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Supplement D
August 1998

SUPPLEMENT D

TO

COMPILATION

OF

AIR POLLUTANT

EMISSION FACTORS

VOLUME I:

STATIONARY POINT

AND AREA SOURCES

Office of Air Quality Planning and Standards
Office of Air and Radiation
U. S. Environmental Protection Agency
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Instructions for Inserting *Supplement D* of Volume I Into AP-42

Chap. 1, Sect. 1.4	Natural Gas Combustion	Replace entire	Major revision
Chap. 1, Sect. 1.6	Wood Waste Combustion in Boilers	Replace entire	Major revision
Chap. 2, Sect. 2.4	Municipal Solid Waste Landfills	Replace entire	Major revision
Chap. 4, Sect. 4.3	Waste Water Collection, Treatment and Storage	Replace entire	Minor revision
Chap. 7, Sect. 7.1	Organic Liquid Storage Tanks	Replace entire	Major revision
Chap. 8, Sect. 8.8	Nitric Acid	Replace entire	Minor revision
Chap. 9, Sect. 9.9.1	Grain Elevators and Processes	Replace entire	Major revision
Chap. 10, Sect. 10.5	Plