text{liter}} \right) \left(135 \frac{\text{ng}}{J} \right) \left(\frac{1 \text{ kg}}{10^{12} \text{ ng}} \right)$$

$$E_{PM_{10}} = 710 \text{ kg/yr} = 0.71 \text{ Mg/yr}$$

$$E_{SOx} = (6) \left(\frac{5 \text{ liters}}{\text{hour}} \right) \left(\frac{12 \text{ hours}}{\text{day}} \right) \left(\frac{365 \text{ days}}{\text{year}} \right) \left(4.0 \times 10^7 \frac{J}{\text{liter}} \right) \left(126 \frac{\text{ng}}{J} \right) \left(\frac{1 \text{ kg}}{10^{12} \text{ ng}} \right)$$

$$= 662 \text{ kg/yr} = 0.66 \text{ Mg/yr}$$

<center>**Example 1**</center>

<center>**Stationary Internal Combustion Engines - Supplemental Information**</center>

Emission Controls - Air to Fuel Ratio (AFR)

A primary parameter that governs the amount of pollutants produced during combustion is the air to fuel ratio (AFR). The calculation of the AFR is based on the stoichiometric reaction of fuel and air during combustion. Ideal combustion of gasoline (represented as octane) in a spark ignition (SI) engine is chemically represented below.

$$C_8H_{18} + 12.5\ O_2 + 47\ N_2 \Rightarrow 8\ CO_2 + 9\ H_2O + 47\ N_2$$
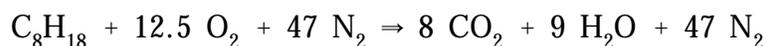
The stoichiometric AFR is simply the ratio of the mass of air over the mass of fuel used in ideal combustion.

Mass of Air: 12.5 g-moles O_2 × 32 g/g-mole   =   400 g
                      47 g-moles N_2 × 28 g/g-mole   =   <u>1,316 g</u>
                                                                          1,716 g

Mass of Fuel: 1 g-mole C_8H_{18} × 114 g/g-mole   =   114 g

$$AFR = \frac{mass\ of\ air}{mass\ of\ fuel} = \frac{1,716}{114} = 15.05$$

Of course, the actual stoichiometric AFR calculated above would be slightly different due to the fact that air is not composed solely of nitrogen and oxygen and that gasoline is not equivalent to octane. In fact, gasoline is a mixture of many hydrocarbon compounds and a typical AFR for gasoline is 14.7. The stoichiometric ratios vary based on engine and fuel type. An engine operating at a stoichiometric AFR is said to be operating at a fuel/air equivalence ratio (FAER) of 1.0 where the FAER is defined as the ratio of stoichiometric AFR over the actual AFR. The FAER is less than 1.0 for leaner burning (i.e., more air) operation and greater than 1.0 for richer burning engine operation. The normal operating range for a conventional spark ignition

(SI) engine using gasoline is $12 \leq AFR \leq 18$, and for compression ignition (CI) engines with diesel $18 \leq AFR \leq 70$.

Engine performance is often optimized to minimize fuel consumption. This usually minimizes TOG and CO emissions because the combustion efficiency is maximized, but NO_x emissions are also near maximum. However, if the AFR ratio is not correct, engine performance decreases, fuel consumption increases, and emissions of TOG and CO increases.

Figure 1-1 illustrates the effect of AFR on TOG, CO, and NO_x emissions from a SI engine. The shapes of the curves indicate the complexity of emissions control through AFR adjustment. The figure shows that TOG emissions decrease as the AFR increases, or as the fuel-air mixture becomes fuel-lean. This decrease in TOG emissions continues as the mixture becomes leaner, until the mixture becomes so lean that combustion quality becomes poor and misfiring begins to occur. The result is a sharp increase in TOG emissions due to increased emissions of unburned hydrocarbons from the exhaust.

Combustion temperature and oxygen availability strongly affect NO_x emissions. Operation of engines near stoichiometric results in near maximum NO_x emissions due to high combustion temperatures. At this equivalence ratio however, oxygen concentrations are low. As the mixture is fuel-enriched, burned gas temperatures fall, resulting in decreased combustion efficiency. This results in increased TOG and CO emissions and decreased NO_x emissions. TOG and CO emissions increase during fuel-rich conditions because the excess fuel is not completely burned during combustion. The steady increase in the curves is due to the increasing excess of fuel. As the mixture becomes fuel-lean from stoichiometric, increasing oxygen concentration initially offsets the decreasing combustion temperature, resulting in an increase in NO_x emissions. As the mixture becomes leaner, reduced combustion temperature becomes more important than oxygen availability for NO_x emissions, and emissions decrease.
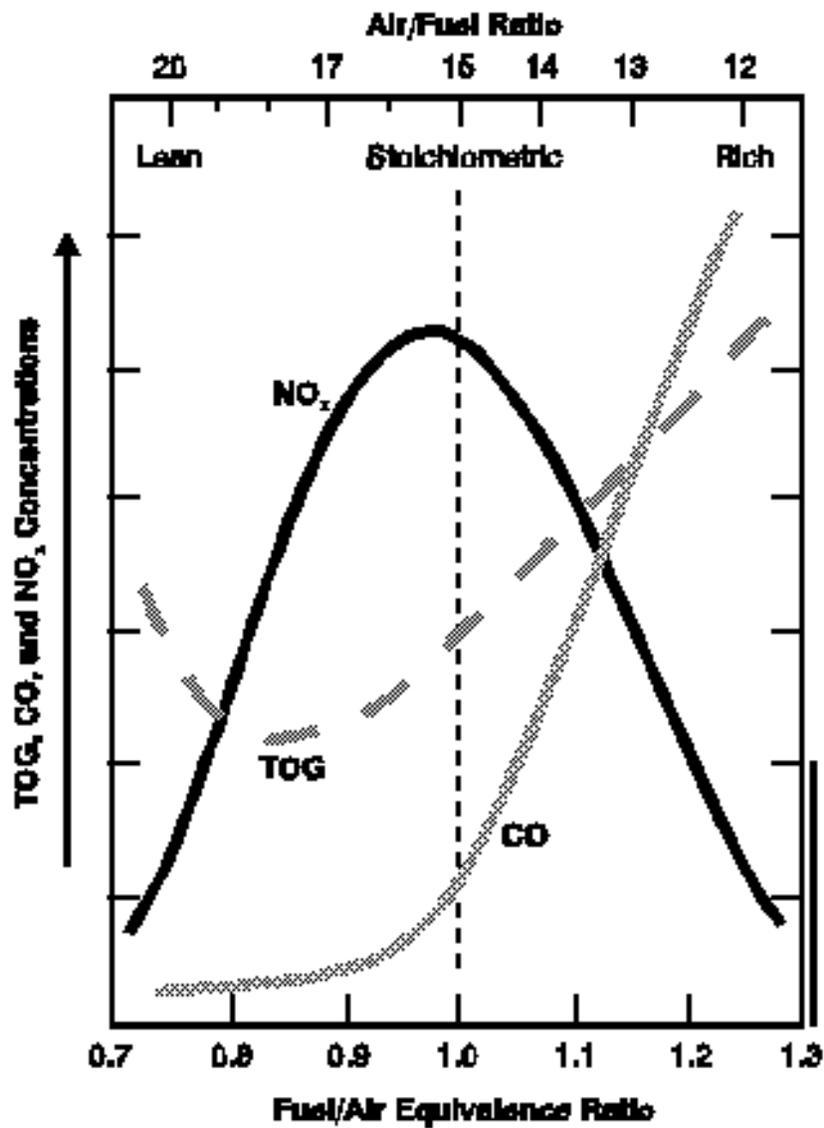
Figure 1-1. Relationship between Air to Fuel Ratio (AFR), Fuel/Air Equivalence Ratio (FAER), and Emitted Pollutants

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Example 2a

External Combustion Devices - Fuel Allocation

</div>

Introduction

The commonly published emission factors for external combustion devices such as those found in AP-42 (U.S. EPA, 1995a) are based on the size of the device and the quantity of fuel consumed. These emission factors are expressed in units of lb/MMscf (10^6 standard cubic feet) for natural gas or lb/gal for liquid fuel such as diesel fuel. Accurate emission estimates are dependent on accurate fuel use data; however, fuel use data are often not available for individual external combustion devices. There is often only one fuel meter for a building or other facility that contains several combustion devices and the fuel throughput to each individual source must be estimated based on device design and operational parameters.

The example presented below illustrates the fuel allocation technique for a case where a fuel meter measures the total fuel supplied to a group of combustion devices. The fuel throughput for the devices in the example is allocated based on hours of operation and size or capacity of the equipment. The same methodology can be used to apportion fuel consumption among any number of devices, if the capacity and operating hours of each device are known.

Problem Statement

Estimate natural gas consumption for individual external combustion devices based upon device capacity and hours of operation.

Available Information

A tortilla factory contains four tortilla manufacturing machines, each with a burner that operates on natural gas, liquified petroleum gas (LPG), or both. There is one meter on the natural gas line to the building, and in 1996, the total gas consumption was 240 MMscf. Table 2-1 shows the burner capacities and operating hours for 1996 and summarizes the results of the

calculations to apportion the total fuel among the four burner. Detailed calculations are shown following Table 2-1.

Table 2-1

Fuel Apportionment to Tortilla Factory External Combustion Devices

	GIVEN		CALCULATED			
Burner	Capacity (MMBtu/hr)	Hours Operated in 1996	Annual Heat Load at Capacity (MMBtu/yr)	% of Total Load	Estimated Fuel Consumption	
					(MMscf/yr)	$(10^6 \text{ m}^3/\text{yr})$
A	21	4,320	90,720	36	86.4	2.45
B	8	4,512	36,096	14	33.6	0.95
C	21	2,880	60,480	24	57.6	1.63
D	7.5	8,760	65,700	26	62.4	1.77
Total			252,996	100	240.0	6.80

To allocate the fuel consumption among the burners, the calculations are as follows:

1. Calculate the annual heat load for each burner at full capacity:

Annual heat load (MMBtu/yr) = Burner capacity (MMBtu/hr) × Annual hours (hr/yr)

For Boiler A, annual heat load = 21 MMBtu/hr × 4,320 hours/yr
= 90,720 MMBtu/yr

2. Find the total annual heat load for all four burners (see table).

90,720 + 36,096 + 60,480 + 65,700 = 252,996 MMBtu/yr

3.   Determine the % of total annual heat load for each burner.

$$\text{For Burner A} = \frac{90,720 \ \text{MMBtu/yr}}{252,996 \ \text{MMBtu/yr}}$$

$$= 36\%$$

4.   Allocate total fuel throughput to each burner based on % of total annual heat load.

$$\text{For Burner A} = 240 \ \text{MMscf/yr} \times 0.36$$
$$= 86.4 \ \text{MMscf/yr}$$

There are many possible sources of uncertainty in this allocation method and the impact of these uncertainties on the estimated emissions from the sources of interest should be examined. Possible sources of uncertainties include:

- Variable operation of the different devices (there is an unstated assumption in this method that each device operates at the same relative percent of its capacity);

- Incomplete or inaccurate records of hours of operation for one or more devices;

- Incomplete or inaccurate records of fuel consumption; and

- Incomplete or unavailable design data for one or more sources (uncertain capacity).

<div align="center">

Example 2b

External Combustion Devices - Emission Factors

</div>

Introduction

This problem demonstrates the use of published emission factors to estimate emissions. Although this problem may seem overly simplistic, it is a valuable estimation technique that is used in virtually all emissions inventories.

Problem Statement

Estimate total NO_x emissions from the four tortilla manufacturing machine burners described in Example 2a.

Available Information

External combustion emission factors in AP-42 are classified based upon the heat input of the external combustion device. This classification is shown below:

- Utility/large industrial (>100 MMBtu/hr);

- Small industrial (10-100 MMBtu/hr);

- Commercial (0.3-10 MMBtu/hr); and

- Residential (<0.3 MMBtu/hr).

Based upon this classification, burners A and C from Example 2a are small industrial devices while burners B and D are commercial devices. None of the four burners have any emission control devices attached to them.

Solution

From Table 1.4-2 of AP-42, the NO_x emission factor for small industrial devices is 2240 kg/10^6 m^3, while the emission factor for commercial devices is 1600 kg/10^6 m^3. Emissions from the burners in the tortilla factory are then calculated using the following equation:

$$E_{Total} = \sum_{d=1}^{n} (FC_d \times EF_d)$$

where:
$$
\begin{array}{lll}
E_{Total} & = & \text{Total emissions (kg/yr);} \\
n & = & \text{Number of devices;} \\
FC_d & = & \text{Fuel consumption for device d (10^6 m^3/yr); and} \\
EF_d & = & \text{Emission factor for device d (kg/10^6 m^3).}
\end{array}
$$

so

$$
\begin{aligned}
E_{Total} &= (2.45 \times 2,240) + (0.95 \times 1,600) + (1.63 \times 2,240) + (1.77 \times 1,600) \\
&= 5,488 + 1,520 + 3,651 + 2,832 = 13,491 \text{ kg/yr} = 13.5 \text{ Mg/yr}
\end{aligned}
$$

Example 2c

External Combustion Devices - Other Estimating Techniques

Introduction

This problem demonstrates limitations of emission factors, which are widely used in the development of emission inventories.

Emission factors are a widely used emission estimating technique primarily because they are relatively inexpensive and easy to use. However, under certain circumstances, they may not provide an accurate estimate of the emissions from a specific process. It is important to understand that emission factors are based on available source test data. While the published factors may be quite accurate for the specific equipment and conditions that were tested, they may be significantly less accurate for other equipment and conditions.

When conducting an emissions inventory, it is not uncommon to encounter a source for which there are no specific emission factors in the literature. In these cases, it has been a common practice to use published emission factors for source types that appear to be similar. While this practice of extrapolation may appear to be reasonable, it can cause significant errors in the emission estimates.

This problem specifically focuses on the external combustion emission factors that are found in Chapter 1 of AP-42 and presents an example to illustrate a case where these emission factors were not applicable. Example source test data and associated calculations are also presented.

Problem Statement

Estimate TOG emissions from a fume incinerator (an air pollution control device designed to destroy the organic compounds emitted from sources such as large paint booths in the automotive industry).

Available Information

The inputs to the incinerator are the large exhaust air stream from the paint booth (containing small quantities of organics to be destroyed) and natural gas as fuel to the incinerator burners. The engineers who made emissions estimates for several fume incinerators were faced with the problem of not having equipment-specific emission factors or source test data for the incinerators. They examined the incinerator process and determined that the emissions would result primarily from the fuel combustion because the quantity of pollutants in the paint booth exhaust air was small in comparison to the fuel quantity. Knowing that emissions from boilers also result only from the fuel combustion, the engineers logically decided to use the emission factors in AP-42 for boilers with similar heat capacities to estimate the emissions for the fume incinerator.

Unfortunately, this decision resulted in inaccurate emission estimates. In subsequent source testing of the fume incinerators, it was shown that the actual NO_x emissions were approximately eight (8) times higher than the estimated emissions based on the boiler emission factors. Upon detailed examination of the incinerator operation, it was determined that the incinerator process parameters were substantially different than the boiler conditions in two respects:

- The incinerators operated at much higher excess air concentrations than the boilers due to the quantity of exhaust air from the paint booths; and

- The incinerators operated at substantially higher temperatures than the boilers to ensure complete combustion of the organic pollutants.

Both of these conditions are conducive to the formation of thermal NO_x (see Note 1 at end of example), which explains the large difference between the estimated and actual NO_x emissions. These conditions also determine the extent of combustion, which affects the formation of CO and the quantity of unburned organics (TOG) in the incinerator stack gas. Using the published boiler emission factors in this case resulted in substantial errors in the estimated emissions for the incinerators because the incinerators were operated at significantly different

conditions than those encountered in the boiler source tests on which the emission factors were based.

The correct methodology for estimating NO_x emissions from the fume incinerator was to conduct source testing. Costly new burner design trials and repeated source testing were required to find a solution that reduced the NO_x emissions from the fume incinerators to acceptable levels without increasing TOG and CO emissions to unacceptable limits. Source test data and calculated emission factors for NO_2 (nitrogen dioxide), NO_x, CO, and non-methane hydrocarbon (NMHC) destruction removal efficiency (DRE) from one of the fume incinerators are presented in Table 2-2. The following paragraphs present the methodology used for calculation of the NO_x and CO emission factors from the source test data. The NMHC DRE data is presented for information only and to illustrate the relationship between NO_x, CO, and TOG emissions from external combustion for varying conditions.

Source test data are often obtained in units that are not useful for estimating emissions. The test data may need to be converted to standard conditions (temperature and pressure) for comparison with other data or may need to be converted from measured units to reportable units. When source testing involves a series of process adjustments to determine the influence of parameters such as temperature or percentage of excess air, then rapid on-site data analysis may be required so the test team can judge the effect of each change. During the fume incinerator source tests conducted in the example above, a spreadsheet was developed to allow the rapid conversion of measured NO_x emissions to the desired emission units. This spreadsheet is presented as Table 2-2 in this workbook and the explanation of how the spreadsheet was used to calculate NO_x and CO emission factors is presented below.

Table 2-2

Source Test Data and Calculated Emission Factors for Fume Incinerator

| SOURCE TEST ID | | NOx EMISSION FACTORS CALCULATED | | | | | | CO EMISSION FACTORS | | | NMHC |
Test Date	Test Temp F	NO2 O2 Bsd lb/MMBtu	NO2 CO2 Bsd lb/MMBtu	NO2 Fuel Bsd lb/MMBtu	NOx @3% O2 ppmv	NOx Emission lb/hr	NOx Emission lb per MMdcfm	CO O2 Bsd lb/MMBtu	CO CO2 Bsd lb/MMBtu	CO Fuel Bsd lb/MMBtu	DRE %
3/25/92	1462	0.78	0.81	0.84	633	3.24	15.63	0.000	0.000	0.000	100.0%
3/25/92	1248	0.44	0.48	0.45	360	1.49	7.05	0.184	0.199	0.185	100.0%
3/25/92	1204	0.37	0.40	0.43	298	1.23	5.63	0.195	0.211	0.227	99.7%
3/25/92	1152	0.30	0.34	0.43	245	1.05	4.47	0.567	0.628	0.800	98.6%
3/25/92	1163	0.31	0.31	#N/A	253	1.25	5.31	0.414	0.412	#N/A	99.2%
3/25/92	1206	0.34	0.35	0.38	275	1.47	6.31	0.287	0.294	0.323	99.8%
3/25/92	1258	0.38	0.38	0.41	308	1.75	7.29	0.175	0.173	0.190	100.0%
2/13/92	1050	0.21	0.24	#N/A	168	0.52	2.16	0.687	0.773	#N/A	93.6%
2/13/92	1100 *	0.24	0.27	#N/A	198	0.64	2.68	0.744	0.797	#N/A	96.6%
2/13/92	1150 *	0.28	0.32	#N/A	226	0.77	3.21	0.715	0.806	#N/A	98.6%
2/13/92	1200 *	0.33	0.36	#N/A	266	0.95	3.95	0.459	0.498	#N/A	99.5%
2/13/92	1250 *	0.39	0.41	#N/A	317	1.18	4.93	0.219	0.230	#N/A	99.8%
1/31/92	1250	#N/A	0.43	#N/A	#N/A	1.39	6.02	#N/A	#N/A	#N/A	#N/A
1/31/92	1300	#N/A	0.48	#N/A	#N/A	1.67	7.23	#N/A	#N/A	#N/A	#N/A
1/31/92	1350	#N/A	0.56	#N/A	#N/A	2.20	9.53	#N/A	#N/A	#N/A	#N/A
1/31/92	1400	#N/A	0.66	#N/A	#N/A	2.73	11.83	#N/A	#N/A	#N/A	#N/A
1/31/92	1450	#N/A	0.80	#N/A	#N/A	3.49	15.09	#N/A	#N/A	#N/A	#N/A
1/16/92	1450 *	0.74	0.90	#N/A	563	2.90	12.55	0.019	0.019	0.019	99.8%

NOTES

Table 2-2

(Continued)

SOURCE TEST ID			Inlet					NOx	Exhaust				Exhaust gas	Fuel delta P	Firing Rate
Test Date	Test Temp F	NOx ppmv	O2 %	CO2 ppmv	CO ppmv	HC ppmv		NOx ppmv	O2 %	CO2 %	CO ppmv	HC ppmv	scfm	P	MMBtu/hr
3/25/92	1462	0.25	20.9	1030	0.5	476.7		129.4	17.25	2.11	0.5	0	3454	7.5	3.87
3/25/92	1248	0.25	20.9	1020	0.5	434		58.5	18	1.62	40.1	0	3532	5.6	3.35
3/25/92	1204	0.25	20.9	1010	0.5	450		46.8	18.1	1.57	41	1.3	3646	4.15	2.88
3/25/92	1152	0.25	20.9	850	0.5	423		37.2	18.2	1.46	114.2	5.8	3897	3	2.45
3/25/92	1163	0.25	20.9	860	0.5	423		44.1	17.8	1.85	95.8	3.5	3942	#N/A	#N/A
3/25/92	1206	0.25	20.9	905	0.5	453		52.4	17.5	1.98	73	0.7	3886	7.45	3.86
3/25/92	1238	0.25	20.9	980	0.5	457		60.5	17.4	2.11	46	0	4603	9	4.24
2/13/92	1050	0.25	20.9	480	0.5	380		18.1	19	1	97.5	24.5	3992	#N/A	0N/A
2/13/92	1100	0.25	20.9	490	0.5	410		22.4	18.9	1.1	111	13.9	3992	#N/A	#N/A
2/13/92	1150	0.25	20.9	505	0.5	415		26.8	18.8	1.1	112	6	3992	#N/A	#N/A
2/13/92	1200	0.25	20.9	530	0.5	510		32.9	18.7	1.2	75.5	2.7	3992	#N/A	#N/A
2/13/92	1250	0.25	20.9	525	0.5	575		41	18.6	1.3	38	1.1	3992	#N/A	#N/A
1/31/92	1250	0.25	20.9	400	0.5	#N/A		50	0N/A	1.5	#N/A	#N/A	3850	#N/A	0N/A
1/31/92	1300	0.25	20.9	600	0.5	#N/A		60	#N/A	1.6	#N/A	#N/A	3850	#N/A	0N/A
1/31/92	1350	0.25	20.9	400	0.5	#N/A		79	#N/A	1.8	#N/A	#N/A	3850	0N/A	0N/A
1/31/92	1400	0.25	20.9	400	0.5	#N/A		98	#N/A	1.9	#N/A	#N/A	3850	#N/A	#N/A
1/31/92	1450	0.25	20.9	400	0.5	#N/A		125	#N/A	2	#N/A	#N/A	3850	#N/A	#N/A
1/16/92	1450	0.25	20.7	550	3	283		104	17.6	1.5	2.5	0.3	3830	#N/A	#N/A
NOTES								2	1,2	1,2	1,2	1,2			

Notes and Abbreviations for Table 2-2

Notes:

1. %CO_2 and O_2 in the exhaust gas samples = ppmv/10,000
2. Exhaust gas measurements are on a dry basis

Abbreviations:

NMHC	Non-methane hydrocarbons
DRE	Destruction removal efficiency
F	Temperature, degrees Fahrenheit
NO_2	Nitrogen dioxide
O_2	Oxygen
CO	Carbon monoxide
CO_2	Carbon dioxide
O_2 Bsd	Emission factor calculation based on %O_2 in exhaust
CO_2 Bsd	Emission factor calculation based on %CO_2 in exhaust
Fuel Bsd	Emission factor calculation based on fuel flow rate
NO_x	Nitrogen oxides
Temp	Temperature
lb	Pounds
MMBtu	Million British thermal units
ppmv	parts per million (volume)
hr	hour
MMcf	Million cubic feet of inlet gas
HC	Hydrocarbon
scfm	Standard cubic feet per minute
delta P	Differential pressure

Given the following operating parameters, the NO_x emission factor (lb/Btu) can be estimated:

- Measured inlet and outlet source test data (all gas concentrations are on a dry basis);

- Test temperature (°F);

- Exhaust gas flow rate (scfm); and

- Natural gas (fuel) firing rate.

The emission factor can be determined based on either the O_2 or CO_2 concentration in the exhaust gas or on the fuel firing rate. All three of these methods are appropriate to use when calculating emission factors from source testing. Both the O_2 and CO_2 based emission factors are calculated using the F Factor method which was promulgated in the October 6, 1975 United States Federal Register as a procedure to replace the original method of determining emission factors. The U.S. EPA has published F factors for common fuels and the F factor values used in these calculations were taken from Stack Sampling Technical Information (U.S. EPA, 1978). The F factor for the O_2 based emission factor for natural gas is 8,740 scf/MMBtu. The F factor for the CO_2 based emission factor for natural gas is 1,040 scf/MMBtu. In this example, the 3/25/92 test data at 1462 °F were used from Table 2-1.

The equation for calculating an O_2 based NO_x emission factor using the F factor method is:

$$E = Cd \times Fd \times \frac{20.9}{20.9 - \%O_2}$$

where:

E	=	Emission rate in lb/MMBtu;
Cd	=	Pollutant concentration in dry exhaust gas minus pollutant concentration in inlet gas (lb/scf);
Fd	=	Oxygen based F factor (8,740 scf/MMBtu);
$\%O_2$	=	O_2 percent in dry exhaust gas; and
20.9	=	Assumed O_2 percent in inlet gas (ambient atmosphere).

The calculation of Cd in lb/scf exhaust gas from the measured concentrations of NO_x (measured as NO_2) in ppmv is shown below.

$$Cd = \frac{[C]_{ppmv} \times MW}{CF_1}$$

where: $[C]_{ppmv}$ =   Concentration of pollutant in exhaust minus concentration of pollutant in inlet gas in ppmv (scf pollutant/MMscf exhaust gas);

               MW   =   Molecular weight of NO_2 (46 lb/lb-mole); and

               CF_1 =   Conversion factor based on ideal gas law that 1 lb-mole ideal gas = 380 scf.

Using data from Table 2-1 for the 3/25/92 test data at 1462 °F, the calculation of Cd is:

$$Cd = \frac{\left[(129.4 - 0.25) \dfrac{scf\ NO_x}{10^6\ scf\ exhaust\ gas}\right] \times \dfrac{46\ lb}{lb-mole}}{380\ scf/1\ lb-mole}$$

$$= 1.563 \times 10^{-5} \frac{lb\ NO_x}{scf\ exhaust\ gas}$$

Then the calculation of the NO_x emission factor using the oxygen based F factor is:

$$E = \left(1.563 \times 10^{-5} \frac{lb\ NO_x}{scf}\right) \times \frac{8,740\ scf}{10^6\ Btu} \times \left(\frac{20.9}{20.9 - 17.25}\right)$$

$$E = \frac{0.78\ lb\ NO_x}{10^6\ Btu}$$

The equation for calculating a CO_2 based NO_x emission factor using the F factor method is:

$$E = Cd \times Fc \times \left(\frac{100}{\%CO_2} \right)$$

where:
$\quad$ E $\quad = \quad$ Emission rate (lb/MMBtu);
$\quad$ Cd $\quad = \quad$ Pollutant concentration in dry exhaust gas minus pollutant concentration in inlet gas (lb/scf);
$\quad$ Fc $\quad = \quad$ Carbon dioxide based F factor (1,040 scf/MMBtu); and
$\quad$ $\%CO_2$ $\quad = \quad$ CO_2 percent in dry exhaust gas minus CO_2 percent in inlet gas.

The calculation of Cd in lb/scf from the measured concentrations of NO_x in ppmv was done above. The calculation of $\%CO_2$ is as follows:

$$\%CO_2 = \%CO_2 \text{ (in dry exhaust gas as measured)} - \frac{ppmv\ CO_2\ in\ inlet\ gas}{10,000}$$

$$E = 2.11 - \frac{1,030}{10,000} = 2.007$$

Then the calculation of the NO_x emission factor using the CO_2 based F factor is:

$$E = \left(\frac{1.563 \times 10^{-5}\ lb\ NO_x}{scf} \right) \times \frac{1,040\ scf}{10^6\ Btu} \times \frac{100}{2.007}$$

$$E = \frac{0.81\ lb\ NO_x}{10^6\ Btu}$$

If the fuel firing rate is used to calculate a NO_x emission factor, then the following equation is used:

$$E = \frac{Cd \times Q \times 60}{FR}$$

where:

	E	=	Emission rate (lb/MMBtu);
	Cd	=	Pollutant concentration in dry exhaust gas minus pollutant concentration in inlet gas (lb/scf);
	Q	=	Exhaust flow rate (scf/minute);
	60	=	Conversion factor from minutes to hours; and
	FR	=	Fuel firing rate (MMBtu/hour).

The calculation of Cd in lb/scf from the measured concentrations of NO_x in ppmv was done above.

So the emission factor based on the fuel firing rate is:

$$E = \frac{\left(\dfrac{1.563 \times 10^{-5} \text{ lb } NO_x}{\text{scf}}\right) \times \left(\dfrac{3,454 \text{ scf}}{\text{min}}\right) \times \left(\dfrac{60 \text{ min}}{\text{hr}}\right)}{3.87 \times 10^6 \text{ Btu/hr}},$$

$$E = \frac{0.84 \text{ lb } NO_x}{10^6 \text{ Btu}}$$

A comparison of the calculated emission factors with a emission factor from AP-42 is given in Table 2-3.

Table 2-3

Comparison of Calculated Emission Factors

Calculation Method	Emission Factor (lb $NO_x/10^6$ Btu)
O_2 Based F Factor	0.78
CO_2 Based F Factor	0.81
Fuel Firing Rate	0.84
AP-42, Table 1.4-2 Uncontrolled Commercial Boiler*	0.10

* Assumes a natural gas fired higher heating value of 1,000 Btu/scf.

As mentioned earlier, the emission factor taken from AP-42 can be seen to be low by a factor of eight (8).

In order to compare emission factors on an equivalent basis, it is sometimes necessary to adjust the estimated emission factors to a given excess O_2 concentration. This is often done for regulatory purposes. This is done with the following equation.

$$EF_{ex} = EF \times \frac{(20.9 - O_{2(ex)})}{(20.9 - O_2)}$$

where:
EF_{ex} = NO_x emission factor at desired excess O_2 level (lb/MMBtu);
EF = Calculated NO_x emission factor (lb/MMBtu);
20.9 = Assumed atmospheric O_2 concentration (%);
$O_{2(ex)}$ = Desired excess O_2 concentration (%); and
O_2 = Measured O_2 concentration in dry exhaust gas (%).

Using the O_2-based emission factor calculated above, the NO_x emission factor at 3% excess O_2 for the 3/25/92 test data at 1462 °F is calculated as:

$$NO_x \ (3\%) \ = \ 0.78 \ \frac{lb \ NO_x}{10^6 \ Btu} \ \times \ \left(\frac{20.9 \ - \ 3}{20.9 \ - \ 17.25} \right)$$

$$= \ \frac{3.83 \ lb \ NO_x}{10^6 \ Btu}$$

The adjusted emission factor differs from the calculated emission factor because the desired excess O_2 concentration (3%) is quite different compared to the actual measured O_2 concentration (17.25%). If the desired excess O_2 concentration is equal to the measured O_2 concentration, then the adjusted emission factor will be identical to the calculated emission factor.

Note 1: NO_x is formed in external combustion in primarily two ways: thermal NO_x and fuel NO_x. Thermal NO_x is formed when nitrogen and oxygen in the combustion air react at high temperatures in the flame. Fuel NO_x is formed by the reaction of any nitrogen in the fuel with combustion air. Thermal NO_x is the primary source of NO_x in natural gas and light oil combustion and the most significant factor affecting its formation is flame temperature. Excess air level and combustion air temperature also are factors in the formation of thermal NO_x. Fuel NO_x formation is dependent on the nitrogen content of the fuel and can account for as much as 50% of the NO_x emissions from the combustion of high-nitrogen fuels - primarily heavy oils.

Example 3
Residential Fuel Combustion

Introduction

This example illustrates a common situation where emissions must be estimated with minimal data. In many instances, the inventory specialist will be faced with a shortage of data that requires a creative approach to developing emission estimates. Because of the lack of data, typical emission estimating methods are not always a feasible option. Rather, alternative methods must be identified and examined. Each of the alternative methods will have positive and negative points that must be evaluated before one is selected. In some cases, more than one of the alternative methods may be selected in order to provide a possible range of emission estimates (i.e., bounding calculations). Although one of the estimates will likely be incorporated into the emissions database, the range of estimates provides one measure of the possible uncertainty associated with that specific source category. This is an added benefit of performing bounding calculations.

The following example is based upon the actual data and methodology used in an air toxics inventory for Nogales, Sonora (Radian, 1997). This example is not intended to provide a specific, recommended estimating method, rather, it is designed to present the thought processes that should be employed in order to estimate emissions when faced with incomplete data.

Problem Statement

Determine the annual CO emissions from the combustion of non-commercial fuels. Include only those fuels for heating or cooking purposes. Exclude any waste burning.

Available Information

In Mexico, PEMEX (Petróleos Mexicanos), as well as some government agencies, maintain fairly detailed statistics for the consumption of commercial fuels (e.g., distillate oil, LPG [liquefied petroleum gas], etc.). However, significant quantities of non-commercial fuels are also used in some areas of the country for residential heating and cooking. Examples of non-commercial fuels include wood, other biomass, manure, scrap materials, tires, waste solvents, and other waste-derived fuels. In this problem, these fuels are referred to as biomass/waste fuels. Statistics for these types of fuels are almost nonexistent in most countries, including Mexico.

Although several local officials and residents cited statistics that 98% of the homes in Nogales use LPG as of 1994 (Carrillo, 1996; Gastelum, 1996; Guerrero, 1996), the use of waste derived fuels was considered a potentially significant source of emissions. Unfortunately, very little data regarding the combustion of biomass/waste fuels were available for collection during a local site visit. Overall population and household statistics were available for the inventory domain, but residential biomass/waste fuel combustion rates were not.

Selection of Methodology

Ideally, biomass/waste fuel combustion rates derived from statistically valid surveys would be combined with emission factors to yield emission estimates. However, because survey data were not available, alternate estimation methods were used. Three possible methods were devised that would allow biomass/waste combustion rates to be estimated. These included:

- The Heating Load method;

- The LPG Equivalence method; and

- The Micro-Inventory method.

Each of these methods is described in detail below.

The Heating Load method:

This method uses the average monthly heating load for a typical Nogales house to estimate emissions. The required average monthly heating load for a building can be determined by the following equation (Harris et al., 1985):

$$Q_i = (UA + 0.018V) \times DD_i \times 24$$

where:

	Q_i	=	Average monthly heating load (Btu/month) for month i;
	UA	=	Hourly transmission heat loss per degree of design temperature difference (Btu/hr-°F);
	0.018V	=	Infiltration-ventilation hourly heat loss per degree of design temperature difference (Btu/hr-°F);
	DD_i	=	Monthly degree-days [65°F base temperature] (°F-day/month) for month i; and
	24	=	Conversion factor from days to hours.

The UA term is actually the product of an overall heat transmission coefficient for a given structural element (U) and the surface area of that structural element (A). The V term represents the hourly volume of infiltration air (the product of hourly air changes and space volume). Guidelines for estimating values for UA and 0.018V for an entire building can be obtained from various engineering handbooks (e.g., ASHRAE, 1997 - chapters 24 and 25). In order to estimate these two variables, some characteristics of a "typical" house must be determined (building material, average floor space, average building height, wall thickness, number of doors, number and size of windows, etc.). A degree-day is the difference between a fixed base temperature (usually 65°F) and the daily mean outdoor temperature, summed up for a specified period of time, such as a month or a year. A higher degree-day total indicates a higher heating load. Degree-days data are typically available from meteorological stations.

The required average annual heating load for a single household is calculated by aggregating each of the average monthly heating loads using different degree days for each month as shown below.

$$Q_{Annual} = \sum_{i=1}^{12} Q_i$$

where: Q_{Annual} = Annual heating load (Btu/year); and
        Q_i = Average monthly heating load (Btu/month) for month i.

Once an annual heating load has been estimated, the amount of biomass/waste fuel that provides the required amount of heat can be estimated using an average energy content for that specific fuel. This is shown in the next equation.

$$Fuel_{Annual,f} = \frac{Q_{Annual}}{EC_f}$$

where: $Fuel_{Annual,f}$ = Annual fuel use (lb/year) for fuel f;
        Q_{Annual} = Annual heating load (Btu/year); and
        EC_f = Energy content (Btu/lb) for fuel f.

This estimated amount of biomass/waste material would need to be adjusted upward to account for cooking activities that use similar fuels.

The LPG Equivalence method:

This method uses average household LPG usage to estimate non-commercial fuel consumption. Since the number of households using LPG in Nogales was known, average per household LPG usage can be estimated if the total amount of LPG consumption is available.

$$LPG_{Usage} = \frac{LPG_{Res}}{Households_{LPG}}$$

where: LPG_{Usage} = Annual per household LPG usage (lb/yr);
                        LPG_{Res} = Annual total residential LPG usage (lb/yr); and
                        $Households_{LPG}$ = Total households using LPG.

Using the energy content of LPG and typical biomass/waste fuels, equivalent average per household biomass/waste usage can be estimated.

$$Bio/Waste_{Usage} \ = \ LPG_{Usage} \ \times \ \frac{EC_{LPG}}{EC_{Bio/Waste}} \ \times \ \frac{Eff_{LPG}}{Eff_{Bio/Waste}}$$

where: $Bio/Waste_{Usage}$ = Annual per household biomass/waste fuel usage (kg/yr);
                        LPG_{Usage} = Annual per household LPG usage (liters/yr);
                        EC_{LPG} = Energy content of LPG (kcal/liter);
                        $EC_{Bio/Waste}$ = Energy content of biomass/waste fuel (kcal/kg);
                        Eff_{LPG} = Efficiency of LPG combustion; and
                        $Eff_{Bio/Waste}$ = Efficiency of biomass/waste fuel combustion.

The Micro-Inventory method

This method involves performing a micro-inventory of 25 or 30 houses that use biomass or waste fuels. A short interview should provide sufficient information. The most important information is the quantity of fuel burned. Most people interviewed will not be able to estimate annual or monthly usage, but they should be able to estimate usage over a shorter period of time. Information should also be collected concerning seasonal usage variations and other burning practices. Annual biomass or waste fuel usage could then be derived using these data.

Analysis and Selection of Emission Estimating Methods

After establishing three alternative methods, it was necessary to select one of these methods. The selection was based upon several selection criteria and general engineering judgment. Selection criteria included such things as ease of use, representativeness, amount of uncertainty, reasonableness, etc. For the Nogales, Sonora air toxics inventory, the LPG Equivalence method was ultimately selected.

The Heating Load and Micro-Inventory methods were not selected for several reasons:

- **Potential for bias.** It would be very difficult to assure that the "typical house" selected for the Heating Load method actually represented the types of houses present in the inventory domain. Likewise, it would be hard to guarantee that the households selected to be interviewed for the Micro-Inventory method would actually be representative of households that burned biomass or waste fuels. The potential for bias would decrease if large scale surveying was conducted to determine house characteristics or fuel usage, but the associated cost would be prohibitive.

- **Availability of data and types of assumptions.** Although available data are limited, the LPG Equivalence method uses these limited data and several reasonable assumptions to estimate emissions. The Heating Load method, on the other hand, would require some additional data collection, as well as a few "less reasonable" assumptions.

- **Reluctant survey participants.** Given that LPG is used in 98% of the homes, the number of households using biomass or waste fuels is in the minority. For the Micro-Inventory method, some of these households might be reluctant to volunteer information regarding their burning practices. Even if responses were given, there might be some question about the validity of the responses.

Solution

Now that the LPG Equivalence method has been selected, it is possible to estimate emissions. The four main steps are outlined below.

1. **Determine number of households that use biomass/waste fuels for heating or cooking.** Based upon census data, geographic information system (GIS) data, and recent growth trends, it was estimated that there are approximately 38,018 households in Nogales (Radian, 1997). As previously mentioned, 98% of the Nogales households have been identified as using LPG. It was assumed that the remaining 2% of the Nogales households use biomass/waste fuels. The total number of households using biomass/waste is given below:

$$\text{Households}_{\text{Bio/Waste}} = \%_{\text{Bio/Waste}} \times \text{Households}_{\text{Total}} = 2\% \times 38,018 = 760 \text{ households}$$

where:
$\text{Households}_{\text{Bio/Waste}}$ = Number of households using biomass/waste fuels;
$\%_{\text{Bio/Waste}}$ = Percentage of households using biomass/waste fuels; and
$\text{Households}_{\text{Total}}$ = Total number of households.

2. **Determine per household LPG usage.** Per household LPG usage is determined by dividing the total residential LPG usage by the number of households that use LPG. PEMEX statistics indicated that the 1994 LPG usage for Nogales was 30,203,870 kilograms (Estrada, 1996). It has been determined that 80% of total LPG usage in Mexico is residential usage (Dirección General de Ecología et al., 1995).

The mass usage of LPG is converted to volume usage by estimating the density of LPG. Unfortunately, the exact chemical composition and density of LPG in Nogales is unknown. However, the approximate density of LPG in Nogales can be estimated using the dimensions of a 45 kilogram LPG cylinder and its reported weight. The measurements of a 45 kg LPG cylinder indicated that the height is 1.04 m and the circumference is 1.19 m. As shown below, a cylinder volume and then a density can be calculated from these cylinder dimensions. For a cylinder, the volume is calculated as shown below:

$$V = \pi r^2 h; \ C = 2\pi r$$

$$V = \pi\left(\frac{C}{2\pi}\right)^2 h = \frac{C^2 h}{4\pi}$$

$$V = \frac{(1.19 \ m)^2 \times 1.04 \ m}{4 \times 3.14} = 0.1173 \ m^3$$

where: V   =   cylinder volume (m);
                  C   =   cylinder circumference (m);
                  r   =   cylinder radius (m); and
                  h   =   cylinder height (m).

The approximate density of the LPG is then:

$$\rho = \frac{m}{V} = \frac{45 \ kg}{0.1173 \ m^3} = 383.6 \ \frac{kg}{m^3} = 0.384 \ \frac{kg}{liter}$$

where: ρ =   LPG density (kg/liter);
                  m   =   LPG mass in a cylinder (kg); and
                  V   =   LPG cylinder volume (m^3).

The conversion of LPG from kilograms to liters is then:

$$LPG_v = \frac{LPG_m}{\rho} = \frac{30,203,870 \ kg}{0.384 \ kg/liter} = 78,655,911 \ liters$$

where: LPG_v =   Total LPG volume (liter);
                LPG_m =   Total LPG mass (kg); and
                ρ =   LPG density (kg/liter).

Total residential LPG use is estimated to be 80% of the total LPG use with the remainder being industrial/commercial usage (Dirección General de Ecología et al., 1995).

$$\text{LPG}_{\text{Res}} = \%_{\text{Res}} \times \text{LPG}_{\text{Total}} = 80\% \times 78{,}655{,}911 \text{ liters} = 62{,}924{,}729 \text{ liters}$$

where:
    LPG_{Res} = Residential LPG usage (liters/yr);
    $\%_{\text{Res}}$ = Percentage of total LPG usage that is residential; and
    $\text{LPG}_{\text{Total}}$ = Total LPG usage (liters/yr).

The number of households using LPG is given below:

$$\text{Households}_{\text{LPG}} = \%_{\text{LPG}} \times \text{Households}_{\text{Total}} = 98\% \times 38{,}018 = 37{,}258$$

where:
    $\text{Households}_{\text{LPG}}$ = Number of households using LPG;
    $\%_{\text{LPG}}$ = Percentage of total households using LPG; and
    $\text{Households}_{\text{Total}}$ = Number of total households.

Finally, per household LPG usage is calculated using the following equation:

$$\text{Usage}_{\text{LPG}} = \frac{\text{LPG}_{\text{Res}}}{\text{Households}_{\text{LPG}}} = \frac{62{,}924{,}729 \text{ liters}}{37{,}258 \text{ households}} = 1{,}689 \text{ liters/household}$$

where:
    $\text{Usage}_{\text{LPG}}$ = Annual per household LPG usage (liters/yr);
    LPG_{Res} = Residential LPG usage (liters/yr); and
    $\text{Households}_{\text{LPG}}$ = Number households using LPG.

This per household LPG usage should be checked to see if it is reasonable. A very limited number of informal interviews conducted with local residents indicate that a typical household uses one large (45 kg) LPG cylinder per month during the summer and two large cylinders per month during the winter (Monroy, 1996). Assuming that there are eight summer months and four winter months, then a typical household would use approximately 16 large cylinders per year. Using the LPG density calculated above and the weight per cylinder, the number of cylinders used per household can be estimated.

$$\frac{1{,}689 \text{ liters}}{\text{households}} \times \frac{0.384 \text{ kg}}{\text{liter}} \times \frac{1 \text{ cylinder}}{45 \text{ kg}} = \frac{14.4 \text{ cylinders}}{\text{household}}$$

Given that these estimates are within 10% of each other, the estimate of 1,689 liters of LPG per household per year seems quite reasonable.

3. **Convert per household LPG usage to per household biomass/waste fuel usage.** The annual per household LPG usage value of 1,689 liter/household calculated above represents the amount of LPG used by an average household for all of its heating and cooking requirements. An equivalent amount of biomass/waste fuel can be estimated based upon fuel energy contents.

Although local residents of Nogales refer to LPG as butane, the exact chemical composition of Nogales LPG is unknown. The local LPG is assumed to be similar to the average national composition of 60% propane and 40% butane (PEMEX, 1996). If the energy content of propane is 6,090 kcal/liter and the energy content of butane is 6,790 kcal/liter (U.S. EPA, 1995a), then the weighted energy content of LPG is calculated as shown below:

$$_{\text{LPG}} = \%_{\text{prop}} \times EC_{\text{prop}} + \%_{\text{but}} \times EC_{\text{but}} = (0.6 \times 6{,}090) + (0.4 \times 6{,}790) = 6{,}370 \text{ kcal/l}$$

where:
EC_{LPG} = Energy content of LPG (kcal/liter);
$\%_{\text{prop}}$ = Percentage of propane in LPG;
EC_{prop} = Energy content of propane (kcal/liter);
$\%_{\text{but}}$ = Percentage of butane in LPG; and
EC_{but} = Energy content of butane (kcal/liter).

Assuming that the energy content of biomass/waste fuels is approximately that of pallet wood (4,445 kcal/kg) (Summit et al, 1996) and that the combustion efficiencies of LPG and biomass/waste fuels are equal, then the annual per household biomass/waste fuel usage can be estimated.

$$\text{Bio/Waste}_{\text{Usage}} = \text{LPG}_{\text{Usage}} \times \frac{\text{EC}_{\text{LPG}}}{\text{EC}_{\text{Bio/Waste}}} \times \frac{\text{Eff}_{\text{LPG}}}{\text{Eff}_{\text{Bio/Waste}}}$$

$$\text{Bio/Waste}_{\text{Usage}} = \frac{1,689 \text{ liters LPG}}{\text{household}} \times \frac{6,370 \text{ kcal/liter LPG}}{4,445 \text{ kcal/kg bio/waste}} = \frac{2,420 \text{ kg bio/waste}}{\text{household}}$$

where:
	$\text{Bio/Waste}_{\text{Usage}}$	=	Annual per household biomass/waste fuel usage (kg/yr);
	$\text{LPG}_{\text{Usage}}$	=	Annual per household LPG usage (liters/yr);
	EC_{LPG}	=	Energy content of LPG (kcal/liter);
	$\text{EC}_{\text{Bio/Waste}}$	=	Energy content of biomass/waste fuels (kcal/kg);
	Eff_{LPG}	=	Efficiency of LPG combustion; and
	$\text{Eff}_{\text{Bio/Waste}}$	=	Efficiency of biomass/waste fuel combustion.

4. **Calculate overall CO emissions.** Now that an annual per household biomass/waste fuel usage has been estimated, CO emissions can be calculated using the number of households and a CO emission factor. The CO emission factor for biomass/waste fuels is based upon source test data for combustion of Mexican pallet wood (Summit et al., 1996).

$$\text{Emissions}_{\text{CO}} = \text{Bio/Waste}_{\text{Usage}} \times \text{Households}_{\text{Bio/Waste}} \times \text{EF}_{\text{CO}}$$

$$\text{Emissions}_{\text{CO}} = \frac{2,420 \text{ kg bio/waste}}{\text{household}} \times 760 \text{ households} \times \frac{31 \text{ g CO}}{\text{kg bio/waste}}$$

$$\text{Emissions}_{\text{CO}} = 57,015 \text{ kg/yr CO} = 57.0 \text{ Mg/yr CO}$$

where:
	$\text{Emissions}_{\text{CO}}$	=	Total CO emissions (kg/yr or Mg/yr);
	$\text{Bio/Waste}_{\text{Usage}}$	=	Annual per household biomass/waste fuel usage (kg/yr);
	$\text{Household}_{\text{Bio/Waste}}$	=	Number of households using biomass/waste fuels; and
	EF_{CO}	=	CO emission factor (g CO/kg bio/waste).

Discussion of Results

Although the annual CO emissions from residential biomass/waste combustion were estimated to be 57 Mg/yr, the quality of this emission estimate and its underlying

assumptions should be examined to determine areas of improvement and possible sources of uncertainty. Several important issues are discussed below.

1. **Number of households using biomass/waste fuels.** Local officials had estimated that 98% of the households used LPG. It was then assumed that the remaining 2% of the households used biomass/waste fuels. This assumption did not account for the possibility that some portion of the remaining 2% of households might use kerosene, distillate fuel, or other types of fuel.

2. **Number of households using LPG.** As mentioned earlier, local officials had estimated that 98% of the households used LPG. However, it is not exactly clear what the basis of this estimate is or how accurate it is. Even if the percentage of houses using LPG was slightly different, it could have a significant impact on the estimate of emissions from biomass/waste fuels. For example, if the actual percentage of households using LPG was 97%, instead of 98%, then emissions from LPG combustion would decline slightly. However, emissions from biomass/waste fuel combustion would be greatly affected; the percentage of houses using biomass/waste would increase from 2% to 3% -- a 50% increase.

3. **Fraction of residential LPG use.** It was assumed in this problem that 80% of the overall LPG used is residential usage. This assumption is based upon national statistics. Local consumption patterns may differ from this.

4. **Combustion efficiencies.** It was assumed in this problem that the combustion efficiencies of LPG and biomass/waste fuels were equal. In reality, the combustion of LPG is likely to be more efficient than the combustion of biomass/waste fuels. This would increase biomass/ waste emissions.

5. **Fuel usage patterns.** In converting LPG usage to biomass/waste fuel usage, an implicit assumption is that fuel usage patterns are the same. This is probably not the case. For example, if LPG is used for heating or cooking purposes, then the combustion device can easily be turned off when the desired amount of heat has been obtained. However, biomass/waste fuel combustion will often continue even after the desired amount of heat has been reached, because it is not desirable or practical to extinguish the fire.

6. **Composition of the biomass/waste fuel.** It was assumed in this problem that the biomass/waste fuel was pallet wood. In reality, biomass/waste fuel is likely to be composed of a wide variety of materials. Each of these materials will have its own energy content and emission factor.

Given the limited data available for this emission estimation problem, it was necessary to make all of the assumptions described above. Ideally, additional information could be gathered that would eliminate the need for some of these assumptions. This would improve the quality of the emission estimates and decrease the associated uncertainty.

Example 4
Gasoline Distribution System

Introduction

The next example is divided into seven parts which are all related to the gasoline distribution system. Although each part addresses an individual source category, these source categories are often conceptually grouped together. This is primarily because the distribution of gasoline is a potentially large source of evaporative total organic gas (TOG) emissions. A typical gasoline distribution system may have hundreds or thousands of individual sources and it is important that all of these sources are accounted for in an emissions inventory. By treating the entire distribution system as a whole, it is often easier to ensure that all possible sources are included.

A hypothetical gasoline distribution system with a manageable number of elements is presented in Figure 4-1. This simplified system contains a bulk terminal and four gasoline stations. Tank trucks transport the gasoline between the bulk terminal and the gasoline stations. This system does <u>not</u> include the petroleum refinery upstream from the bulk terminal or transport from the refinery to the bulk terminal by tank truck, rail car, or marine vessel. In reality, a gasoline distribution system will usually be much more complex than the one presented here. The distribution system in Figure 4-1 will be used throughout Example 4. The concepts presented in these seven problems are not limited to gasoline distribution; they are also applicable to other liquid fuels (e.g., aviation fuel, diesel, or LPG) and gaseous fuels (e.g., natural gas). The specific details and emission factors, however, would be different.
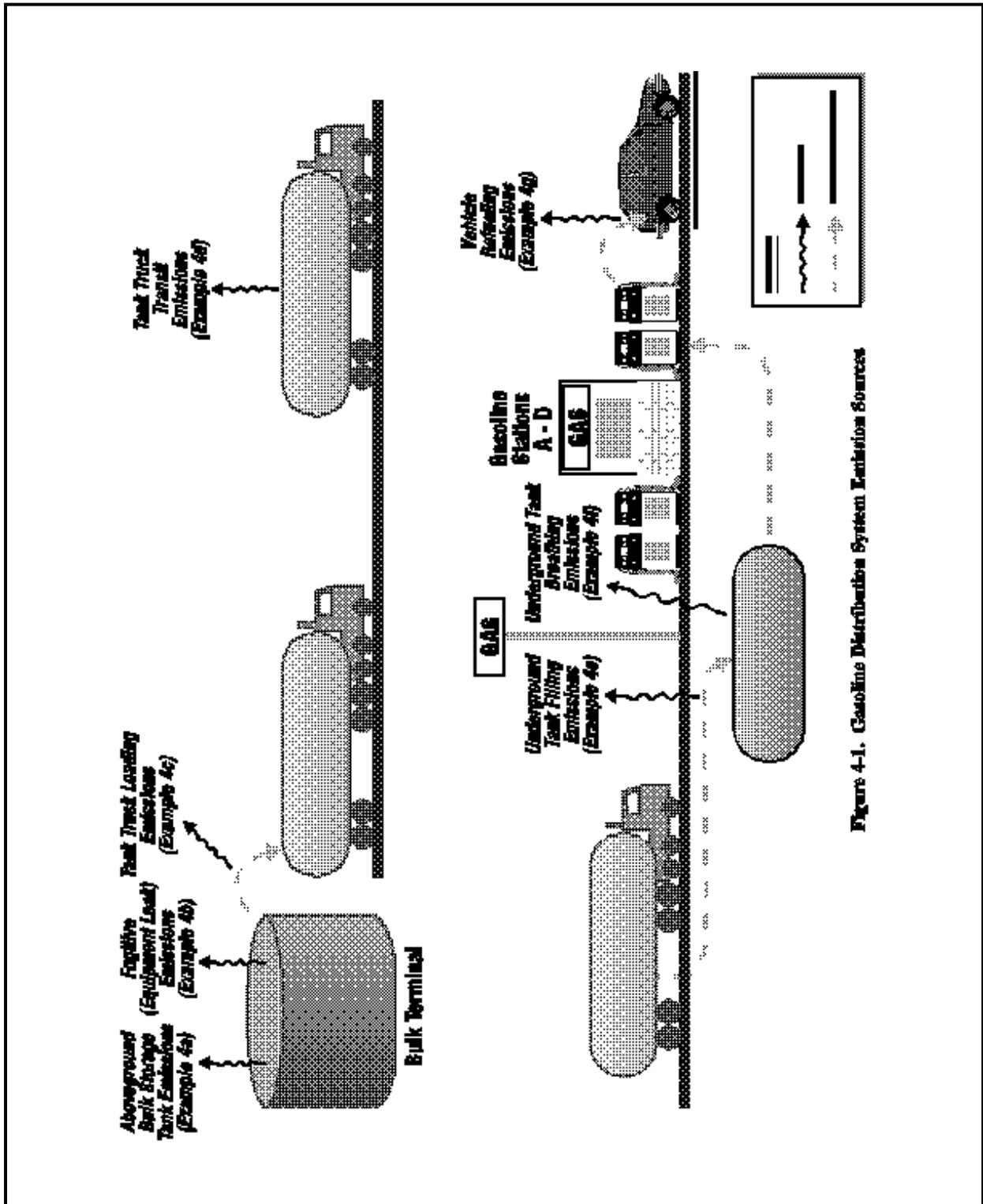
Figure 4-1. Gasoline Distribution System Emission Sources

<h1 style="text-align:center">Example 4a</h1>
<h2 style="text-align:center">Aboveground Bulk Storage Tank</h2>

Problem Statement

Estimate TOG emissions from standing and working losses at the bulk terminal's aboveground bulk storage tank.

Available Information

The total amount of RVP 9 gasoline pumped through the bulk terminal tank is determined to be 10,000,000 liters per year (2,642,000 gallons per year). The bulk terminal tank is a fixed roof aboveground storage tank (AST) with a capacity of 210,000 gallons. The AST has a cone roof. The liquid height within the tank is unknown at any given time. Meteorological conditions are assumed to be similar to Corpus Christi, Texas.

The following information is also known about the aboveground bulk storage tank:

Stored material = gasoline (RVP 9)
Tank diameter (D) = 37.6 feet
Tank shell height (H_S) = 24 feet
Tank average liquid height (H_L) = 12 feet (the liquid height within the tank is unknown at any given time; assumed to be half of tank shell height)
Tank capacity (V_{LX}) = 210,000 gallons
Tank color = light gray
Tank paint solar absorption (α) = 0.54 (AP-42, Table 7.1-6 for light gray paint in good condition)
Daily maximum ambient temperature (annual average) (T_{AX}) = 81.6°F = 541.27°R (AP-42, Table 7.1-7)
Daily minimum ambient temperature (annual average) (T_{AN}) = 62.5°F = 522.17°R (AP-42, Table 7.1-7)
Insolation (I) = 1521 Btu/ft^2-day (AP-42, Table 7.1-7)
Breather vent pressure setting (P_{BP}) = 0.03 psig (AP-42 default value)
Breather vent vacuum setting (P_{BV}) = -0.03 psig (AP-42 default value)

Molecular Weight Vapor (M_V) = 66.7 lb/lb-mol (Interpolated from AP-42, Table 7.1-2)

Slope of ASTM distillation curve at 10% evaporated (S) = 3.0 (AP-42, Figure 7.1-14a, Note 1)

Solution

        Total TOG emissions from fixed roof storage tanks are estimated based on the methodology outlined in AP-42 (U.S. EPA, 1995a), Section 7.1.3.1, Total Losses from Fixed Roof Tanks, February 1996. Estimation methodologies for other types of storage tanks can also be found in AP-42. The AP-42 methodology uses a series of equations rather than emission factors to estimate emissions from storage of organic liquids. Total fixed roof storage tank emissions are the sum of standing and working losses. Standing losses occur from changes in temperature leading to venting of tank vapor to the atmosphere. Working losses result from changes in the liquid level of the tank, primarily from tank filling and emptying operations. These equations are quite involved in order to provide a more accurate estimate of storage tank emissions. Typically, the TANKS software (U.S. EPA, 1996) developed by U.S. EPA will be used to estimate emissions from bulk storage tanks. This example demonstrates the equations that are used within TANKS. Because the TANKS software uses English units, this example was done in English units, rather than metric units. Uncontrolled standing losses will be calculated first followed by uncontrolled working losses.

1.   **Calculation of Uncontrolled Standing Losses**

$$L_S = 365 \times V_V \times W_V \times K_E \times K_S$$

where:

L_s	=	Standing losses (lb/yr);
365	=	Constant (days/yr);
V_V	=	Vapor space volume) (ft^3);
W_V	=	Vapor space density (lb/ft^3);
K_E	=	Vapor space expansion factor; and
K_S	=	Vented vapor saturation factor.

Calculation of Vapor Space Volume (V_V)

$$V_V = \frac{\pi}{4} \times D^2 \times H_{VO}$$

where: D =   Tank diameter (ft); and

               H_{VO} =   Vapor space outage (ft).

$$H_{VO} = H_S - H_L + H_{RO}$$

where: H_S =   Tank shell height (ft);

               H_L =   Liquid height (ft), (if unknown this value can be assumed to be 0.5H_s [i.e., this means that the tank is, on average, one-half full]); and

               H_{RO} =   Roof outage (ft).

$$H_{RO} = \frac{1}{3} \times H_R$$

where: H_R =   Tank roof height (ft).

$$H_R = R_S \times S_R$$

where: R_S =   Tank shell radius (ft); and

               S_R =   Cone roof slope (ft/ft) (if unknown, use a standard value of 0.0625 ft/ft [AP-42, page 7.1-12])

For Bulk Terminal Tank:

R_S = $0.5 \times D$

       = $0.5 \times (37.6 \text{ ft}) = 18.80 \text{ ft}$

S_R =   0.0625 ft/ft

H_R = $(18.80 \text{ ft}) \times (0.0625 \text{ ft/ft}) = 1.175 \text{ ft}$

H_{RO} = $(1/3) \times (1.175 \text{ ft}) = 0.3917 \text{ ft}$

$$H_L \quad = \quad (0.5) \times (24 \text{ ft}) = 12 \text{ ft}$$

$$H_{VO} \quad = \quad 24 - 12 + 0.3917 = 12.39 \text{ ft}$$

$$V_V \quad = \quad (\pi/4) \times (37.6 \text{ ft})^2 \times (12.39 \text{ ft}) = 13{,}759 \text{ ft}^3$$

Calculation of Vapor Density (W_V)

$$W_V = \frac{(M_V \times P_{VA})}{(R \times T_{LA})}$$

where:
M_V	=	Vapor molecular weight (lb/lb-mol);
P_{VA}	=	Vapor pressure at average liquid surface temperature (psia);
R	=	Ideal gas constant (10.731 psia-ft^3/lb-mol°R); and
T_{LA}	=	Daily average liquid surface temperature (°R).

$$T_{LA} = 0.44 T_{AA} + 0.56 T_B + 0.0079 \alpha I$$

where:
T_{AA}	=	Daily average ambient temperature (°R);
T_B	=	Liquid bulk temperature (°R);
α	=	Tank paint solar absorption; and
I	=	Daily total solar insolation factor (Btu/ft^2-day) (The solar insolation factor is a function of cloud cover and latitude. Some U.S. values are presented in AP-42, Table 7.1-7.)

$$T_{AA} = \frac{(T_{AX} + T_{AN})}{2}$$

where:
T_{AX}	=	Daily maximum ambient temperature (°R); and
T_{AN}	=	Daily minimum ambient temperature (°R).

$$T_B = T_{AA} + 6\alpha - 1$$

T_{AA}	=	$(T_{AN} + T_{AX})/2 = (522.17 + 541.27)/2 = 531.72$°R
T_B	=	531.72°R + 6(0.54) - 1 = 533.96°R
T_{LA}	=	$(0.44) \times (531.72$°R$) + (0.56) \times (533.96$°R$) + (0.0079) \times (0.54) \times (1521$ Btu/ft^2-day$) = 539.47$°R

$$P_{VA} = \exp \left\{ \left[0.7553 - \left(\frac{413}{T_{LA}} \right) \right] S^{0.5} \log_{10}(RVP) - \left[1.854 - \left(\frac{1042}{T_{LA}} \right) \right] S^{0.5} \right\}$$
$$\left\{ + \left[\left(\frac{2416}{T_{LA}} \right) - 2.013 \right] \log_{10}(RVP) - \left(\frac{8742}{T_{LA}} \right) + 15.64 \right\}$$

(Per AP-42 Figure 7.1-13b)

where: T_{LA} =   Average liquid surface temperature (°R); and
          RVP =   Reid vapor pressure (psia).

$$P_{VA} = \exp \left\{ \left[0.7553 - \left(\frac{413}{539.47_a} \right) \right] 3^{0.5} \log_{10}(9) - \left[1.854 - \left(\frac{1042}{539.47} \right) \right] 3^{0.5} \right\}$$
$$\left\{ + \left[\left(\frac{2416}{539.47} \right) - 2.013 \right] \log_{10}(9) - \left(\frac{8742}{539.47_a} \right) + 15.64 \right\} = 6.72 \text{ psia}$$

Then for RVP 9 Gasoline:

Ideally, measured vapor pressure values should be used rather than calculated values from the above equation. The emission calculations are very sensitive to vapor pressure values (P_{VA}). Therefore, it is important to obtain the most accurate value possible.

$$W_V = \frac{\left(\frac{66.7 \text{ lb}}{\text{lb-mol}} \right) (6.72 \text{ psia})}{\left(\frac{10.731 \text{ psia-ft}^3}{\text{lb-mol-°R}} \right) (539.47°R)} = 0.0774 \text{ lb/ft}^3$$

Calculation of the Vapor Expansion Factor (K_E)

$$K_E = \frac{\Delta T_V}{T_{LA}} + \frac{(\Delta P_V - \Delta P_B)}{P_A - P_{VA}}$$

where: ΔT_V =   Daily vapor temperature range (°R);
          T_{LA} =   Daily average liquid surface temperature (°R);
          ΔP_V =   Daily vapor pressure range (psi);

ΔP_B = Breather vent pressure setting range (psi);
P_A = Atmospheric pressure (normally 14.7 psia, however this may be adjusted for high elevations if necessary); and
P_{VA} = Vapor pressure at the daily average surface temperature (psia).

ΔP_B = $P_{BP} - P_{BV}$

where: P_{BP} = Breather vent pressure setting
P_{BV} = Breather vent vacuum setting
ΔP_B = (0.03) - (-0.03) = 0.06 psia

ΔT_V = $0.72\Delta T_A + 0.028\alpha I$

where: ΔT_A = Daily average ambient temperature range (°R)

ΔT_A = $T_{AX} - T_{AN}$

where: T_{AX} = Daily maximum ambient temperature (°R); and
T_{AN} = Daily minimum ambient temperature (°R).
ΔT_A = 541.27 - 522.17 = 19.1°R

ΔT_V = $(0.72) \times (19.1\ °R) + (0.028) \times (0.54) \times (1521\ Btu/ft^2\text{-}day) = 36.75$ °R
T_{LA} = 539.47°R (previously calculated)
ΔP_V = $P_{VX} - P_{VN}$

(P_{VX} and P_{VN} estimated using same equation as P_{VA} except using T_{LX} and T_{LV} rather than T_{LA})

where: P_{VX} = vapor pressure at the daily maximum liquid surface temp (psia); and
P_{VN} = vapor pressure at the daily minimum liquid surface temp (psia).

$$P_{VX} = \exp\left\{\left[0.7553 - \left(\frac{413}{T_{LX}}\right)\right] S^{0.5} \log_{10}(RVP) - \left[1.854 - \left(\frac{1042}{T_{LX}}\right)\right] S^{0.5}\right\}$$
$$\left\{+ \left[\left(\frac{2416}{T_{LX}}\right) - 2.013\right] \log_{10}(RVP) - \left(\frac{8742}{T_{LX}}\right) + 15.64\right\}$$

$$P_{VN} = \exp\left\{\left[0.7553 - \left(\frac{413}{T_{LN}}\right)\right] S^{0.5} \log_{10}(RVP) - \left[1.854 - \left(\frac{1042}{T_{LN}}\right)\right] S^{0.5}\right\}$$
$$\left\{+ \left[\left(\frac{2416}{T_{LN}}\right) - 2.013\right] \log_{10}(RVP) - \left(\frac{8742}{T_{LN}}\right) + 15.64\right\}$$

T_{LX} = Maximum liquid surface temperature

$$\begin{aligned} &= && T_{LA} + 0.25\,(\Delta T_V) = 539.47 + 0.25\,(36.75) = 548.66°R \\ T_{LN} &= && \text{Minimum liquid surface temperature} \\ &= && T_{LA} - 0.25\,(\Delta T_V) = 539.47 - 0.25\,(36.75) = 530.28°R \end{aligned}$$

Thus, for RVP 9 Gasoline:

$$P_{VX} = \exp\left\{\left[0.7553 - \left(\frac{413}{548.66_a}\right)\right]3^{0.5}\log_{10}(9) - \left[1.854 - \left(\frac{1042}{548.66}\right)\right]3^{0.5}\right\}$$

$$\left\{{}_+ \left[\left(\frac{2416}{548.66_a}\right) - 2.013\right]\log_{10}(9) - \left(\frac{8742}{548.66}\right) + 15.64\right\} = 7.93 \text{ psia}$$

$$P_{VN} = \exp\left\{\left[0.7553 - \left(\frac{413}{530.28_a}\right)\right]3^{0.5}\log_{10}(9) - \left[1.854 - \left(\frac{1042}{530.28}\right)\right]3^{0.5}\right\}$$

$$\left\{{}_+ \left[\left(\frac{2416}{530.28_a}\right) - 2.013\right]\log_{10}(9) - \left(\frac{8742}{530.28}\right) + 15.64\right\} = 5.67 \text{ psia}$$

$$\begin{aligned} \Delta P_V &= && P_{VX} - P_{VN} \\ &= && 7.93 - 5.67 \\ &= && 2.26 \text{ psia} \end{aligned}$$

$$K_E = \frac{36.75°R}{539.47°R} + \frac{(2.26 \text{ psia} - 0.06 \text{ psia})}{(14.7 \text{ psia} - 6.72 \text{ psia})} = 0.3438$$

Calculation of Vapor Saturation Factor (K_S)

$$K_S = \frac{1}{1 + 0.053 P_{VA} H_{VO}}$$

where: P_{VA} =   Vapor pressure at daily average liquid surface temp (psia); and
              H_{VO} =   Vapor space outage (ft).

For RVP 9 Gasoline:

P_{VA} =   6.72 psia;   (previously calculated)
H_{VO} =   12.39 ft   (previously calculated)

$$K_s = \frac{1}{1 + (0.053)(6.72)(12.39)} = 0.1847$$

Solving for standing losses:

L_S = $365 \times V_V \times W_V \times K_E \times K_S$

V_V =   13,759 ft^3
W_V =   0.0774 lb/ft^3
K_E =   0.3187
K_S =   0.1847
L_S = $(365) \times (13,759) \times (0.0774) \times (0.3438) \times (0.1847)$
      =   24,683 lb/yr

2.   **Calculation of Uncontrolled Working Losses**

$$L_W = 0.0010 \times M_V \times P_{VA} \times Q \times K_N \times K_P$$

where:　　　M_V　　=　　Vapor molecular weight (lb/mol);
　　　　　　P_{VA}　=　　Vapor pressure at the daily average liquid surface temp (psia);
　　　　　　Q　　=　　Annual net throughput (bbl/yr);
　　　　　　K_N　=　　Turnover factor; (For N>36, K_N = [180 + N]/6N; For N≤36, K_N = 1) (AP-42, page 7.1-18); and
　　　　　　K_P　=　　working loss product factor (0.75 for crude oils, 1.0 for all other organic liquids; AP-42, page 7.1-18)

$$N = \frac{5.614Q}{V_{LX}}$$

where:　　　N　　=　　Number of turnovers per year;
　　　　　　5.614　=　　Conversion factor from bbl to ft^3;
　　　　　　Q　　=　　Annual net throughput (bbl/yr); and
　　　　　　V_{LX}　=　　Tank maximum liquid volume (ft^3)

For RVP 9 Gasoline:

　　　　　　M_V　　=　　66.7 lb/lb-mol
　　　　　　P_{VA}　=　　6.72 psia
　　　　　　Q　　=　　2.642×10^6 gals/yr = 62,905 bbls/yr
　　　　　　V_{LX}　=　　210,000 gallons = 28,066 ft^3

$$N = \frac{5.614 \ (62,905 \ \text{bbl/yr})}{(28,066 \ \text{ft}^3)} = 12.58/\text{yr}$$

Therefore,　K_N　=　　1.0

　　　　　　K_P　=　　1.0

　　　　　　L_W　=　　$(0.0010) \times (66.7$ lb/lb-mol$) \times (6.72$ psia$) \times (62,905$ bbls/yr$) \times (1.0) \times (1.0)$
　　　　　　　　=　　28,196 lb/yr

3.　　Calculation of Total Uncontrolled Losses

　　　　　　L_{Total}　=　　$L_S + L_W$ = 24,683 lb/yr + 28,196 lb/yr = 52,879 lb/yr
　　　　　　　　=　　23,981 kg/yr = 24.0 Mg/yr

Introduction

In some air quality applications, estimates of individual species are required. For some source categories, sampling for individual chemical species is performed. However, when this sampling is impractical or too expensive, alternative methods must be used. For tank emissions, Raoult's Law provides a useful method for estimating emissions from individual species.

Problem Statement

Using Raoult's Law, estimate cyclohexane emissions from the bulk terminal tank standing and working losses due to storage and pumping of RVP 9 gasoline.

Available Information

As estimated earlier, the bulk liquid temperature, (T_{LA}), is 80 ^{o}F. The bulk terminal tank is a fixed roof AST. After analysis of the RVP 9 gasoline, it is determined that the liquid gasoline is 0.58 wt% cyclohexane ($x_{liq,c} = 0.0058$).

Solution

To determine the speciated emissions from tank standing and working losses, the following steps are necessary:

1. Determine the liquid phase speciation of gasoline in the tank.

2. Find the saturated vapor pressure of each species of concern at the bulk liquid temperature.

3.	Determine the true vapor pressure of the mixture at the bulk liquid temperature.

4.	Using Raoult's Law, determine the vapor phase speciation of the gasoline in the tank.

5.	Calculate the chemical-specific emissions using above steps and results from calculations such as those presented in Problem 4a.

Raoult's Law can be used to determine the vapor phase mole fraction of a particular constituent or species in a mixture based on the liquid phase mole fraction. It is assumed that the vapor is an ideal gas and the liquid is an ideal solution. It also assumed that both are well-mixed and in equilibrium with each other. Simply stated, if the liquid phase composition in a tank is known, then the vapor phase composition in the tank's vapor space can be calculated. The assumptions of ideal behavior and vapor/liquid equilibrium are often not strictly enforced since they are rarely achieved in the real world, and often Raoult's law or another equation of state is the only way to determine vapor phase compositions without actually sampling the tank to measure them.

For a mixture of N species, Raoult's law is expressed as:

$$Y_i P = X_i P_i^{sat}; \qquad i = 1, 2, 3,...,N$$

where:	Y_i	=	Vapor phase mole fraction of component i;
	P	=	True vapor pressure of the mixture at the bulk liquid temperature;
	X_i	=	Liquid phase mole fraction of component i; and
	P_i^{sat}	=	Saturated vapor pressure of species i at the bulk liquid temperature.

Also, $x_{vap,c}$	=	the mass fraction of cyclohexane in the vapor phase

Note that extra steps may be required to convert mass fractions to mole fractions. The above equation is written in terms of mole fractions, however data are commonly available as mass fractions only.

Given:

$$P_g \quad = \quad \text{True vapor pressure of gasoline} = 6.72 \text{ psia at } 80 \text{ }^\circ\text{F}$$
(previously calculated value for P_{VA}; see Page 4-7)

$$P_{cyclohexane}{}^{sat} \quad = \quad \text{Saturated vapor pressure of cyclohexane} = 2.069 \text{ psia (AP-42, Table 7.1-3)}$$

Rearranging Raoult's Law gives:

$$Y_i = \frac{X_i P_i{}^{Sat}}{P}$$

Before using this equation, the mass fraction in the liquid phase must be converted to a mole fraction. This is done as follows, using the molecular weights:

$$MW_g \quad = \quad \text{Molecular weight of liquid gasoline} = 100 \text{ lb/lb-mol (This is typically obtained from manufacturers or other published values.)}$$

$$MW_v \quad = \quad \text{Molecular weight of gasoline vapor} = 66.7 \text{ lb/lb-mol (extrapolated from AP-42, Table 7.1-2)}$$

$$MW_c \quad = \quad \text{Molecular weight of cyclohexane} = 84.16 \text{ lb/lb-mol (AP-42, Table 7.1-3)}$$

$$X_c \text{ (mole fraction of cyclohexane in liquid phase)} = \frac{X_{liq,c} MW_g}{MW_c} = \frac{(0.0058)\ (100)}{84.16} = 0.0069$$

$$Y_c \text{ (mole fraction of cyclohexane in vapor phase)} = \frac{X_c P_c{}^{sat}}{P_g} = \frac{(0.0069)\ (2.069)}{6.72} = 0.00212$$

We need the, $x_{vap,c}$, the mass fraction of cyclohexane in the vapor phase. Hence, converting as above:

$$X_{vap,c} = \frac{Y_c MW_c}{MW_v} = \frac{(0.00212)\ (84.16)}{66.7}$$

$$= 0.00267 \text{ lb cyclohexane } / \text{ lb gasoline vapor}$$

Now, calculate cyclohexane emissions from standing and working losses from the aboveground storage tanks.

L_{Total} = total standing and working losses

= 23,164 kg/yr

$$L_{cyclohexane} = \left(\frac{23{,}164 \;\; kg \;\; gasoline \;\; vapor}{yr} \right) \left(\frac{0.00267 \;\; kg \;\; cyclohexane}{1 \;\; kg \;\; gasoline \;\; vapor} \right)$$

= 62 kg cyclohexane/yr

Example 4a - Supplemental Information
Comparison of Raoult's Law with Other Methods

Problem Statement

Compare results obtained using Raoult's Law to measure vapor composition with other techniques.

Solution

Table 4-1 (summer blend gasoline) presents an array of measured and predicted results for the concentrations of several chemicals in vapor and liquid phase gasoline. The results presented here are unrelated to the information presented in the previous Supplemental Information section. As the data clearly show, Raoult's Law predicts both more precise and accurate vapor phase concentrations than either the Peng-Robinson or Redlich-Kwong-Soave equations of state. Equations of state relate the intensive thermodynamic properties (e.g., temperature, pressure, or specific volume) of any substance. Information on the Peng-Robinson or Redlich-Kwong-Soave equations of state can be found in standard chemical engineering thermodynamics textbooks (i.e., Smith and Van Ness, 1987). In addition, Raoult's Law is much easier to use than either of the equations of state. The relative errors shown in the tables are also within reason for the purposes of emissions estimation.

Table 4-1

Summary of Results for Summer Blend Unleaded Gasoline

Toxic Species	Measured		Predicted Vapor Concentration		
	Liquid wt%	Vapor wt%	Raoult[a]	P-R EOS[b]	R-K-S EOS[c]
Cyclohexane	0.58	0.20	0.25	0.27	0.26
Benzene	1.93	0.73	0.83	1.05	0.99
Toluene	10.32	0.81	1.29	1.57	1.45
O-Xylene	3.39	0.05	0.00	0.00	0.00
Isomers of Xylene	9.16	0.21	0.31	0.33	0.30
Ethylbenzene	2.05	0.05	0.00	0.00	0.00
Isopropylbenzene	0.19	—	0.00	0.00	0.00
1,2,4-Trimethylbenzene	3.52	0.04	0.00	0.00	0.00
Molecular Weight of Vapor		67.6	67.0	67.4	67.2
Predicted Vapor Pressure			3.92	4.04	4.00
Relative Concentration Errors:					
Average for all Species			4.0%	10.4%	7.3%
Average for Toxics			22.7%	36.5%	29.6%
Absolute Value for all Species			16.7%	22.2%	19.5%
Absolute Value for Toxics			22.7%	36.5%	29.6%

Notes: [a]   Raoult   = Raoult's Law
         [b]   P-R EOS   = Peng-Robinson equation of state
         [c]   R-K-S EOS   = Redlich-Kwong-Soave equation of state

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Example 4b

Fugitive (Equipment Leak) Emissions

</div>

Problem Statement

Estimate fugitive TOG emissions from equipment leaks at the bulk terminal. Example 4a addressed breathing and working losses associated with the aboveground storage tank (AST) at the bulk terminal. This problem accounts for leaks of hydrocarbon vapors from various types of process equipment.

Available Information

The hypothetical gasoline bulk terminal contains the following equipment types: 520 valves, 230 pump seals, 180 flanges, 120 connectors, and 70 other equipment types. Equipment leak emission control techniques have not been implemented at the bulk terminal.

Solution

There are four approaches that are used to estimate fugitive TOG emissions. These approaches, in order of increasing refinement, are:

- Average Emission Factor approach;

- Screening Ranges approach;

- EPA Correlation approach; and

- Unit-Specific Correlation approach.

These approaches are detailed in the U.S. EPA's Protocol Document (U.S. EPA, 1995b). For a facility with a relatively small number of equipment, such as a bulk terminal, usually only the first two approaches would be used. For more complex facilities, such as refineries, the correlation

approaches are often utilized. Both the Average Emission Factor and Screening Ranges approaches require equipment counts. However, the Screening Ranges approach requires some additional information. Only the Average Emission Factor and Screening Ranges approaches will be used in this problem.

Average Emission Factor Approach

Using the Average Emission Factor approach, total emissions for a specific equipment type can be calculated using the following equation:

$$E_e = N_e \times EF_e \times t_e$$

where:
E_e = Uncontrolled fugitive emissions (kg/yr) for equipment type e;
N_e = Number of equipment type e;
EF_e = Uncontrolled emission factor for equipment type e (kg/hr); and
t_e = Annual time of process (hr/yr) (assumed to be 8,760 hours per year).

The average emission factors presented in Table 4-2 for gasoline stored at bulk terminals are taken from Table 2-3 of the Protocol Document. Other average emission factors also exist for refineries, oil and gas production operations, and synthetic organic chemical manufacturing operations. These other operations will have average emission factors for pressure relief valves, open-ended lines, and sampling connections.

Table 4-2

Average Emission Factors

Equipment Type	Emission Factor (kg/hr)
Valves	0.000043
Pump Seals	0.00054
Fittings (Connectors and Flanges)	0.000008
Other Equipment	0.00013

The emissions for each equipment type are calculated below.

$$E_{Valves} = 520 \text{ valves} \times 0.000043 \text{ kg/hr} \times 8{,}760 \text{ hr/yr} = 195.9 \text{ kg/yr}$$

$$E_{Pump\ Seals} = 230 \text{ pump seals} \times 0.00054 \text{ kg/hr} \times 8{,}760 \text{ hr/yr} = 1{,}088 \text{ kg/yr}$$

$$E_{Flanges} = 180 \text{ flanges} \times 0.000008 \text{ kg/hr} \times 8{,}760 \text{ hr/yr} = 12.6 \text{ kg/yr}$$

$$E_{Connectors} = 120 \text{ connectors} \times 0.000008 \text{ kg/hr} \times 8{,}760 \text{ hr/yr} = 8.4 \text{ kg/yr}$$

$$E_{Other} = 70 \text{ other equipment} \times 0.00013 \text{ kg/hr} \times 8{,}760 \text{ hr/yr} = 79.7 \text{ kg/yr}$$

The total fugitive emissions are then summed up as shown below.

$$E_{Total} = 195.9 + 1{,}088 + 12.6 + 8.4 + 79.7 = 1{,}385 \text{ kg/yr} = 1.4 \text{ Mg/yr of TOG}$$

Screening Ranges Approach

If the Screening Ranges approach is used, then each equipment component is assigned either a "leak" or "no-leak" designation. This assignment is done by screening each component. Screening is done by measuring the TOG concentration in the air right next to the component. If the screening value is $\geq 10{,}000$ ppmv, then the component is given a "leak" designation. Conversely, if the screening value is $< 10{,}000$ ppmv, then the component is given a "no-leak" designation. Emissions from "leaking" components are estimated using "leaking" emission factors; emissions from "non-leaking" components are estimated using "non-leaking" emission factors. In spite of their designation, the "non-leaking" components are actually leaking -- they just are leaking at a lesser rate than the "leaking" components.

Using the Screening Ranges approach, total emissions for a specific type of equipment can be calculated using the following equation:

$$E_e = ([N_L \times EF_L] + [N_{NL} \times EF_{NL}]) \times t_e$$

where:
E_e	=	Uncontrolled fugitive emissions (kg/yr) for equipment type e;
N_L	=	Number of "leaking" equipment components;
EF_L	=	Uncontrolled emission factor for "leaking" equipment components (kg/hr);
N_{NL}	=	Number of "non-leaking" equipment components;

$$EF_{NL} = \text{Uncontrolled emission factor for "non-leaking" equipment components (kg/hr); and}$$

$$t_e = \text{Annual time of process (hr/yr) (assumed to be 8,760 hours per year).}$$

The screening ranges emission factors presented in Table 4-3 for gasoline stored at bulk terminals are taken from Table 2-7 of the Protocol Document. Like the average emission factors presented earlier, screening ranges emission factors also exist for refineries, oil and gas production operations, and synthetic organic chemical manufacturing operations. There are also screening ranges emission factors for pressure relief valves, open-ended lines, and sampling connections.

Table 4-3

Screening Range Emission Factors

Equipment Type	"Leaking" Emission Factor ($\geq$10,000 ppmv) (kg/hr)	"Non-Leaking" Emission Factor (<10,000 ppmv) (kg/hr)
Valves	0.023	0.000015
Pump Seals	0.077	0.00024
Fittings (Connectors and Flanges)	0.0065	0.0000072
Other Equipment	0.034	0.000024

After screening, it is determined that the following pieces of equipment are "leaking" (i.e., screening value $\geq$ 10,000 ppmv): 1 valve, 2 flanges, 2 connectors, and 1 piece of other equipment. The TOG emissions for each equipment type are then calculated as follows.

$$E_{Valves} = ([1 \text{ valve} \times 0.023 \text{ kg/hr}] + [519 \text{ valves} \times 0.000015 \text{ kg/hr}]) \times 8,760 \text{ hr/yr} = 270 \text{ kg/yr}$$

$$E_{Pump\ Seals} = ([0 \text{ pump seals} \times 0.077 \text{ kg/hr}] + [230 \text{ pump seals} \times 0.00024 \text{ kg/hr}]) \times 8,760 \text{ hr/yr} = 484 \text{ kg/yr}$$

$$E_{Flanges} = ([2 \text{ flanges} \times 0.0065 \text{ kg/hr}] + [178 \text{ flanges} \times 0.0000072 \text{ kg/hr}]) \times 8,760 \text{ hr/yr} = 125 \text{ kg/yr}$$

$$E_{Connectors} = ([2 \text{ connectors} \times 0.0065 \text{ kg/hr}] + [118 \text{ connectors} \times 0.0000072 \text{ kg/hr}]) \times 8,760 \text{ hr/yr} = 121 \text{ kg/yr}$$

$$E_{Other\ Equipment} = ([1 \text{ other equipment} \times 0.034 \text{ kg/hr}] + [69 \text{ other equipment} \times 0.000024 \text{ kg/hr}] \times 8,760 \text{ hr/yr} = 312 \text{ kg/yr}$$

The total fugitive emissions are then summed up as shown below.

$$E_{Total} = 270 + 484 + 125 + 121 + 312 = 1,312 \text{ kg/yr} = 1.3 \text{ Mg/yr}$$

Although this sample problem is hypothetical, it shows that a more refined approach might produce significantly different results than a more simplified approach. In general, the Screening Ranges approach will give lower results than the Average Emission Factor approach. However, the increased data collection requirements associated with the more refined approaches must be weighed against the need for more accurate results.

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Example 4c

Tank Truck Loading Emissions

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Problem Statement

Estimate TOG emissions from gasoline tank truck loading at the bulk terminal. Tank trucks are used to transport gasoline from the bulk terminal to the individual gasoline stations. This problem addresses the actual loading of the tank trucks.

Available Information

The total amount of gasoline loaded at the bulk terminal into gasoline tank trucks is 10,000,000 liters per year. All of the gasoline tank trucks transporting product to the four gasoline stations are loaded using dedicated normal service splash loading. For splash loading, the fill pipe that dispenses gasoline is lowered only part way into the cargo tank. Emissions are caused by the resulting "splashing" and turbulence. The product temperature of all delivered gasoline and ambient temperature is 80 °F. There is not any vapor balance control used.

Solution

The quantity of uncontrolled emissions from tank truck loading is dependent upon whether the tank truck is equipped for submerged, splash, or vapor balance filling. Uncontrolled emissions are also dependent upon the vapor pressure of the unloaded gasoline, the molecular weight of the vapors expelled from the cargo tank, and the temperature at which the gasoline is loaded. In addition, vapor balance filling, which returns vapors displaced from the truck cargo tank back to a vapor recovery unit at the bulk terminal, will have a control efficiency ranging from 90 to over 99 percent. The following equation can be used to estimate uncontrolled loading losses (AP-42, Section 5.2.2.1.1).

$$EF_{UL} = 12.46 \times \frac{SPM}{T}$$

where:
EF_{UL} = Uncontrolled loading loss emission factor (lb/1000 gal);
S = Saturation factor;
P = True vapor pressure of gasoline (pounds per square inch absolute [psia]);
M = Molecular weight of vapors (lb/lb-mole); and
T = Temperature of loaded gasoline (°R).

Saturation factors (S) for various modes of operation, which represent how close the expelled vapor comes to saturation, are presented in Table 4-4.

Table 4-4

Saturation Factors (S) for Calculating Petroleum Liquid Loading Losses

Type of Service	Splash Loading	Submerged Loading
Clean Cargo Tank	1.45	0.50
Dedicated Normal Service	1.45	0.60
Dedicated Vapor Balance Service	1.00	1.00

True vapor pressures and molecular weights of gasoline vapors can be derived from Figure 7.1-5, Figure 7.1-6, and Table 7.1-2 of AP-42. Excerpted information from Table 7.1-2 is presented in Table 4-5.

Table 4-5

Physical Properties of Gasoline

Gasoline RVP	Vapor Molecular Weight at 60°F (lb/lb-mole)	True Vapor Pressure (psi)						
		40 °F	50 °F	60 °F	70 °F	80 °F	90 °F	100 °F
13 psia	62	4.7	5.7	6.9	8.3	9.9	11.7	13.8
10 psia	66	3.4	4.2	5.2	6.2	7.4	8.8	10.5
7 psia	68	2.3	2.9	3.5	4.3	5.2	6.2	7.4

The vapor molecular weight and true vapor pressure for RVP 9 gasoline values must be interpolated from values presented in the table above. This interpolation is shown below.

$$VMW_i = VMW_x + \left(\frac{RVP_x - RVP_i}{RVP_x - RVP_n} \right) \left(VMW_n - VMW_x \right)$$

$$TVP_i = TVP_x - \left(\frac{RVP_x - RVP_i}{RVP_x - RVP_n} \right) \left(TVP_x - TVP_n \right)$$

where: VMW_i =   Vapor molecular weight interpolated to RVP 9;
          VMW_x =   Vapor molecular weight at maximum RVP (10) in interpolation range;
          VMW_n =   Vapor molecular weight at minimum RVP (7) in interpolation range;
          RVP_i =   Interpolated RVP (9);
          RVP_x =   Maximum RVP (10);
          RVP_n =   Minimum RVP (7);
          TVP_i =   True vapor pressure interpolated to RVP 9;
          TVP_x =   True vapor pressure at maximum RVP (10); and
          TVP_u =   True vapor pressure at minimum RVP (7).

$$VMW_9 = 66 + \left(\frac{10-9}{10-7} \right) \left(68-66 \right) = 66.7 \text{ lb/lb-mole}$$

$$TVP_9 = 7.4 - \left(\frac{10-9}{10-7} \right) \left(7.4-5.2 \right) = 6.7 \text{ psi}$$

The saturation factor for dedicated normal service splash loading is 1.45. Finally, converting the gasoline temperature from Fahrenheit degrees to Rankine degrees gives a temperature of 540 °R.

Thus, the uncontrolled loading emission factors are calculated below.

$$EF_{UL(RVP9)} = \frac{12.46 \times 1.45 \times 6.7 \times 66.7}{540} = 14.95 \text{ lb/1000 gal}$$

Controlled loading emission factors are then calculated using the following equation.

$$EF_{CL} = (1 - CE) \times EF_{UL}$$

where: EF_{CL} =   Controlled loading loss emission factor (lb/1000 gal);
                         CE   =   Vapor control efficiency; and
                         EF_{UL} =   Uncontrolled loading loss emission factor (lb/1000 gal).

However, for this problem, vapor control is not utilized during tank truck loading, so controlled loading loss emission factors need not be calculated.

Total tank truck loading losses can be estimated by the following equation.

$$\text{Emissions} = \sum_{i=1}^{n} EF_{UL,CL} \times \text{Fuel}_i$$

where: Emissions   =   Total tank truck loading emissions (kg/yr);
                       n   =   Number of different types of operation modes and fuel types;
                       $EF_{UL,CL}$ =   Uncontrolled or controlled tank truck loading emission factor for operation mode or fuel type i (mg/liter); and
                       Fuel_i =   Annual amount of fuel delivered for each operation mode or fuel type i (liters/yr).

Converting the loading emission factors from units of lb/1000 gal to units of mg/liter:

$$EF_{UL(RVP9)} = \left(\frac{14.95 \text{ lb}}{1000 \text{ gal}} \right) \left(\frac{453.6 \text{ g}}{1 \text{ lb}} \right) \left(\frac{1000 \text{ mg}}{1 \text{ g}} \right) \left(\frac{1 \text{ gal}}{3.785 \text{ liter}} \right) = 1{,}792 \text{ mg liter}$$

$$\text{Emissions} = \frac{1{,}792 \text{ mg}}{\text{liter}} \times (1 \times 10^7 \text{ liters}) = 17{,}920 \text{ kg/yr} = 17.9 \text{ Mg/yr}$$

Example 4d

Tank Truck Transit Emissions

Problem Statement

After gasoline is loaded into tank trucks, it is transported to gasoline stations. Although tank trucks do have enclosed cargo tanks, emissions do occur while in transit. This problem focuses on the emissions that occur while the tank truck is in transit.

Estimate TOG emissions from gasoline tank trucks in transit from the bulk terminal to PEMEX gasoline stations A, B, C, and D.

Available Information

The following amounts of gasoline are transported to the four gasoline stations for sale:

Gasoline Station	Gasoline Dispensed (liters/yr)
A	4,000,000
B	2,500,000
C	2,000,000
D	1,500,000

Solution

The quantity of emissions from gasoline tank trucks is dependent upon the extent of venting that occurs during transit, which in turn depends upon the vapor tightness of the tank, the pressure relief valve settings, the pressure in the tank at the start of the trip, the vapor pressure of the fuel being transported, and the degree of fuel vapor saturation of the space in the tank. The emissions are <u>not</u> directly proportional to the time spent in transit.

AP-42, Table 5.2-5 presents transit loss emission factors for gasoline tank trucks both loaded with product and returning with vapors for RVP 10 gasoline. These emission factors are presented in Table 4-6 for both "typical" and "extreme" transit conditions. Extreme conditions refer to the unlikely event that all of the determining factors listed above combine to cause maximum emissions.

Table 4-6

Total Uncontrolled Emission Factors for Gasoline Tank Trucks

Transit Conditions	Loaded with product (mg/liter of gasoline)	Returning with vapor (mg/liter of gasoline)
Typical	0 - 1.0	0 - 13.0
Extreme	0 - 9.0	0 - 44.0

Total transit loss emissions will include both the trip from the bulk terminal to the gas stations (loaded with product) and the return trip from the gas stations back to the bulk terminal (empty tanks). Total transit loss emissions can be estimated by the following equation.

$$\text{Emissions} = \sum_{i=1}^{n} ([EF_{l,c} + EF_{r,c}] \times Fuel_i)$$

where:

	Emissions	=	Total refueling emissions (kg/yr);
	n	=	Number of gasoline stations;
	$EF_{l,c}$	=	"Loaded with product" transit loss emission factor for gasoline transported to station i under transit conditions c (mg/liter);
	$EF_{r,c}$	=	"Returning with vapor" transit loss emission factor for gasoline transported to station i under transit conditions c (mg/liter); and
	$Fuel_i$	=	Annual amount of fuel dispensed from gasoline station i (liters/yr).

Assuming that gasoline transported to stations A, B, and C is transported under "typical" conditions and gasoline transported to stations D is transported under "extreme"

conditions, estimate overall transit emissions. For each emission factor, assume that the midpoint of the range listed in the table above provides a reasonable estimate.

$$\text{Emissions} = ([0.5 + 6.5] \text{ mg/liter}) \times ([4 \times 10^6] + [2.5 \times 10^6] + [2 \times 10^6] \text{ liters})$$
$$+ ([4.5 + 22] \text{ mg/liter}) \times (1.5 \times 10^6 \text{ liters})$$
$$= 59.5 \text{ kg/yr} + 39.75 \text{ kg/yr}$$
$$= 99 \text{ kg/yr}$$

Note that the amount of gasoline sold in this problem is equal to the amount of gasoline transported. This, however, is not always the case. If transit emissions are estimated for the transport of gasoline from a refinery to a bulk terminal and then from the bulk terminal to gasoline stations, then the transit emissions would be twice as much because the gasoline is "transported" twice. Gasoline may also be transported through an inventory domain even though its origin and/or destination may lie outside of the inventory domain.

Example 4e

Underground Tank Filling Emissions

Problem Statement

Estimate TOG emissions from gasoline tank truck unloading at gasoline stations A, B, C, and D. After tank trucks arrive at the gasoline stations, they unload their cargo into the underground storage tanks at the gasoline station. This unloading is similar to the loading of the tank trucks at the bulk terminal.

Available Information

The following amounts of gasoline are transported to the four gasoline stations for sale:

Gasoline Station	Gasoline Delivered (liters/yr)
A	4,000,000
B	2,500,000
C	2,000,000
D	1,500,000

The following modes of operation are in place at the four gasoline stations:

Gasoline Station	Mode of Operation
A	Submerged loading - normal service
B	Submerged loading - vapor balance service
C	Splash loading - normal service
D	Splash loading - normal service

For splash loading, the fill pipe that dispenses gasoline is lowered only part way into the storage tank. Emissions are caused by the resulting "splashing" and turbulence. For submerged loading, the fill pipe extends nearly to the bottom of the storage tank. Because of this, liquid turbulence and the resulting emissions are reduced relative to splash loading. Vapor balance service retrieves the vapors displaced during gasoline unloading and transports the vapors back to the tank truck.

Solution

The quantity of emissions from underground tank filling is dependent upon whether the gasoline station tank is equipped for submerged, splash, or submerged vapor balance filling. Vapor balance filling, which returns vapors displaced from the gasoline station tank back to the tank truck, will have a control efficiency ranging from 93 to 100 percent relative to uncontrolled emissions. Table 4-7 shows the emission factors for underground tank filling (AP-42, Table 5.2-7).

Table 4-7

Emission Factors for Underground Tank Filling at Gasoline Stations

Type of Operation	Emission Factor (mg/liter throughput)
Submerged	880
Splash	1,380
Balanced Submerged	40

Total underground tank filling emissions can be estimated by the following equation.

$$\text{Emissions} \ = \ \sum_{i=1}^{n} \text{EF}_i \ \times \ \text{Fuel}_i$$

where:

	Emissions	=	Total underground tank filling emissions (kg/yr);
	EF_i	=	Underground tank filling emission factor for operation type i (mg/liter); and
	$Fuel_i$	=	Annual amount of fuel delivered for operation type i (liters/yr).

$$\text{Emissions} = (880 [4 \times 10^6] + 40 [2.5 \times 10^6] + 1{,}380 [2 \times 10^6] + 1{,}380 [1.5 \times 10^6])$$

$$\text{Emissions} = 3{,}520 + 100 + 2{,}760 + 2{,}070 \quad = \; 8{,}450 \text{ kg/yr}$$
$$= \; 8.45 \text{ Mg/yr}$$

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Example 4f

Underground Tank Breathing Emissions

</div>

Problem Statement

Estimate TOG emissions from underground tank breathing at gasoline stations A, B, C, and D.

Available Information

The following amounts of gasoline were sold at the four gasoline stations in the region:

Gasoline Station	Gasoline Dispensed (liters/yr)
A	4,000,000
B	2,500,000
C	2,000,000
D	1,500,000
Total	10,000,000

Solution

The quantity of emissions from underground breathing losses is mainly dependent upon evaporation and barometric pressure changes. Also, the frequency of gasoline withdrawal from the tank also has an effect on the emissions quantity because fresh air brought into the tank will enhance the evaporation rate. An average breathing emission rate for U.S. gasoline stations has been estimated to be 120 mg/liter of gasoline throughput (AP-42, Table 5.2-7). The tank equations presented in AP-42, Section 7 could be used to estimate emissions from underground gasoline storage tanks at gasoline stations. However, the large number of gasoline station tanks

usually precludes the use of these equations. Total underground breathing losses can be estimated using the following equation with the average breathing emission rate.

$$\text{Emissions} = \sum_{i=1}^{n} \text{EF}_{UB} \times \text{Fuel}_i$$

where:

Emissions	=	Total underground tank breathing emissions (kg/yr);
n	=	Number of gasoline stations;
EF_{UB}	=	Underground breathing loss emission factor for gasoline station i (mg/liter) [U.S. average value - 120 mg/liter];
Fuel_i	=	Annual amount of fuel delivered to gasoline station i (liters/yr).

$$\text{Emissions} = (120[4 \times 10^6] + 120[2.5 \times 10^6] + 120[2 \times 10^6] + 120[1.5 \times 10^6])$$

$$\text{Emissions} = 480 + 300 + 240 + 180 = 1,200 \text{ kg/yr} = 1.2 \text{ Mg/yr}$$

Example 4g

Vehicle Refueling Emissions

Problem Statement

Estimate TOG emissions from vehicle refueling at gasoline stations A, B, C, and D. Refueling emissions consist of both vapors displaced from the vehicle tank by dispensed gasoline, as well as gasoline spillage.

Available Information

The four gasoline stations in the distribution system dispense the following quantities of RVP 9 of gasoline:

Gasoline Station	Gasoline Dispensed (liters/yr)
A	4,000,000
B	2,500,000
C	2,000,000
D	1,500,000

The temperature of the dispensed fuel is 24 °C (75 °F) and the temperature of the fuel in the vehicle tank is about 30 °C (86 °F). Stations A and C are uncontrolled; stations B and D are controlled using vapor control which transfers displaced vapors from the vehicle fuel tank back to the underground storage tank vapor space.

Solution

The quantity of emissions from displaced vapors depends upon the gasoline temperature, vehicle tank temperature, gasoline Reid vapor pressure (RVP), and dispensing rate.

The following equation can be used to estimate uncontrolled displacement losses based upon the factors mentioned above (AP-42, Section 5.2.2.3).

$$EF_u = 264.2[(-5.909) - 0.0949(\Delta T) + 0.0884(T_D) + 0.485(RVP)]$$

where: EF_u = Uncontrolled TOG emission factor for vehicle refueling (mg/liter);

ΔT = Difference between temperature of fuel in vehicle tank and temperature of dispensed fuel (°F);

T_D = Temperature of dispensed fuel (°F); and

RVP = Reid vapor pressure (psia).

The uncontrolled displacement loss emission factors for each gas station are calculated below.

$$EF_u = 264.2[(-5.909) - 0.0949(11°) + 0.0884(75°) + 0.485(9)] = 1,068 \text{ mg/liter}$$

Controlled displacement losses must be estimated for stations B and D. AP-42 indicates that typical U.S. vapor control efficiencies range from 88-92% (AP-42, Section 5.2.2.3). The equation for calculating a controlled displacement loss factor is shown below.

$$EF_c = (1 - CE) \times EF_u$$

where: EF_c = Controlled TOG emission factor for vehicle refueling (mg/liter);

CE = Vapor control efficiency; and

EF_u = Uncontrolled TOG emission factor for vehicle refueling (mg/liter).

Assuming that the Stage II vapor control efficiency is 88%, then the controlled displacement loss emission factors for stations B and D are calculated as follows.

$$EF_{cB, \ cD} = (1 - 0.88) \times 1{,}068 \text{ mg/liter} = 128 \text{ mg/liter}$$

In addition to displacement losses, spillage losses occur during vehicle refueling. The U.S. spillage emission factor (EF_s) has been estimated to be 80 mg/liter of fuel dispensed. The actual amount of spillage is dependent upon several factors such as gasoline station business characteristics, tank configuration, and operator techniques.

Total refueling losses can be estimated by the following equation.

$$\text{Emissions} = \sum_{i=1}^{n} \left([EF_{u,c} + EF_s] \times Fuel_i \right)$$

where:

Emissions	=	Total refueling emissions (kg/yr);
n	=	Number of gasoline stations;
$EF_{u,c}$	=	Uncontrolled or controlled displacement loss emission factor for gasoline station i (mg/liter);
EF_s	=	Spillage emission factor for gasoline station i (mg/liter); and
$Fuel_i$	=	Annual amount of fuel dispensed from gasoline station i (liters/yr).

Assuming that the U.S. spillage emission factor of 80 mg/liter is appropriate for Mexico, estimate overall refueling emissions.

$$\text{Emissions} = ([1{,}068 + 80][4 \times 10^6] + [128 + 80][2.5 \times 10^6] + [1{,}068 + 80][2 \times 10^6] + [128 + 80][1.5 \times 10^6])$$

$$\text{Emissions} = 4{,}592 + 520 + 2{,}296 + 312 = 7{,}720 \text{ kg/yr}$$
$$= 7.72 \text{ Mg/yr}$$

<div align="center">

Example 4 - Summary

</div>

   Emission estimates from the seven sources within a typical gasoline distribution system have been shown in Examples 4a through 4g. These hypothetical emission estimates are presented in Table 4-8.

<div align="center">

Table 4-8

Summary of Emissions from Gasoline Distribution System

</div>

Emission Source	Emission Estimate (kg/yr)	Percentage of Total Emissions
Aboveground Bulk Storage Tank (4a)	23,981	39.5%
Fugitive (Equipment Leak) [Screening Range] (4b)	1,312	2.2%
Tank Truck Loading (4c)	17,920	29.5%
Tank Truck Transit (4d)	99	0.2%
Underground Tank Filling (4e)	8,450	13.9%
Underground Tank Breathing (4f)	1,200	2.0%
Vehicle Refueling (4g)	7,720	12.7%
Total	**60,682**	**100.0%**

From the table above, it can be seen that fugitive, tank truck transit, and underground tank breathing emissions are relatively small compared to the other emission sources. The emission estimates and distribution presented above are hypothetical; actual emission estimates will be different. Efforts to improve future inventory accuracy should focus on the larger sources in the gasoline distribution system.

Example 5a
Solvent Evaporation - Degreasing

Introduction

Solvent degreasing or surface cleaning operations occur at a wide variety of manufacturing, scientific, and repair facilities. Surface cleaning operations involve the use of solvent liquids or vapors to remove water-insoluble contaminants such as grease, oils, waxes, carbon deposits, fluxes, and tars from metal, plastic, glass, and other surfaces. Solvent degreasing operations may involve the use of a number of different solvents, such as acetone, methyl ethyl ketone (MEK), alcohols, 1,1,1-trichloroethane, or CFC-113.

Typical solvent cleaning equipment can be categorized as:

- **Batch cold cleaning machines**. These machines are batch loaded and liquid solvent is sprayed, dipped, or brushed onto the surfaces that are to be cleaned.

- **Batch vapor cleaning machines**. These machines are batch loaded, and the materials to be cleaned are exposed to vaporized solvent. The condensing solvent flushes the contaminants from the surfaces to be cleaned.

- **In-line cleaning machines**. These machines are loaded using a conveyor on a continual basis and are often custom-made for large-scale operations. An in-line solvent cleaning machine may use liquid or vapor solvent.

Problem Statement

Estimate annual TOG emissions from a batch cold cleaning machine and a batch vapor cleaning machine.

Available Information

Batch cold cleaning machine

- Solvent used is aliphatic hydrocarbon (e.g., Stoddard solvent, petroleum naphtha);

- Cold cleaner capacity is 200 liters;

- Solvent density is 0.8 g/ml (0.8 kg/liter);

- Solvent log data are shown in Table 5-1.

Table 5-1

Solvent Log Data

Date	Solvent Added (liters)	Waste Liquid Removed (liters)	Waste Sludge Removed (kg)
2 Feb	200	195	--
30 May	200	203	--
15 Aug	200	198	1.3
28 Nov	200	205	--

- Added fresh solvent is 100% TOG;

- Waste liquid is 95 wt% TOG (includes contaminants such as water, grease, oil, flux, etc.);

- Waste liquid is assumed to have the same density as fresh solvent;

- Solid waste (sludge) is 10 wt% TOG.

Batch vapor cleaning machine

- Solvent used is perchloroethylene;

- Capacity is 200 liters;

- Solvent density is 1.6 g/ml (1.6 kg/liter);

- Solvent consumption data are shown in Table 5-2.

Table 5-2

Solvent Consumption Data

Date	Solvent Added (liters)	Waste Liquid Removed (liters)	Waste Sludge Removed (kg)
14 Jan	20	--	--
8 Feb	35	--	--
26 Mar	200	178	--
10 Apr	20	--	--
2 May	25	--	--
18 May	20	--	--
20 Jun	200	160	--
4 Jul	15	--	--
6 Aug	30	--	--
18 Sep	200	167	2
3 Nov	50	--	--
15 Dec	200	185	--

- Fresh solvent is 100% TOG;

- Waste liquid is 95 wt% TOG (includes contaminants such as water, grease, oil, flux, etc.);

- Waste liquid is assumed to have the same density as fresh solvent; and

- Solid waste (sludge) is 10 wt% TOG.

Solution

Emissions from cold cleaning occur through waste solvent and sludge evaporation, solvent carryout or "dragout," solvent bath evaporation, spray evaporation and agitation. Emissions from vapor degreasing are due to diffusion and convection, solvent carryout or "dragout," exhaust systems, and waste solvent and sludge evaporation.

Since it would be very time- and cost-intensive to collect data on all of these loss mechanisms, emission rates are usually estimated from solvent consumption data for the particular degreasing operation under consideration. If solvent consumption data are not available, emission factors based on number of employees or population data are available in literature (e.g., U.S. EPA, 1991b). For point source emission calculations, it is highly recommended that the following mass balance equation be used to estimate emissions:

$$E = (Q_{in} \times \rho_{in} \times TOG_{in}) - (Q_{out(liq)} \times \rho_{out(liq)} \times TOG_{out(liq)}) - (Q_{out(solid)} \times TOG_{out(solid)})$$

where:

	E	=	Total TOG emissions (kg);
	Q_{in}	=	Amount of solvent added to the degreaser (liters);
	ρ_{in}	=	Density of solvent added to the degreaser (kg/liter);
	TOG_{in}	=	TOG content of the solvent added to the degreaser (wt%);
	$Q_{out(liq)}$	=	Amount of liquid waste removed from the degreaser (liters);
	$\rho_{out(liq)}$	=	Density of liquid waste removed from the degreaser (kg/liter);
	$TOG_{out(liq)}$	=	TOG content of liquid waste removed from the degreaser (wt%);
	$Q_{out(solid)}$	=	Amount of solid waste (sludge) removed from the degreaser (kg); and
	$TOG_{out(solid)}$	=	TOG content of solid waste (sludge) removed from the degreaser (wt%).

Batch cold cleaning machine

Emissions from the batch cold cleaning machine are calculated using the mass balance equation given above. Data from the solvent log are used to calculate the amount of solvent added (Q_{in}), the amount of liquid waste removed ($Q_{out(liq)}$), and the amount of sludge removed ($Q_{out(solid)}$).

$$Q_{in} = (200 + 200 + 200 + 200) = 800 \text{ liters}$$
$$Q_{out(liq)} = (195 + 203 + 198 + 205) = 801 \text{ liters}$$
$$Q_{out(solid)} = 1.3 \text{ kg}$$

Total emissions are then calculated as follows:

$$E = (800 \times 0.8 \times 100\%) - (801 \times 0.8 \times 95\%) - (1.3 \times 10\%) = 31 \text{ kg TOG/yr}$$

Batch vapor cleaning machine

Emissions from the batch vapor cleaning machine are calculated using the same mass balance equation given above. Once again, data from the solvent log are used to calculate Q_{in}, $Q_{out(liq)}$, and $Q_{out(solids)}$.

where:
$$Q_{in} = (20 + 35 + 200 + 20 + 25 + 20 + 200 + 15 + 30 + 200 + 50 + 200) = 1015 \text{ liters}$$
$$Q_{out(liq)} = (178 + 160 + 167 + 185) = 690 \text{ liters}$$
$$Q_{out(solid)} = 2 \text{ kg}$$

Total emissions are then calculated as follows:

$$E = (1015 \times 1.6 \times 100\%) - (690 \times 1.6 \times 95\%) - (2 \times 10\%) = 575 \text{ kg TOG/yr}$$

The following issues should be considered when estimating emissions from solvent degreasing:

- Cold cleaner solvent consumption logs usually only include records of changeouts (i.e., all the liquid waste is removed and fresh solvent is added for the full cleaner capacity).

- Vapor degreaser consumption logs usually include records of changeouts and replenishments (i.e., fresh solvent is added to replace evaporated solvent without any liquid waste being removed at the same time).

- The TOG content of the liquid and solid wastes should preferably be determined using periodic sampling. However, frequent sampling is usually cost-prohibitive, so engineering judgement is often used to estimate the TOG content of liquid and solid wastes.

- The amount of TOG recovered in the solid waste (sludge) is usually very small compared to the amount of TOG recovered in the liquid waste. Therefore, it is often conservatively assumed that the TOG in the solid waste is emitted to the air.

- Emissions from some degreasing solvents (e.g., perchloroethylene, freons, etc.) should not be included in ROG (reactive organic gas) inventories.

- Engineering judgement may be needed to reconcile the time period defined by the consumption log with the time period needed for the emission calculations. For example, the batch cold cleaner consumption log contains no data after 28 Nov, but the cold cleaner is still emitting until the end of the annual emission period (i.e., 31 Dec). For actual emission inventories, it is generally assumed that these additional emissions will be reflected at the time of the next consumption entry (i.e., in the next calendar year).

Introduction

Surface coating includes all processes in which a liquid material is applied to the surface of a solid substrate. Air emissions result from both the evaporation of the solvents or other organic carriers in the coatings, and from the "overspray" of particulate materials that do not adhere to each part. Particulate emissions can be reduced through the use of paint booths and other control devices. In addition to the actual surface coating materials, emissions also result from materials used for surface preparation prior to the application of surface coatings and for cleanup afterwards.

Problem Statement

Estimate TOG, PM, and zinc compound emissions from the surface coating operation described below. Include all surface coating, thinning, surface preparation, and cleanup materials. There are no records that indicate the amount of paint used.

Available Information

Two types of paint (polyurethane and primer) are used. The polyurethane paint consists of a base and a hardener that must be mixed together. In addition, the polyurethane paint must be thinned with a thinner. The mixing ratio of the polyurethane is 7:2:1 (base:hardener:thinner). The primer does not have component parts and does not require thinning. The material characteristics of the base, hardener, thinner, primer, and other surface preparation and cleanup solvents are given in Table 5-3.

Table 5-3

Surface Coating Material Characteristics

Material	Density (grams/liter)	VOC Content (grams/liter)	Solids Content (%)
Polyurethane-base	700	520	31
Polyurethane-hardener	750	330	35
Polyurethane-thinner	820	820	-
Primer	680	460	40
Surface Preparation Solvent	820	820	-
Cleanup Solvent	820	820	-

Also, 2% of the solids of Paint 1 (as mixed) and 1.5% of the solids of Paint 2 are zinc compounds.

Half of the polyurethane is applied using high volume/low pressure (HVLP) spray equipment, while the other half is applied using conventional spray equipment. The primer is applied using aerosol spray cans. The polyurethane is used in a paint booth equipped with dry particulate filters (approximate control efficiency [CE] of 90%), but the primer is used in an open area.

The surface coating operation paints kitchen appliance parts. Annual throughput of the operation is 25,000 parts. Painters working at the surface coating operation estimate that each part requires 0.8 liters of polyurethane and 0.2 liters of primer. The painters also estimate that the solvents used for surface preparation are 40% of the volume of paint applied on each part, while cleanup solvents are 15% of the volume of paint applied. It is assumed that all surface preparation and cleanup solvents are applied in a wipe application and that 100% of the applied solvent evaporates. Only about 95% of polyurethane or primer in a given container can actually be applied to the parts to be painted; the remaining 5% cannot be used. Nonetheless, it should be assumed that all solvents in the waste paint evaporate to the atmosphere.

Solution - TOG

Determine the amount of polyurethane, primer, surface preparation solvent, and cleanup solvent required.

The amount of applied paint is calculated by multiplying the number of parts by the amount of polyurethane and primer required for each part.

$$\text{Applied Polyurethane} = 25{,}000 \text{ parts} \times \frac{0.8 \text{ liters}}{\text{part}} = 20{,}000 \text{ liters}$$

$$\text{Applied Primer} = 25{,}000 \text{ parts} \times \frac{0.2 \text{ liters}}{\text{part}} = 5{,}000 \text{ liters}$$

$$\text{Total Applied Paint} = 20{,}000 + 5{,}000 = 25{,}000 \text{ liters}$$

The amount of paint applied is actually only 95% of the amount of paint used. The amount of paint actually mixed is calculated below.

$$\text{Mixed Polyurethane} = \frac{20{,}000 \text{ liters}}{0.95} = 21{,}053 \text{ liters}$$

$$\text{Mixed Primer} = \frac{5{,}000 \text{ liters}}{0.95} = 5{,}263 \text{ liters}$$

The amount of preparation and cleanup solvents are calculated from the amount of paint actually applied.

$$\text{Preparation Solvent} = \frac{0.40 \text{ liters solvent}}{\text{liter paint}} \times 25{,}000 \text{ liters} = 10{,}000 \text{ liters}$$

$$\text{Cleanup Solvent} = \frac{0.15 \text{ liters solvent}}{\text{liter paint}} \times 25{,}000 \text{ liters} = 3{,}750 \text{ liters}$$

The TOG content of the polyurethane is calculated as the weighted average of the TOG content of each of the components (base, hardener, and thinner).

$$TOG_{poly} = (\%_{base} \times TOG_{base}) + (\%_{hard} \times TOG_{hard}) + (\%_{thin} \times TOG_{thin})$$
$$TOG_{poly} = (0.7 \times 520) + (0.2 \times 330) + (0.1 \times 820) = 512 \text{ grams/liter}$$

Emissions are then calculated by multiplying the quantity of each paint or solvent used by its respective TOG content.

$$Emissions_{Poly} = 21,053 \text{ liters} \times \frac{512 \text{ grams}}{liter} = 10,779 \text{ kg}$$

$$Emissions_{Primer} = 5,263 \text{ liters} \times \frac{460 \text{ grams}}{liter} = 2,421 \text{ kg}$$

$$Emissions_{Prep} = 10,000 \text{ liters} \times \frac{820 \text{ grams}}{liter} = 8,200 \text{ kg}$$

$$Emissions_{Cleanup} = 3,750 \text{ liters} \times \frac{820 \text{ grams}}{liter} = 3,075 \text{ kg}$$

$$Emissions_{TOG-Total} = 10,779 + 2,421 + 8,200 + 3,075 = 24,475 \text{ kg} = 24.5 \text{ Mg}$$

Solution - PM

Uncontrolled PM emissions can be calculated using the following equation.

$$Emissions_i = P_i \times \rho_i \times SC_i \times (1 - \eta)$$

where:

$Emissions_i$	=	Total uncontrolled emissions for surface coating, i (kg);
P_i	=	Amount of paint applied (liter);
ρ_i	=	Density of surface coating, i (g/liter);
SC_i	=	Solids content of surface coating, i (fraction); and
η	=	Transfer efficiency of application method (fraction).

First, the density and solids content of the polyurethane paint needs to be determined. Density and solids content information are taken from the material characteristics table.

$$\rho_{poly} = (\%_{base} \times \rho_{base}) + (\%_{hard} \times \rho_{hard}) + (\%_{thin} \times \rho_{thin})$$

$$\rho_{poly} = 0.7 \times 700 + 0.2 \times 750 + 0.1 \times 820 = 722 \text{ grams/liter}$$

$$SC_{poly} = \frac{\rho_{base}SC_{base}\%_{base} + \rho_{hard}SC_{hard}\%_{hard} + \rho_{thin}SC_{thin}\%_{thin}}{\rho_{poly}}$$

$$SC_{Tot} = \frac{(700)(0.31)(0.70) + (750)(0.35)(0.20) + (820)(0.00)(0.10)}{722} = 28.3\%$$

Transfer efficiencies for various application methods are presented in Table 5-4.

Table 5-4

Surface Coating Transfer Efficiencies

Application Method	Transfer Efficiency
Aerosol Spray Can	0.24
Airless Spray Equipment	0.35
Brush or Roller	0.95
Conventional Air Spray Equipment	0.30
High Volume/Low Pressure (HVLP) Spray Equipment	0.60

Source: SCAQMD, 1996

Uncontrolled PM emissions are calculated below.

$$\text{Emissions}_{\text{Poly,HVLP}} = \frac{722 \text{ grams}}{\text{liter}} \times 0.283 \times (1 - 0.60) \times 10,000 \text{ liters} = 817 \text{ kg}$$

$$\text{Emissions}_{\text{Poly,other}} = \frac{722 \text{ grams}}{\text{liter}} \times 0.283 \times (1 - 0.30) \times 10,000 \text{ liters} = 1,430 \text{ kg}$$

$$\text{Emissions}_{\text{Primer}} = \frac{680 \text{ grams}}{\text{liter}} \times 0.4 \times (1 - 0.24) \times 5,000 \text{ liters} = 1,034 \text{ kg}$$

The controlled PM emissions for the polyurethane are calculated below.

$$\text{Emissions}_{\text{Poly,cont}} = (1 - \text{CE}) \, (\text{Emissions}_{\text{Poly,HVLP}} + \text{Emissions}_{\text{Poly,other}})$$

where:　　CE　=　control efficiency

$$\text{Emissions}_{\text{Poly,cont}} = (1 - 0.90) \, (817 + 1,430) = 225 \text{ kg}$$

Finally, total combined PM emissions for the polyurethane and the primer are calculated.

$$\text{Emissions}_{\text{Total}} = 225 + 1,034 = 1,259 \text{ kg} = 1.3 \text{ Mg}$$

Solution - Zinc Compounds

Emissions of a specific species are simply calculated by multiplying overall PM emissions by the percentage of that specific species. Using this method, zinc compound emissions are calculated below.

$$\text{Emissions}_{\text{Zn,poly}} = 2\% \times 225 \text{ kg PM}_{10} = 4.5 \text{ kg}$$
$$\text{Emissions}_{\text{Zn,primer}} = 1.5\% \times 1,034 \text{ kg PM}_{10} = 15.5 \text{ kg}$$
$$\text{Emissions}_{\text{Zn,total}} = 4.5 + 15.5 = 20 \text{ kg}$$

<center>**Example 6**</center>

<center>**Point Source Stack Emissions**</center>

Introduction

Among the various emission estimating techniques, source sampling provides the most reliable emission estimates (although the costs also tend to be the highest). The reason for the high accuracy is that the effects of equipment- and process-specific parameters are actually being measured by the sampling equipment. Although source sampling can provide accurate emission estimates, sometimes much effort is required to convert sampling data into emission estimates. This example demonstrates the process of converting concentration measurements into mass emission rates.

Problem Statement

Determine the average hourly and annual emissions of NO_x from a process stack given typical stack measurements.

Available Information

The following average measurements have been collected from the stack through approved source testing methods:

Actual stack gas flow rate: 7486 cfm

Stack gas temperature:
80.0°C

Stack diameter:
0.75 m

Water vapor content: 2.1%vol

CO_2 content:
9.5%vol

NO$_x$ concentration:
48 ppmv

The remainder of the stack gas should be assumed to be air. The process operates 24 hours per day, 330 days per year.

Solution

The steps necessary to determine the daily and annual NO$_x$ emissions from this process stack with the information provided are:

1. Collect the data needed for stack gas calculations and define terms:

   Standard molar volume (V$_s$) (at 20°C):   0.024 m^3/g-mole
   Molecular weight (MW) of NO$_x$:   46 (NO$_x$ is expressed as NO$_2$ by convention)
   Standard conditions: 20°C and 760 mmHg

   Standard conditions (temperature and pressure) are often used so that all emissions are reported on the same basis. Different standard conditions may apply in different jurisdictions and for different applications.

2. Determine the metric flow rate of the stack gas (volume/unit time) at stack conditions (m^3/min):

   a. Given:

      Actual stack gas flow rate: 7486 cfm
      Stack temperature: 80.0°C

   b. Metric flow rate of stack gas at stack conditions:

$$= \left(\frac{7486 \ \text{ft}^3}{\text{min}} \right) \left(\frac{0.3048 \ \text{m}}{\text{ft}} \right)^3 = 2.12 \times 10^2 \ \frac{\text{m}^3}{\text{min}} \ \left(\text{at } 80°\text{C, stack pressure} \right)$$

3. Determine the volumetric flow rate of NO_x in the stack gas (volume/unit time):

    a. The stack gas in this example is wet (2.1% water by volume). The information given does not specify if the NO_x concentration was measured on a wet basis or a dry basis. However, from knowledge of analytical techniques, it is known that NO_x measurements are made and reported on a dry basis, therefore the dry stack gas flow rate must first be calculated.

    b. Calculate the dry stack gas volumetric flow rate:

        1. Given:

Stack gas water content:	2.1% by volume
Wet stack gas flow rate:	2.12×10^2 m³/min
	(at 80°C, stack pressure)

        2. Dry stack gas flow rate:

$$Q_{dry} = Q_{wet} \left(\frac{V_{dry}}{V_{wet}} \right)$$

where:

Q_{dry}	=	dry stack gas flow rate;
Q_{wet}	=	wet stack gas flow rate; and
V_{dry}/V_{wet}	=	fraction of air in wet stack gas.

$$= \left(\frac{2.12 \times 10^2 \text{ m}^3 \text{ stack gas (wet)}}{\text{min}} \right) \left(\frac{(1 - 0.021) \text{ m}^3 \text{ stack gas (dry)}}{1 \text{ m}^3 \text{ stack gas (wet)}} \right)$$

$$= \frac{2.08 \times 10^2 \text{ m}^3 \text{ stack gas (dry)}}{\text{min}}$$

c. Calculate NO_x flow rate:

1. Given:

NO$_x$ concentration: 48 ppmv

2. NO$_x$ flow rate:

$$Q_{NOx} = Q_{dry}C_{NOx}$$

where: Q_{NOx} = NO$_x$ flow rate;
Q_{dry} = dry stack gas flow rate; and
C_{NOx} = NO$_x$ concentration

$$\left(2.08 \times 10^2 \frac{m^3 \text{ stack gas}}{min}\right)\left(\frac{48 \text{ m}^3 \text{ NO}_x}{10^6 \text{ m}^3 \text{ stack gas}}\right) = \frac{9.98 \times 10^{-3} \text{ m}^3 \text{ NO}_x}{min} \text{ (at 80°C, stack pressure, dry basis)}$$

4. Correct the volumetric flow rate of NO$_x$ to standard conditions (20°C and 760 mmHg) using the ideal gas law.

a. For this example, it is assumed that correction is required only for temperature because the stack gas is assumed to be at 1 atmosphere (760 mmHg) due to the stack being open to the atmosphere at sea level.

b. From the ideal gas law (PV = nRT), the relationship between gas volume and gas temperature is:

$$V = nRT/P$$
$$V/T = nR/P$$

c. In this example, regardless of the temperature of the stack, the number of moles (n) of the NO$_x$ in the stack gas, gas constant (R), and pressure (P) of the stack gas are constant. Therefore, the relationship between gas volume and gas temperature can be developed as follows for any two absolute temperatures (T$_1$ and T$_2$):

$$V_1/T_1 = n_1R_1/P_1 \quad \text{and} \quad V_2/T_2 = n_2R_2/P_2$$

Since nR/P is constant, then $n_1R_1/P_1 = n_2R_2/P_2$, therefore:

$$V_1/T_1 \ = \ V_2/T_2$$

d. Solving for the unknown gas volume (V_2) at the new temperature (T_2),

$$V_2 \ = \ V_1T_2/T_1$$

e. The equation for the unknown volume flow rate (Q_2) at the new temperature (T_2) is similar,

$$Q_2 \ = \ Q_1T_2/T_1$$

f. Calculate the volume flow rate of NO_x (Q_2) at the new temperature (20°C) (absolute temperatures must be used in this calculation):

$$Q_2 \ = \ \left(9.96 \times 10^{-3} \ \frac{m^3 \ NO_x}{min} \right) \left(\frac{[20°C \ + \ 273]}{[80°C \ + \ 273]} \right) \ = \ 8.27 \times 10^{-3} \ \frac{Sm^3 \ (standard \ cubic \ meter)}{min} \ (at \ 20°C, \ 760 \ mmHg)$$

5. Determine mass flow rate and daily and annual NO_x emissions (mass/day and mass/year):

a. Given:

Volumetric flow rate of $NO_x \ = \ 8.27 \times 10^{-3} \ \dfrac{Sm^3}{min}$

V_s (standard molar volume) $= 0.024 \ \dfrac{Sm^3}{g-mole} \ (20°C, \ 760 \ mmHg)$

MW of NO_x (as NO_2) $= 46 \ \dfrac{g}{g-mole}$

Annual stack operation $= 24$ hours per day, 330 days per year

b.   Mass flow rate of NO_x:

$$M_{NO_x} = \frac{Q_{NO_x} MW_{NO_x}}{V_S}$$

where: M_{NOx} = NO_x mass flow rate;
        Q_{NOx} = NO_x volumetric flow rate;
        MW_{NOx} = NO_x molecular weight; and
        V_s =   standard molar volume

$$\left(8.27 \times 10^{-3} \frac{Sm^3\ NO_x}{min} \right) \left(\frac{1\ g\text{-mole}\ NO_x}{0.024\ Sm^3\ NO_x} \right) \left(\frac{46\ g\ NO_x}{g\text{-mole}\ NO_x} \right) = 15.8 \frac{g\ NO_x}{min}$$

c.   Hourly emissions:

$$\left(\frac{15.8\ g\ NO_x}{min} \right) \left(\frac{60\ min}{1\ hr} \right) \left(\frac{1\ kg}{10^3\ g} \right) = 0.948 \frac{kg\ NO_x}{hr}$$

d.   Annual emissions:

$$\left(\frac{0.948\ kg\ NO_x}{hr} \right) \left(\frac{24\ hr}{day} \right) \left(\frac{330\ days}{yr} \right) = 7.51 \times 10^3\ kg/yr$$
$$= 7.5\ Mg/yr$$

Example 7

Particulate Matter - Estimation of PM_{10}, $PM_{2.5}$, OC, and EC

Introduction

Particulate emissions consist of particles with a wide range of sizes. They range in size from near molecular dimensions to 100 microns in diameter. Particles with diameters greater than 100 microns do not stay suspended for any significant period of time and settle out near their point of origin. Consequently, these particles are usually not considered in air quality applications. Currently, most inventory efforts focus on PM_{10} (particulate matter with an aerodynamic diameter of less than or equal to 10 microns). However, as the focus of air quality has grown to include visibility issues, more attention has been given to $PM_{2.5}$ (particulate matter with an aerodynamic diameter of less than or equal to 2.5 microns) emissions. Visibility-related research also requires an analysis of particulate composition. The amount of light extinction caused by particulate matter is a function of its chemical composition. Particulate matter containing organic carbon (OC) or elemental carbon (EC) absorbs light; whereas, particulate matter containing other chemical compounds tends to scatter light.

Problem Statement

Estimate PM_{10}, $PM_{2.5}$, OC, and EC emissions given total suspended particulate (TSP) emissions from paved and unpaved roads.

Available Information

Using standard estimating methodologies, it has been estimated that TSP emissions are 600 Mg for paved roads and 3,000 Mg for unpaved roads within a particular inventory domain.

Solution - PM$_{10}$ and PM$_{2.5}$

Ideally, site-specific PM$_{10}$ and PM$_{2.5}$ fractions would be developed for re-entrained paved and unpaved road dust emissions in every location. However, this is often not practical. As a result, average PM$_{10}$ and PM$_{2.5}$ fractions are often used to estimate PM$_{10}$ and PM$_{2.5}$ emissions. There are several sources for these average PM$_{10}$ and PM$_{2.5}$ fractions.

The first source of PM$_{10}$ and PM$_{2.5}$ fractions is AP-42 (U.S. EPA, 1995a). The equations used to estimate re-entrained road dust emissions from paved and unpaved roads utilize particle size multipliers (PSM) (AP-42, Sections 13.2.1 and 13.2.2). These particle size multipliers are listed in Table 7-1.

Table 7-1

AP-42 Paved and Unpaved Road Dust Particle Size Multipliers

Aerodynamic Diameter of Particle	Paved Roads (g/VKT)	Unpaved Roads (dimensionless)
PM$_{30}$*	24	1
PM$_{10}$	4.6	0.36
PM$_{2.5}$	2.1	0.095

*PM$_{30}$ is sometimes termed "suspendable particulate" (SP) and is often used as a surrogate for TSP.

The PM$_{10}$ and PM$_{2.5}$ fractions (F$_{10}$ and F$_{2.5}$) are obtained by dividing the PM$_{10}$ and PM$_{2.5}$ particle size multipliers (PSM$_{10}$ and PSM$_{2.5}$) by the TSP particle size multiplier (PSM$_{TSP}$).

$$F_{10-paved} = \frac{PSM_{10-paved}}{PSM_{TSP-paved}} = \frac{4.6}{24} = 0.192$$

$$F_{2.5-paved} = \frac{PSM_{2.5-paved}}{PSM_{TSP-paved}} = \frac{2.1}{24} = 0.088$$

$$F_{10-unpaved} = \frac{PSM_{10-unpaved}}{PSM_{TSP-unpaved}} = \frac{0.36}{1} = 0.360$$

$$F_{2.5-unpaved} = \frac{PSM_{2.5-unpaved}}{PSM_{TSP-unpaved}} = \frac{0.095}{1} = 0.095$$

Another source of PM_{10} and $PM_{2.5}$ fractions is EPA's SPECIATE database (U.S. EPA, 1992). The SPECIATE database contains speciation profiles for a wide range of emission categories. Many of these profiles are composite profiles. In addition, mass fractions for different size intervals are given for each emission category. Based on composite profiles, the PM_{10} and $PM_{2.5}$ fractions (F_{10} and $F_{2.5}$) for paved and unpaved roads are given in Table 7-2.

Table 7-2

SPECIATE Paved and Unpaved Road Dust Mass Fractions

Particle Size Interval (μm)	Paved Road Fraction (SPECIATE profile 41130)	Unpaved Road Fraction (SPECIATE profile 41220)
0-2.5	0.25	0.3
0-10	0.44	0.73

Similarly, the California Air Resources Board provides its own mass fractions for different size intervals (ARB, 1996). These are given in Table 7-3.

Table 7-3

ARB Paved and Unpaved Road Dust Mass Fractions

Particle Size Interval (μm)	Paved Road Fraction	Unpaved Road Fraction
<1	0.03	0.05
1-2.5	0.05	0.08
2.5-10	0.38	0.49
>10	0.54	0.38

Because the mass fractions do not correspond to PM_{10} and $PM_{2.5}$ fractions, certain mass fractions must be summed together as demonstrated below.

For paved roads:

$$F_{2.5} = F_{<1} + F_{1-2.5} = 0.03 + 0.05 = 0.08$$
$$F_{10} = F_{<1} + F_{1-2.5} + F_{2.5-10} = 0.03 + 0.05 + 0.38 = 0.46$$

For unpaved roads:

$$F_{2.5} = F_{<1} + F_{1-2.5} = 0.05 + 0.08 = 0.13$$
$$F_{10} = F_{<1} + F_{1-2.5} + F_{2.5-10} = 0.05 + 0.08 + 0.49 = 0.62$$

After obtaining PM_{10} and $PM_{2.5}$ fractions, PM_{10} and $PM_{2.5}$ emissions are then calculated using the following equation.

$$Emissions_i = Emissions_{TSP} \times F_i$$

where:

$Emissions_i$ = Emissions of aerodynamic diameter less than i microns;

$Emissions_{TSP}$ = Emissions of total suspended particulate matter; and

F_i = Fraction of total suspended particulate matter of aerodynamic diameter less than i microns.

Because generic PM_{10} and $PM_{2.5}$ fractions are being used rather than site-specific fractions, PM_{10} and $PM_{2.5}$ emissions will be estimated using PM_{10} and $PM_{2.5}$ fractions from each of the three sources presented above. In addition, the average of the three PM_{10} and $PM_{2.5}$ fractions is used to

estimate PM_{10} and $PM_{2.5}$ emissions. All four of the estimates are presented in Table 7-4. It should be noted that none of these estimates have been identified as being better or more accurate than the others. There is still considerable uncertainty associated with paved and unpaved road emission estimates. Research is underway to improve the existing methodologies for these source categories. This example simply demonstrates how to derive PM_{10} and $PM_{2.5}$ estimates from TSP emissions.

Table 7-4

PM_{10} and $PM_{2.5}$ Emissions Calculated Using Different Size Fractions

Road Type	Pollutant	Source of Fraction	Size Fraction	TSP (Mg/yr)	Emissions (Mg/yr)
Paved	PM_{10}	AP-42	0.192	600	115.2
		SPECIATE	0.44		264
		ARB	0.46		276
		Average	0.364		218.4
	$PM_{2.5}$	AP-42	0.088	600	52.8
		SPECIATE	0.25		150
		ARB	0.08		48
		Average	0.139		83.4
Unpaved	PM_{10}	AP-42	0.36	3,000	1,080
		SPECIATE	0.73		2,190
		ARB	0.62		1,860
		Average	0.57		1,710
	$PM_{2.5}$	AP-42	0.095	3,000	285
		SPECIATE	0.30		900
		ARB	0.13		390
		Average	0.175		525

Solution - OC and EC

Like PM_{10} and $PM_{2.5}$ fractions, site-specific OC and EC fractions should be developed whenever possible in order to obtain the most accurate emission estimates. In some instances, however, detailed laboratory analysis is not possible. Generic speciation profiles must then be used. A source for generic speciation profiles is EPA's SPECIATE database. These SPECIATE speciation profiles indicate the percentage of individual compounds relative to overall particulate matter emissions. For paved and unpaved road dust, these speciation profiles include various metal species, in addition to OC and EC.

Hypothetical sampling data gives the following OC and EC fractions for paved and unpaved roads. Three samples were taken for both paved and unpaved roads. Two size fractions were sampled - fine (0-2.5 μm) and coarse (2.5-10 μm). These data are presented in Table 7-5.

Table 7-5

Hypothetical OC and EC Sampling Data

Road Type	Sample	Size Fraction	OC fraction (wt%)	EC fraction (wt%)
Paved	#1	Fine	17.27	0.72
		Coarse	12.35	0.44
	#2	Fine	19.41	0.45
		Coarse	10.89	0.60
	#3	Fine	18.54	0.63
		Coarse	11.37	0.53
	Average	Fine	18.41	0.60
		Coarse	11.54	0.52
Unpaved	#1	Fine	2.46	0.00
		Coarse	1.50	0.00
	#2	Fine	2.71	0.00
		Coarse	1.65	0.00
	#3	Fine	2.77	0.00
		Coarse	1.29	0.00
	Average	Fine	2.65	0.00
		Coarse	1.48	0.00

The OC and EC fractions (F_{OC} and F_{EC}) for $PM_{2.5}$ can be taken directly from the table above because fine particulate is defined as $PM_{2.5}$. The OC and EC fractions for PM_{10} must be calculated using a weighted average of fine and coarse OC and EC fractions. Additional sampling data (not included in the table on the previous page) indicates that paved road dust PM_{10} consists of 54 wt% coarse particulate and 46 wt% fine particulate, whereas unpaved road dust PM_{10} consists of 35 wt% coarse particulate and 65 wt% fine particulate. The weighted OC and EC fractions for PM_{10} are calculated using the following equation.

$$F_i = (F_{i,c} \times \%_c) + (F_{i,f} \times \%_f)$$

where

F_i	=	Overall fraction of species i;
$F_{i,c}$	=	Fraction of species i in coarse portion of particulate;
$\%_c$	=	Weight percent of coarse particulate;
$F_{i,f}$	=	Fraction of species i in fine portion of particulate; and
$\%_f$	=	Weight percent of fine particulate.

The weighted PM_{10} OC and EC fractions are calculated below for both paved and unpaved roads.

$$F_{OC,paved} = (11.54 \times 0.54) + (18.41 \times 0.46) = 14.70$$
$$F_{EC,paved} = (0.52 \times 0.54) + (0.60 \times 0.46) = 0.56$$
$$F_{OC,unpaved} = (1.48 \times 0.35) + (2.65 \times 0.65) = 2.24$$
$$F_{EC,unpaved} = (0.00 \times 0.35) + (0.00 \times 0.65) = 0.00$$

OC and EC emissions are calculated in Table 7-6. PM_{10} and $PM_{2.5}$ emissions are assumed to be equal to the average values calculated earlier.

Table 7-6

Calculated OC and EC Emissions

Road Type	Pollutant	Emissions (Mg/yr)	OC Fraction	OC Emissions (Mg/yr)	EC Fraction	EC Emissions (Mg/yr)
Paved	PM_{10}	218.4	0.1470	32.1	0.0056	1.2
	$PM_{2.5}$	83.4	0.1841	15.4	0.0060	0.5
Unpaved	PM_{10}	1710	0.0224	38.3	0.0000	0.0
	$PM_{2.5}$	525	0.0265	13.9	0.0000	0.0

APPENDIX A

MISCELLANEOUS DATA AND CONVERSION FACTORS

(Information in this appendix is taken from AP-42, Appendix A. Fuel parameters are for U.S.
fuels; Mexico fuels are likely to differ and should be examined carefully.)

SOME USEFUL WEIGHTS AND MEASURES

Unit Of Measure	Equivalent	
grain	0.002	ounces
gram	0.04	ounces
ounce	28.35	grams
kilogram	2.21	pounds
pound	0.45	kilograms
pound (troy)	12	ounces
ton (short)	2000	pounds
ton (long)	2240	pounds
ton (metric)	2200	pounds
ton (shipping)	40	feet^3
centimeter	0.39	inches
inch	2.54	centimeters
foot	30.48	centimeters
meter	1.09	yards
yard	0.91	meters
mile	1.61	kilometers
centimeter^2	0.16	inches^2
inch^2	6.45	centimeters^2
foot^2	0.09	meters^2
meter^2	1.2	yards^2
yard^2	0.84	meters^2
mile^2	2.59	kilometers^2
centimeter^3	0.061	inches^3
inch^3	16.39	centimeters^3
foot^3	283.17	centimeters^3
foot^3	1728	inches^3

SOME USEFUL WEIGHTS AND MEASURES (cont.)

Unit Of Measure	Equivalent	
meter^3	1.31	yeads^3
yard^3	0.77	meters^3
cord	128	feet^3
cord	4	meters^3
peck	8	quarts
bushel (dry)	4	pecks
bushel	2150.4	inches^3
gallon (U. S.)	231	inches^3
barrel	31.5	gallons
hogshead	2	barrels
township	36	miles^2
hectare	2.5	acres

MISCELLANEOUS DATA

One cubic foot of anthracite coal weighs about 53 pounds.

One cubic foot of bituminous coal weighs from 47 to 50 pounds.

One ton of coal is equivalent to two cords of wood for steam purposes.

A gallon of water (U. S. Standard) weighs 8.33 pounds and contains 231 cubic inches.

There are 9 square feet of heating surface to each square foot of grate surface.

A cubic foot of water contains 7.5 gallons and 1728 cubic inches, and weighs 62.5 lbs.

Each nominal horsepower of a boiler requires 30 to 35 pounds of water per hour.

A horsepower is equivalent to raising 33,000 pounds one foot per minute, or 550 pounds one foot per second.

To find the pressure in pounds per square inch of a column of water, multiply the height of the column in feet by 0.434.

TYPICAL PARAMETERS OF VARIOUS FUELS[a]

Type Of Fuel	Heating Value		Sulfur % (by weight)	Ash % (by weight)
	kcal	Btu		
Solid Fuels				
Bituminous Coal	7,200/kg	13,000/lb	0.6-5.4	4-20
Anthracite Coal	6,810/kg	12,300/lb	0.5-1.0	7.0-16.0
Lignite (@ 35% moisture)	3,990/kg	7,200/lb	0.7	6.2
Wood (@ 40% moisture)	2,880/kg	5,200/lb	N	1-3
Bagasse (@ 50% moisture)	2,220/kg	4,000/lb	N	1-2
Bark (@ 50% moisture)	2,492/kg	4,500/lb	N	1-3[b]
Coke, Byproduct	7,380/kg	13,300/lb	0.5-1.0	0.5-5.0
Liquid Fuels				
Residual Oil	$9.98 \times 10^6/m^3$	150,000/gal	0.5-4.0	0.05-0.1
Distillate Oil	$9.30 \times 10^6/m^3$	140,000/gal	0.2-1.0	N
Diesel	$9.12 \times 10^6/m^3$	137,000/gal	0.4	N
Gasoline	$8.62 \times 10^6/m^3$	130,000/gal	0.03-0.04	N
Kerosene	$8.32 \times 10^6/m^3$	135,000/gal	0.02-0.05	N
Liquid Petroleum Gas	$6.25 \times 10^6/m^3$	94,000/gal	N	N
Gaseous Fuels				
Natural Gas	$9,341/m^3$	1,050/SCF	N	N
Coke Oven Gas	$5,249/m^3$	590/SCF	0.5-2.0	N
Blast Furnace Gas	$890/m^3$	100/SCF	N	N

[a] N = negligible.
[b] Ash content may be considerably higher when sand, dirt, etc., are present.

THERMAL EQUIVALENTS FOR VARIOUS FUELS

Type Of Fuel	kcal	Btu (gross)
Solid fuels		
Bituminous coal	$(5.8 \text{ to } 7.8) \times 10^6/\text{Mg}$	$(21.0 \text{ to } 28.0) \times 10^6/\text{ton}$
Anthracite coal	$7.03 \times 10^6/\text{Mg}$	$25.3 \times 10^6/\text{ton}$
Lignite	$4.45 \times 10^6/\text{Mg}$	$16.0 \times 10^6/\text{ton}$
Wood	$1.47 \times 10^6/\text{m}^3$	$21.0 \times 10^6/\text{cord}$
Liquid fuels		
Residual fuel oil	$10 \times 10^3/\text{liter}$	$6.3 \times 10^6/\text{bbl}$
Distillate fuel oil	$9.35 \times 10^3/\text{liter}$	$5.9 \times 10^6/\text{bbl}$
Gaseous fuels		
Natural gas	$9,350/\text{m}^3$	$1,050/\text{ft}^3$
Liquefied petroleum gas		
Butane	$6,480/\text{liter}$	$97,400/\text{gal}$
Propane	$6,030/\text{liter}$	$90,500/\text{gal}$

WEIGHTS OF SELECTED SUBSTANCES

Type Of Substance	g/liter	lb/gal
Asphalt	1030	8.57
Butane, liquid at 60°F	579	4.84
Crude oil	850	7.08
Distillate oil	845	7.05
Gasoline	739	6.17
Propane, liquid at 60°F	507	4.24
Residual oil	944	7.88
Water	1000	8.4

DENSITIES OF SELECTED SUBSTANCES

Substance	Density	
Fuels		
Crude Oil	874 kg/m^3	7.3 lb/gal
Residual Oil	944 kg/m^3	7.88 lb/gal
Distillate Oil	845 kg/m^3	7.05 lb/gal
Gasoline	739 kg/m^3	6.17 lb/gal
Natural Gas	673 kg/m^3	1 lb/23.8 ft^3
Butane	579 kg/m^3	4.84 lb/gal (liquid)
Propane	507 kg/m^3	4.24 lb/gal (liquid)
Wood (Air dried)		
Elm	561 kg/m^3	35 lb/ft^3
Fir, Douglas	513 kg/m^3	32 lb/ft^3
Fir, Balsam	400 kg/m^3	25 lb/ft^3
Hemlock	465 kg/m^3	29 lb/ft^3
Hickory	769 kg/m^3	48 lb/ft^3
Maple, Sugar	689 kg/m^3	43 lb/ft^3
Maple, White	529 kg/m^3	33 lb/ft^3
Oak, Red	673 kg/m^3	42 lb/ft^3
Oak, White	769 kg/m^3	48 lb/ft^3
Pine, Southern	641 kg/m^3	40 lb/ft^3
Agricultural Products		
Corn	25.4 kg/bu	56 lb/bu
Milo	25.4 kg/bu	56 lb/bu
Oats	14.5 kg/bu	32 lb/bu
Barley	21.8 kg/bu	48 lb/bu
Wheat	27.2 kg/bu	60 lb/bu
Cotton	226 kg/bale	500 lb/bale
Mineral Products		
Brick	2.95 kg/brick	6.5 lb/brick
Cement	170 kg/bbl	375 lb/bbl
Cement	1483 kg/m^3	2500 lb/yd^3
Concrete	2373 kg/m^3	4000 lb/yd^3
Glass, Common	2595 kg/m^3	162 lb/ft^3
Gravel, Dry Packed	1600 - 1920 kg/m^3	100 - 120 lb/ft^3
Gravel, Wet	2020 kg/m^3	126 lb/ft^3
Gypsum, Calcined	880 - 960 kg/m^3	55 - 60 lb/ft^3
Lime, Pebble	850 - 1025 kg/m^3	53 - 64 lb/ft^3
Sand, Gravel (Dry, loose)	1440 - 1680 kg/m^3	90 - 105 lb/ft^3

CONVERSION FACTORS

The table of conversion factors on the following pages contains factors for converting English to metric units and metric to English units as well as factors to manipulate units within the same system. The factors are arranged alphabetically by unit within the following property groups.

- Area
- Density
- Energy
- Force
- Length
- Mass
- Pressure
- Velocity
- Volume
- Volumetric Rate

To convert a number from one unit to another:

1. Locate the unit in which the number is currently expressed in the left-hand column of the table;

2. Find the desired unit in the center column; and

3. Multiply the number by the corresponding conversion factor in the right-hand column.

CONVERSION FACTORS[a]

To Convert From	To	Multiply By
Area		
Acres	Sq feet	4.356×10^4
Acres	Sq kilometers	4.0469×10^{-3}
Acres	Sq meters	4.0469×10^3
Acres	Sq miles (statute)	1.5625×10^{-3}
Acres	Sq yards	4.84×10^3
Sq feet	Acres	2.2957×10^{-5}
Sq feet	Sq cm	929.03
Sq feet	Sq inches	144.0
Sq feet	Sq meters	0.092903
Sq feet	Sq miles	3.587×10^{-8}
Sq feet	Sq yards	0.111111
Sq inches	Sq feet	6.9444×10^{-3}
Sq inches	Sq meters	6.4516×10^{-4}
Sq inches	Sq mm	645.16
Sq kilometers	Acres	247.1
Sq kilometers	Sq feet	1.0764×10^7
Sq kilometers	Sq meters	1.0×10^6
Sq kilometers	Sq miles	0.386102
Sq kilometers	Sq yards	1.196×10^6
Sq meters	Sq cm	1.0×10^4
Sq meters	Sq feet	10.764
Sq meters	Sq inches	1.55×10^3
Sq meters	Sq kilometers	1.0×10^{-6}
Sq meters	Sq miles	3.861×10^{-7}
Sq meters	Sq mm	1.0×10^6
Sq meters	Sq yards	1.196
Sq miles	Acres	640.0
Sq miles	Sq feet	2.7878×10^7
Sq miles	Sq kilometers	2.590

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Sq miles	Sq meters	2.59×10^6
Sq miles	Sq yards	3.0976×10^6
Sq yards	Acres	2.0661×10^{-4}
Sq yards	Sq cm	8.3613×10^3
Sq yards	Sq ft	9.0
Sq yards	Sq inches	1.296×10^3
Sq yards	Sq meters	0.83613
Sq yards	Sq miles	3.2283×10^{-7}
Density		
Dynes/cu cm	Grams/cu cm	1.0197×10^{-3}
Grains/cu foot	Grams/cu meter	2.28835
Grams/cu cm	Dynes/cu cm	980.665
Grams/cu cm	Grains/milliliter	15.433
Grams/cu cm	Grams/milliliter	1.0
Grams/cu cm	Pounds/cu inch	1.162
Grams/cu cm	Pounds/cu foot	62.428
Grams/cu cm	Pounds/cu inch	0.036127
Grams/cu cm	Pounds/gal (Brit.)	10.022
Grams/cu cm	Pounds/gal (U. S., dry)	9.7111
Grams/cu cm	Pounds/gal (U. S., liq.)	8.3454
Grams/cu meter	Grains/cu foot	0.4370
Grams/liter	Pounds/gal (U. S.)	8.345×10^{-3}
Kilograms/cu meter	Grams/cu cm	0.001
Kilograms/cu meter	Pounds/cu ft	0.0624
Kilograms/cu meter	Pounds/cu in	3.613×10^{-5}
Pounds/cu foot	Grams/cu cm	0.016018
Pounds/cu foot	kg/cu meter	16.018
Pounds/cu inch	Grams/cu cm	27.68
Pounds/cu inch	Grams/liter	27.681
Pounds/cu inch	kg/cu meter	2.768×10^4

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Pounds/gal (U. S., liq.)	Grams/cu cm	0.1198
Pounds/gal (U. S., liq.)	Pounds/cu ft	7.4805
Energy		
Btu	Cal. gm (IST.)	251.83
Btu	Ergs	1.05435×10^{10}
Btu	Foot-pounds	777.65
Btu	Hp-hours	3.9275×10^{-4}
Btu	Joules (Int.)	1054.2
Btu	kg-meters	107.51
Btu	kW-hours (Int.)	2.9283×10^{-4}
Btu/hr	Cal. kg/hr	0.252
Btu/hr	Ergs/sec	2.929×10^{6}
Btu/hr	Foot-pounds/hr	777.65
Btu/hr	Horsepower (mechanical)	3.9275×10^{-4}
Btu/hr	Horsepower (boiler)	2.9856×10^{-5}
Btu/hr	Horsepower (electric)	3.926×10^{-4}
Btu/hr	Horsepower (metric)	3.982×10^{-4}
Btu/hr	Kilowatts	2.929×10^{-4}
Btu/lb	Foot-pounds/lb	777.65
Btu/lb	Hp-hr/lb	3.9275×10^{-4}
Btu/lb	Joules/gram	2.3244
Calories, kg (mean)	Btu (IST.)	3.9714
Calories, kg (mean)	Ergs	4.190×10^{10}
Calories, kg (mean)	Foot-pounds	3.0904×10^{3}
Calories, kg (mean)	Hp-hours	1.561×10^{-3}
Calories, kg (mean)	Joules	4.190×10^{3}
Calories, kg (mean)	kg-meters	427.26
Calories, kg (mean)	kW-hours (Int.)	1.1637×10^{-3}
Ergs	Btu	9.4845×10^{-11}
Ergs	Foot-poundals	2.373×10^{-6}

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Ergs	Foot-pounds	7.3756×10^{-8}
Ergs	Joules (Int.)	9.99835×10^{-8}
Ergs	kW-hours	2.7778×10^{-14}
Ergs	kg-meters	1.0197×10^{-8}
Foot-pounds	Btu (IST.)	1.2851×10^{-3}
Foot-pounds	Cal. kg (IST.)	3.2384×10^{-4}
Foot-pounds	Ergs	1.3558×10^{7}
Foot-pounds	Foot-poundals	32.174
Foot-pounds	Hp-hours	5.0505×10^{-7}
Foot-pounds	Joules	1.3558
Foot-pounds	kg-meters	0.138255
Foot-pounds	kW-hours (Int.)	3.76554×10^{-7}
Foot-pounds	Newton-meters	1.3558
Foot-pounds/hr	Btu/min	2.1432×10^{-5}
Foot-pounds/hr	Ergs/min	2.2597×10^{5}
Foot-pounds/hr	Horsepower (mechanical)	5.0505×10^{-7}
Foot-pounds/hr	Horsepower (metric)	5.121×10^{-7}
Foot-pounds/hr	Kilowatts	3.766×10^{-7}
Horsepower (mechanical)	Btu (mean)/hr	2.5425×10^{3}
Horsepower (mechanical)	Ergs/sec	7.457×10^{9}
Horsepower (mechanical)	Foot-pounds/hr	1.980×10^{6}
Horsepower (mechanical)	Horsepower (boiler)	0.07602
Horsepower (mechanical)	Horsepower (electric)	0.9996
Horsepower (mechanical)	Horsepower (metric)	1.0139
Horsepower (mechanical)	Joules/sec	745.70
Horsepower (mechanical)	Kilowatts (Int.)	0.74558
Horsepower (boiler)	Btu (mean)/hr	3.3446×10^{4}
Horsepower (boiler)	Ergs/sec	9.8095×10^{10}
Horsepower (boiler)	Foot-pounds/min	4.341×10^{5}
Horsepower (boiler)	Horsepower (mechanical)	13.155

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Horsepower (boiler)	Horsepower (electric)	13.15
Horsepower (boiler)	Horsepower (metric)	13.337
Horsepower (boiler)	Joules/sec	9.8095×10^3
Horsepower (boiler)	Kilowatts	9.8095
Horsepower (electric)	Btu (mean)/hr	2.5435×10^3
Horsepower (electric)	Cal. kg/hr	641.87
Horsepower (electric)	Ergs/sec	7.46×10^9
Horsepower (electric)	Foot-pounds/min	3.3013×10^4
Horsepower (electric)	Horsepower (boiler)	0.07605
Horsepower (electric)	Horsepower (metric)	1.0143
Horsepower (electric)	Joules/sec	746.0
Horsepower (electric)	Kilowatts	0.746
Horsepower (metric)	Btu (mean)/hr	2.5077×10^3
Horsepower (metric)	Ergs/sec	7.355×10^9
Horsepower (metric)	Foot-pounds/min	3.255×10^4
Horsepower (metric)	Horsepower (mechanical)	0.98632
Horsepower (metric)	Horsepower (boiler)	0.07498
Horsepower (metric)	Horsepower (electric)	0.9859
Horsepower (metric)	kg-meters/sec	75.0
Horsepower (metric)	Kilowatts	0.7355
Horsepower-hours	Btu (mean)	2.5425×10^3
Horsepower-hours	Foot-pounds	1.98×10^6
Horsepower-hours	Joules	2.6845×10^6
Horsepower-hours	kg-meters	2.73745×10^5
Horsepower-hours	kW-hours	0.7457
Joules (Int.)	Btu (IST.)	9.4799×10^{-4}
Joules (Int.)	Ergs	1.0002×10^7
Joules (Int.)	Foot-poundals	12.734
Joules (Int.)	Foot-pounds	0.73768
Joules (Int.)	kW-hours	2.778×10^{-7}

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Joules (Int.)/sec	Btu (mean)/min	0.05683
Joules (Int.)/sec	Cal. kg/min	0.01434
Joules (Int.)/sec	Horsepower	1.341×10^{-3}
Kilogram-meters	Btu (mean)	9.2878×10^{-3}
Kilogram-meters	Cal. kg (mean)	2.3405×10^{-3}
Kilogram-meters	Ergs	9.80665×10^{7}
Kilogram-meters	Foot-poundals	232.715
Kilogram-meters	Foot-pounds	7.233
Kilogram-meters	Hp-hours	3.653×10^{-6}
Kilogram-meters	Joules (Int.)	9.805
Kilogram-meters	kW-hours	2.724×10^{-6}
Kilogram-meters/sec	Watts	9.80665
Kilowatts (Int.)	Btu (IST.)/hr	3.413×10^{3}
Kilowatts (Int.)	Cal. kg (IST.)/hr	860.0
Kilowatts (Int.)	Ergs/sec	1.0002×10^{10}
Kilowatts (Int.)	Foot-poundals/min	1.424×10^{6}
Kilowatts (Int.)	Foot-pounds/min	4.4261×10^{4}
Kilowatts (Int.)	Horsepower (mechanical)	1.341
Kilowatts (Int.)	Horsepower (boiler)	0.10196
Kilowatts (Int.)	Horsepower (electric)	1.3407
Kilowatts (Int.)	Horsepower (metric)	1.3599
Kilowatts (Int.)	Joules (Int.)/hr	3.6×10^{6}
Kilowatts (Int.)	kg-meters/hr	3.6716×10^{5}
Kilowatt-hours (Int.)	Btu (mean)	3.41×10^{3}
Kilowatt-hours (Int.)	Foot-pounds	2.6557×10^{6}
Kilowatt-hours (Int.)	Hp-hours	1.341
Kilowatt-hours (Int.)	Joules (Int.)	3.6×10^{6}
Kilowatt-hours (Int.)	kg-meters	3.6716×10^{5}
Newton-meters	Gram-cm	1.01972×10^{4}
Newton-meters	kg-meters	0.101972
Newton-meters	Pound-feet	0.73756

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Force		
Dynes	Newtons	1.0×10^{-5}
Dynes	Poundals	7.233×10^{-5}
Dynes	Pounds	2.248×10^{-6}
Newtons	Dynes	1.0×10^{-5}
Newtons	Pounds (avdp.)	0.22481
Poundals	Dynes	1.383×10^{4}
Poundals	Newtons	0.1383
Poundals	Pounds (avdp.)	0.03108
Pounds (avdp.)	Dynes	4.448×10^{5}
Pounds (avdp.)	Newtons	4.448
Pounds (avdp.)	Poundals	32.174
Length		
Feet	Centimeters	30.48
Feet	Inches	12
Feet	Kilometers	3.048×10^{-4}
Feet	Meters	0.3048
Feet	Miles (statute)	1.894×10^{-4}
Inches	Centimeters	2.540
Inches	Feet	0.08333
Inches	Kilometers	2.54×10^{-5}
Inches	Meters	0.0254
Kilometers	Feet	3.2808×10^{3}
Kilometers	Meters	1000
Kilometers	Miles (statute)	0.62137
Kilometers	Yards	1.0936×10^{3}
Meters	Feet	3.2808
Meters	Inches	39.370
Micrometers	Angstrom units	1.0×10^{4}

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Micrometers	Centimeters	1.0×10^{-3}
Micrometers	Feet	3.2808×10^{-6}
Micrometers	Inches	3.9370×10^{-5}
Micrometers	Meters	1.0×10^{-6}
Micrometers	Millimeters	0.001
Micrometers	Nanometers	1000
Miles (statute)	Feet	5280
Miles (statute)	Kilometers	1.6093
Miles (statute)	Meters	1.6093×10^{3}
Miles (statute)	Yards	1760
Millimeters	Angstrom units	1.0×10^{7}
Millimeters	Centimeters	0.1
Millimeters	Inches	0.03937
Millimeters	Meters	0.001
Millimeters	Micrometers	1000
Millimeters	Mils	39.37
Nanometers	Angstrom units	10
Nanometers	Centimeters	1.0×10^{-7}
Nanometers	Inches	3.937×10^{-8}
Nanometers	Micrometers	0.001
Nanometers	Millimeters	1.0×10^{-6}
Yards	Centimeters	91.44
Yards	Meters	0.9144
Mass		
Grains	Grams	0.064799
Grains	Milligrams	64.799
Grains	Pounds (apoth. or troy)	1.7361×10^{-4}
Grains	Pounds (avdp.)	1.4286×10^{-4}
Grains	Tons (metric)	6.4799×10^{-8}
Grams	Dynes	980.67

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Grams	Grains	15.432
Grams	Kilograms	0.001
Grams	Micrograms	1×10^6
Grams	Pounds (avdp.)	2.205×10^{-3}
Grams	Tons, metric (megagrams)	1×10^{-6}
Kilograms	Grains	1.5432×10^4
Kilograms	Poundals	70.932
Kilograms	Pounds (apoth. or troy)	2.679
Kilograms	Pounds (avdp.)	2.2046
Kilograms	Tons (long)	9.842×10^{-4}
Kilograms	Tons (metric)	0.001
Kilograms	Tons (short)	1.1023×10^{-3}
Megagrams	Tons (metric)	1.0
Milligrams	Grains	0.01543
Milligrams	Grams	1.0×10^{-3}
Milligrams	Ounces (apoth. or troy)	3.215×10^{-5}
Milligrams	Ounces (avdp.)	3.527×10^{-5}
Milligrams	Pounds (apoth. or troy)	2.679×10^{-6}
Milligrams	Pounds (avdp.)	2.2046×10^{-6}
Ounces (apoth. or troy)	Grains	480
Ounces (apoth. or troy)	Grams	31.103
Ounces (apoth. or troy)	Ounces (avdp.)	1.097
Ounces (avdp.)	Grains	437.5
Ounces (avdp.)	Grams	28.350
Ounces (avdp.)	Ounces (apoth. or troy)	0.9115
Ounces (avdp.)	Pounds (apoth. or troy)	0.075955
Ounces (avdp.)	Pounds (avdp.)	0.0625
Pounds (avdp.)	Poundals	32.174
Pounds (avdp.)	Pounds (apoth. or troy)	1.2153
Pounds (avdp.)	Tons (long)	4.4643×10^{-4}

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Pounds (avdp.)	Tons (metric)	4.5359×10^{-4}
Pounds (avdp.)	Tons (short)	5.0×10^{-4}
Pounds (avdp.)	Grains	7000
Pounds (avdp.)	Grams	453.59
Pounds (avdp.)	Ounces (apoth. or troy)	14.583
Pounds (avdp.)	Ounces (avdp.)	16
Tons (long)	Kilograms	1.016×10^{3}
Tons (long)	Pounds (apoth. or troy)	2.722×10^{3}
Tons (long)	Pounds (avdp.)	2.240×10^{3}
Tons (long)	Tons (metric)	1.016
Tons (long)	Tons (short)	1.12
Tons (metric)	Grams	1.0×10^{6}
Tons (metric)	Megagrams	1.0
Tons (metric)	Pounds (apoth. or troy)	2.6792×10^{3}
Tons (metric)	Pounds (avdp.)	2.2046×10^{3}
Tons (metric)	Tons (long)	0.9842
Tons (metric)	Tons (short)	1.1023
Tons (short)	Kilograms	907.18
Tons (short)	Pounds (apoth. or troy)	2.4301×10^{3}
Tons (short)	Pounds (avdp.)	2000
Tons (short)	Tons (long)	0.8929
Tons (short)	Tons (metric)	0.9072
Pressure		
Atmospheres	cm of H_2O ($4°C$)	1.033×10^{3}
Atmospheres	Ft of H_2O ($39.2°F$)	33.8995
Atmospheres	In. of Hg ($32°F$)	29.9213
Atmospheres	kg/sq cm	1.033
Atmospheres	mm of Hg ($0°C$)	760
Atmospheres	Pounds/sq inch	14.696
Inches of Hg ($60°F$)	Atmospheres	0.03333

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Inches of Hg (60°F)	Grams/sq cm	34.434
Inches of Hg (60°F)	mm of Hg (60°F)	25.4
Inches of Hg (60°F)	Pounds/sq ft	70.527
Inches of H_2O (4°C)	Atmospheres	2.458×10^{-3}
Inches of H_2O (4°C)	In. of Hg (32°F)	0.07355
Inches of H_2O (4°C)	kg/sq meter	25.399
Inches of H_2O (4°C)	Pounds/sq ft	5.2022
Inches of H_2O (4°C)	Pounds/sq inch	0.036126
Kilograms/sq cm	Atmospheres	0.96784
Kilograms/sq cm	cm of Hg (0°C)	73.556
Kilograms/sq cm	Ft of H_2O (39.2°F)	32.809
Kilograms/sq cm	In. of Hg (32°F)	28.959
Kilograms/sq cm	Pounds/sq inch	14.223
Millimeters of Hg (0°C)	Atmospheres	1.3158×10^{-3}
Millimeters of Hg (0°C)	Grams/sq cm	1.3595
Millimeters of Hg (0°C)	Pounds/sq inch	0.019337
Pounds/sq inch	Atmospheres	0.06805
Pounds/sq inch	cm of Hg (0°C)	5.1715
Pounds/sq inch	cm of H_2O (4°C)	70.309
Pounds/sq inch	In. of Hg (32°F)	2.036
Pounds/sq inch	In. of H_2O (39.2°F)	27.681
Pounds/sq inch	kg/sq cm	0.07031
Pounds/sq inch	mm of Hg (0°C)	51.715
Velocity		
Centimeters/sec	Feet/min	1.9685
Centimeters/sec	Feet/sec	0.0328
Centimeters/sec	Kilometers/hr	0.036
Centimeters/sec	Meters/min	0.6
Centimeters/sec	Miles/hr	0.02237

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Feet/minute	cm/sec	0.508
Feet/minute	Kilometers/hr	0.01829
Feet/minute	Meters/min	0.3048
Feet/minute	Meters/sec	5.08×10^{-3}
Feet/minute	Miles/hr	0.01136
Feet/sec	cm/sec	30.48
Feet/sec	Kilometers/hr	1.0973
Feet/sec	Meters/min	18.288
Feet/sec	Miles/hr	0.6818
Kilometers/hr	cm/sec	27.778
Kilometers/hr	Feet/hr	3.2808×10^{3}
Kilometers/hr	Feet/min	54.681
Kilometers/hr	Meters/sec	0.27778
Kilometers/hr	Miles (statute)/hr	0.62137
Meters/min	cm/sec	1.6667
Meters/min	Feet/min	3.2808
Meters/min	Feet/sec	0.05468
Meters/min	Kilometers/hr	0.06
Miles/hr	cm/sec	44.704
Miles/hr	Feet/hr	5280
Miles/hr	Feet/min	88
Miles/hr	Feet/sec	1.4667
Miles/hr	Kilometers/hr	1.6093
Miles/hr	Meters/min	26.822
Volume		
Barrels (petroleum, U. S.)	Cu feet	5.6146
Barrels (petroleum, U. S.)	Gallons (U. S.)	42
Barrels (petroleum, U. S.)	Liters	158.98
Barrels (U. S., liq.)	Cu feet	4.2109
Barrels (U. S., liq.)	Cu inches	7.2765×10^{3}

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Barrels (U. S., liq.)	Cu meters	0.1192
Barrels (U. S., liq.)	Gallons (U. S., liq.)	31.5
Barrels (U. S., liq.)	Liters	119.24
Cubic centimeters	Cu feet	3.5315×10^{-5}
Cubic centimeters	Cu inches	0.06102
Cubic centimeters	Cu meters	1.0×10^{-6}
Cubic centimeters	Cu yards	1.308×10^{-6}
Cubic centimeters	Gallons (U. S., liq.)	2.642×10^{-4}
Cubic centimeters	Quarts (U. S., liq.)	1.0567×10^{-3}
Cubic feet	Cu centimeters	2.8317×10^{4}
Cubic feet	Cu meters	0.028317
Cubic feet	Gallons (U. S., liq.)	7.4805
Cubic feet	Liters	28.317
Cubic inches	Cu cm	16.387
Cubic inches	Cu feet	5.787×10^{-4}
Cubic inches	Cu meters	1.6387×10^{-5}
Cubic inches	Cu yards	2.1433×10^{-5}
Cubic inches	Gallons (U. S., liq.)	4.329×10^{-3}
Cubic inches	Liters	0.01639
Cubic inches	Quarts (U. S., liq.)	0.01732
Cubic meters	Barrels (U. S., liq.)	8.3864
Cubic meters	Cu cm	1.0×10^{6}
Cubic meters	Cu feet	35.315
Cubic meters	Cu inches	6.1024×10^{4}
Cubic meters	Cu yards	1.308
Cubic meters	Gallons (U. S., liq.)	264.17
Cubic meters	Liters	1000
Cubic yards	Bushels (Brit.)	21.022
Cubic yards	Bushels (U. S.)	21.696
Cubic yards	Cu cm	7.6455×10^{5}

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Cubic yards	Cu feet	27
Cubic yards	Cu inches	4.6656×10^4
Cubic yards	Cu meters	0.76455
Cubic yards	Gallons	168.18
Cubic yards	Gallons	173.57
Cubic yards	Gallons	201.97
Cubic yards	Liters	764.55
Cubic yards	Quarts	672.71
Cubic yards	Quarts	694.28
Cubic yards	Quarts	807.90
Gallons (U. S., liq.)	Barrels (U. S., liq.)	0.03175
Gallons (U. S., liq.)	Barrels (petroleum, U. S.)	0.02381
Gallons (U. S., liq.)	Bushels (U. S.)	0.10742
Gallons (U. S., liq.)	Cu centimeters	3.7854×10^3
Gallons (U. S., liq.)	Cu feet	0.13368
Gallons (U. S., liq.)	Cu inches	231
Gallons (U. S., liq.)	Cu meters	3.7854×10^{-3}
Gallons (U. S., liq.)	Cu yards	4.951×10^{-3}
Gallons (U. S., liq.)	Gallons (wine)	1.0
Gallons (U. S., liq.)	Liters	3.7854
Gallons (U. S., liq.)	Ounces (U. S., fluid)	128.0
Gallons (U. S., liq.)	Pints (U. S., liq.)	8.0
Gallons (U. S., liq.)	Quarts (U. S., liq.)	4.0
Liters	Cu centimeters	1000
Liters	Cu feet	0.035315
Liters	Cu inches	61.024
Liters	Cu meters	0.001
Liters	Gallons (U. S., liq.)	0.2642
Liters	Ounces (U. S., fluid)	33.814

CONVERSION FACTORS (cont.)

To Convert From	To	Multiply By
Volumetric Rate		
Cu ft/min	Cu cm/sec	471.95
Cu ft/min	Cu ft /hr	60. 0
Cu ft/min	Gal (U. S.)/min	7.4805
Cu ft/min	Liters/sec	0.47193
Cu meters/min	Gal (U. S.)/min	264.17
Cu meters/min	Liters/min	999.97
Gallons (U. S.)/hr	Cu ft/hr	0.13368
Gallons (U. S.)/hr	Cu meters/min	6.309×10^{-5}
Gallons (U. S.)/hr	Cu yd/min	8.2519×10^{-5}
Gallons (U. S.)/hr	Liters/hr	3.7854
Liters/min	Cu ft/min	0.0353
Liters/min	Gal (U. S., liq.)/min	0.2642

[a] Where appropriate, the conversion factors appearing in this table have been rounded to four to six significant figures for ease in use. The accuracy of these numbers is considered suitable for use with emissions data; if a more accurate number is required, tables containing exact factors should be consulted.

CONVERSION FACTORS FOR COMMON AIR POLLUTION MEASUREMENTS

AIRBORNE PARTICULATE MATTER

To Convert From	To	Multiply By
Milligrams/cu m	Grams/cu ft	283.2×10^{-6}
	Grams/cu m	0.001
	Micrograms/cu m	1000.0
	Micrograms/cu ft	28.32
	Pounds/1000 cu ft	62.43×10^{-6}
Grams/cu ft	Milligrams/cu m	35.3145×10^{3}
	Grams/cu m	35.314
	Micrograms/cu m	35.314×10^{6}
	Micrograms/cu ft	1.0×10^{6}
	Pounds/1000 cu ft	2.2046
Grams/cu m	Milligrams/cu m	1000.0
	Grams/cu ft	0.02832
	Micrograms/cu m	1.0×10^{6}
	Micrograms/cu ft	28.317×10^{3}
	Pounds/1000 cu ft	0.06243
Micrograms/cu m	Milligrams/cu m	0.001
	Grams/cu ft	28.317×10^{-9}
	Grams/cu m	1.0×10^{-6}
	Micrograms/cu ft	0.02832
	Pounds/1000 cu ft	62.43×10^{-9}
Micrograms/cu ft	Milligrams/cu m	35.314×10^{-3}
	Grams/cu ft	1.0×10^{-6}
	Grams/cu m	35.314×10^{-6}
	Micrograms/cu m	35.314
	Pounds/1000 cu ft	2.2046×10^{-6}
Pounds/1000 cu ft	Milligrams/cu m	16.018×10^{3}
	Grams/cu ft	0.35314
	Micrograms/cu m	16.018×10^{6}
	Grams/cu m	16.018
	Micrograms/cu ft	353.14×10^{3}

CONVERSION FACTORS FOR COMMON AIR POLLUTION MEASUREMENTS (cont.).

SAMPLING PRESSURE

To Convert From	To	Multiply By
Millimeters of mercury (0°C)	Inches of water (60°F)	0.5358
Inches of mercury (0°C)	Inches of water (60°F)	13.609
	Millimeters of mercury (0°C)	1.8663
Inches of water (60°F)	Inches of mercury (0°C)	73.48×10^{-3}

CONVERSION FACTORS FOR COMMON AIR POLLUTION MEASUREMENTS (cont.).

ATMOSPHERIC GASES

To Convert From	To	Multiply By
Milligrams/cu m	Micrograms/cu m	1000.0
	Micrograms/liter	1.0
	ppm by volume (20°C)	24.04/M
	ppm by weight	0.8347
	Pounds/cu ft	62.43×10^{-9}
Micrograms/cu m	Milligrams/cu m	0.001
	Micrograms/liter	0.001
	ppm by volume (20°C)	0.02404/M
	ppm by weight	834.7×10^{-6}
	Pounds/cu ft	62.43×10^{-12}
Micrograms/liter	Milligrams/cu m	1.0
	Micrograms/cu m	1000.0
	ppm by volume (20°C)	24.04/M
	ppm by weight	0.8347
	Pounds/cu ft	62.43×10^{-9}
ppm by volume (20°C)	Milligrams/cu m	M/24.04
	Micrograms/cu m	M/0.02404
	Micrograms/liter	M/24.04
	ppm by weight	M/28.8
	Pounds/cu ft	$M/385.1 \times 10^{6}$
ppm by weight	Milligrams/cu m	1.198
	Micrograms/cu m	1.198×10^{-3}
	Micrograms/liter	1.198
	ppm by volume (20°C)	28.8/M
	Pounds/cu ft	7.48×10^{-6}
Pounds/cu ft	Milligrams/cu m	16.018×10^{6}
	Micrograms/cu m	16.018×10^{9}
	Micrograms/liter	16.018×10^{6}
	ppm by volume (20°C)	$385.1 \times 10^{6}/M$
	ppm by weight	133.7×10^{3}

M = Molecular weight of gas.

CONVERSION FACTORS FOR COMMON AIR POLLUTION MEASUREMENTS (cont.).

VELOCITY

To Convert From	To	Multiply By
Meters/sec	Kilometers/hr	3.6
	Feet/sec	3.281
	Miles/hr	2.237
Kilometers/hr	Meters/sec	0.2778
	Feet/sec	0.9113
	Miles/hr	0.6214
Feet/sec	Meters/sec	0.3048
	Kilometers/hr	1.09728
	Miles/hr	0.6818
Miles/hr	Meters/sec	0.4470
	Kilometers/hr	1.6093
	Feet/sec	1.4667

ATMOSPHERIC PRESSURE

To Convert From	To	Multiply By
Atmospheres	Millimeters of mercury	760.0
	Inches of mercury	29.92
	Millibars	1013.2
Millimeters of mercury	Atmospheres	1.316×10^{-3}
	Inches of mercury	39.37×10^{-3}
	Millibars	1.333
Inches of mercury	Atmospheres	0.03333
	Millimeters of mercury	25.4005
	Millibars	33.35
Millibars	Atmospheres	0.00987
	Millimeters of mercury	0.75
	Inches of mercury	0.30

VOLUME EMISSIONS

To Convert From	To	Multiply By
Cubic m/min	Cubic ft/min	35.314
Cubic ft/min	Cubic m/min	0.0283

BOILER CONVERSION FACTORS

1 Megawatt	=	10.5×10^6 Btu/hr (8 to 14×10^6 Btu/hr)	NOTES: In the relationships,
1 Megawatt	=	8×10^3 lb steam/hr (6 to 11×10^3 lb steam/hr)	Megawatt is the net electric production of a steam electric power plant.
1 BHP	=	34.5 lb steam/hr	BHP is boiler horsepower.
1 BHP	=	45×10^3 Btu/hr (40 to 50×10^3 Btu/hr)	lb steam/hr is the steam production rate of the boiler.
1 lb steam/hr	=	1.4×10^3 Btu/hr (1.2 to 1.7×10^3 Btu/hr)	Btu/hr is the heat input rate to the boiler (based on the gross or high heating value of the fuel burned).

For less efficient (generally older and/or smaller) boiler operations, use the higher values expressed. For more efficient operations (generally newer and/or larger), use the lower values.

Volume	cu in	ml	liters	ounces (U. S. fl.)	gallons (U. S.)	barrels (U. S.)	cu ft
Cubic inches		16.3868	0.0163868	0.5541	4.3290×10^{-3}	1.37429×10^{-4}	5.78704×10^{-4}
Milliliters	0.061024		0.001	0.03381	2.6418×10^{-4}	8.387×10^{-6}	3.5316×10^{-5}
Liters	61.024	1000		33.8147	0.26418	8.387×10^{-3}	0.035316
Ounces (U. S. fl.)	1.80469	29.5729	0.029573		7.8125×10^{-3}	2.48×10^{-4}	1.0443×10^{-3}
Gallons (U. S.)[a]	231	3785.3	3.7853	128		0.031746	0.13368
Barrels (U. S.)	7276.5	1.1924×10^5	119.2369	4032.0	31.5		4.2109
Cubic feet	1728	2.8316×10^4	28.316	957.568	7.481	0.23743	

[a] U. S. gallon of water at 16.7°C (62°F) weighs 3.780 kg or 8.337 pounds (avoir.)

Mass	grams	kilograms	ounces (avoir.)	pounds (avoir.)	grains	tons (U. S.)	milligrams
Grams		0.001	3.527×10^{-2}	2.205×10^{-3}	15.432	1.102×10^{-6}	1000
Kilograms	1000		35.274	2.2046	15432	1.102×10^{-3}	1×10^6
Ounces (avoir.)	28.350	0.028350		0.0625	437.5	3.125×10^{-5}	2.8350×10^4
Pounds (avoir.)[a]	453.59	0.45359	16.0		7000	5.0×10^{-4}	4.5359×10^5
Grains	0.06480	6.480×10^{-5}	2.286×10^{-3}	1.429×10^{-4}		7.142×10^{-8}	64.799
Tons (U. S.)	9.072×10^5	907.19	3.200×10^4	2000	1.4×10^7		9.0718×10^8
Milligrams	0.001	1×10^{-6}	3.527×10^{-5}	2.205×10^{-6}	0.015432	1.102×10^{-9}	

[a] Mass of 27.692 cubic inches water weighed in air at 4.0°C, 760 mm mercury pressure.

Work and Energy	g cal.	kg cal.	ergs	joules	Btu	ft lb	kg meters	L-Atm	HP hours	ft poundals	kWh	Wh
Gram calories (mean)		0.001	4.186×10^7	4.186	3.9680×10^{-3}	3.0874	0.42685	0.041311	1.5593×10^{-6}	99.334	1.1628×10^{-6}	1.1628×10^{-3}
Kilogram calories	1000		4.186×10^{10}	4186	3.9680	3087.4	426.85	41.311	1.5593×10^{-3}	99334	1.1628×10^{-3}	1.1628
Ergs	2.3889×10^{-8}	2.3889×10^{-11}		1×10^{-7}	9.4805×10^{-11}	7.3756×10^{-8}	1.0197×10^{-8}	9.8689×10^{-10}	3.7251×10^{-14}	2.3730×10^{-6}	2.7778×10^{-14}	2.7778×10^{-11}
Joules	0.23889	2.3889×10^{-4}	1×10^7		9.4805×10^{-4}	0.73756	0.10197	9.8689×10^{-3}	3.7251×10^{-7}	23.730	2.7778×10^{-7}	2.7778×10^{-4}
Btu (mean)	251.98	0.25198	1.0548×10^{10}	1054.8		777.98	107.56	10.409	3.9292×10^{-4}	2.5030×10^4	2.930×10^{-4}	0.2930
Foot pounds	0.32389	3.2389×10^{-4}	1.355582×10^7	1.3558	1.28542×10^{-3}		0.13825	0.013381	5.0505×10^{-7}	32.174	3.7662×10^{-7}	3.7662×10^{-4}
Kilogram meters	2.3427	2.3427×10^{-3}	9.8066×10^7	9.8066	9.2967×10^{-3}	7.2330		0.096781	3.6529×10^{-6}	232.71	2.7241×10^{-6}	2.7241×10^{-3}
Liter atmospheres (normal)	24.206	2.4206×10^{-2}	1.0133×10^9	101.328	0.09606	74.735	10.333		3.7745×10^{-5}	2404.5	2.8164×10^{-5}	2.8164×10^{-2}
Horsepower hours	6.4130×10^5	641.30	2.6845×10^{13}	2.6845×10^6	2454.0	1.9800×10^6	2.7374×10^5	26494		6.3705×10^7	0.7457	745.7
Foot poundals	0.010067	10.067×10^{-6}	4.214402×10^5	0.04214	3.9952×10^{-5}	0.031081	4.2972×10^{-3}	4.1558×10^{-4}	1.5697×10^{-8}		1.17055×10^{-8}	1.17055×10^{-5}
Kilowatt hours	8.6001×10^5	860.01	3.6000×10^{13}	3.6000×10^6	3413.0	2.6552×10^6	3.6709×10^5	3.5529×10^4	1.3440	8.5430×10^7		1000
Watt hours	860.01	0.86001	3.6000×10^{10}	3600	3.4130	2655.3	367.09	3.5529×10^3	1.3410×10^{-3}	8.5430×10^4	0.001	

Power	watts	kW	ft lb/sec	erg/sec	Btu/min	g cm/sec	kg cal/min	HP	lumens	joules/sec	Btu/hr
Watts		0.001	0.73756	1×10^7	0.056884	1.0197×10^4	0.01433	1.341×10^{-3}	668	1	3.41304
Kilowatts	1000		737.56	1×10^{10}	56.884	1.0197×10^7	14.3334	1.3410	6.68×10^5	1000	3413.04
Foot pounds per second	1.35582	1.3558×10^{-3}		1.3558×10^7	0.077124	1.3826×10^4	0.019433	1.8182×10^{-3}	906.28	1.3558	4.6274
Ergs per second	1×10^{-7}	1×10^{-10}	7.3756×10^{-8}		5.688×10^{-9}	1.0197×10^{-3}	1.4333×10^{-9}	1.3410×10^{-10}	6.6845×10^{-5}	1×10^{-7}	3.4130×10^{-7}
Btu[a] per minute	17.580	0.017580	12.9600	1.7580×10^8		1.7926×10^5	0.2520	0.023575	11751	17.580	60
Gram centimeters per second	9.8067×10^{-5}	9.8067×10^{-8}	7.2330×10^{-5}	980.665	5.5783×10^{-6}		1.4056×10^{-6}	1.3151×10^{-7}	0.065552	9.8067×10^{-3}	3.3470×10^{-4}
Kilogram calories per minute	69.767	0.069767	51.457	6.9770×10^8	3.9685	7.1146×10^5		0.093557	46636	69.769	238.11
Horsepower (U.S.)	745.7	0.7457	550	7.457×10^9	42.4176	7.6042×10^6	10.688		498129	745.7	2545.1
Lumens	1.496×10^{-3}	1.496×10^{-6}	1.0034×10^{-3}	1.496×10^4	8.5096×10^{-5}	15.254	2.1437×10^{-5}	2.0061×10^{-6}		1.496×10^{-3}	5.1069×10^{-3}
Joules per second	1	0.001	0.73756	1×10^7	0.056884	1.0197×10^4	0.01433	1.341×10^{-3}	668		3.41304
Btu[a] per hour	0.29299	2.9299×10^{-4}	0.21610	2.9299×10^6	0.01667	2.9878×10^3	4.1997×10^{-3}	3.9291×10^{-4}	195.80	0.29299	

[a] British Thermal Units (Mean)

CONVERSION FACTORS FOR VARIOUS SUBSTANCES[a]

Type Of Substance	Conversion Factors
Fuel	
Oil	1 bbl = 159 liters (42 gal)
Natural gas	1 therm = 100,000 Btu (approx.25000 kcal)
Gaseous Pollutants	
O_3	1 ppm, volume = $1960 \mu g/m^3$
NO_2	1 ppm, volume = $1880 \mu g/m^3$
SO_2	1 ppm, volume = $2610 \mu g/m^3$
H_2S	1 ppm, volume = $1390 \mu g/m^3$
CO	1 ppm, volume = $1.14 mg/m^3$
HC (as methane)	1 ppm, volume = $0.654 mg/m^3$
Agricultural products	
Corn	1 bu = 25.4 kg = 56 lb
Milo	1 bu = 25.4 kg = 56 lb
Oats	1 bu = 14.5 kg = 32 lb
Barley	1 bu = 21.8 kg = 48 lb
Wheat	1 bu = 27.2 kg = 60 lb
Cotton	1 bale = 226 kg = 500 lb
Mineral products	
Brick	1 brick = 2.95 kg = 6.5 lb
Cement	1 bbl = 170 kg = 375 lb
Cement	1 yd^3 = 1130 kg = 2500 lb
Concrete	1 yd^3 = 1820 kg = 4000 lb
Mobile sources, fuel efficiency	
Motor vehicles	1.0 mi/gal = 0.426 km/liter
Waterborne vessels	1.0 gal/naut mi = 2.05 liters/km
Miscellaneous liquids	
Beer	1 bbl = 31.5 gal
Paint	1 gal = 4.5 to 6.82 kg = 10 to 15 lb
Varnish	1 gal = 3.18 kg = 7 lb
Whiskey	1 bbl = 190 liters = 50.2 gal
Water	1 gal = 3.81 kg = 8.3 lb

[a] Many of the conversion factors in this table represent average values and approximations and some of the values vary with temperature and pressure. These conversion factors should, however, be sufficiently accurate for general field use.

APPENDIX B

INDEX OF EXAMPLE PROBLEMS IN
MEXICO EMISSIONS INVENTORY MANUALS

Example Problems in Mexico Emissions Inventory Program Manuals

Volume III - Basic Emission Estimating Techniques

Section 3.2	Source Sampling Data
Section 3.3	CEM Data
Section 4.2.2	Multivariate Model
Section 5.10	Survey Results
Section 6.1	Process-Based Emission Factors
Section 6.2	Census-Based Emission Factors
Section 7.0	Material Balance
Section 8.0	Extrapolation
Appendix III-A	Emissions Models (fugitive dust, landfills, storage tanks, petroleum products loading, waste and wastewater)

Volume IV - Point Source Inventory Development

Section 3.1	Emission Factors
Section 3.2	Source Test Data
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Section 4.1	Fuel Analysis
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Volume V - Area Source Inventory Development

Section 4.0	Stationary Source Fuel Combustion
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Volume VI - Motor Vehicle Inventory Development

Section 3.4.1	Effects of Temperature, Altitude, Fuel RVP, Oxygenated Fuels, Inspection and Maintenance (I/M) Programs, and Anti-Tampering Programs (ATP)
Section 3.4.2	Effects of Vehicle Speed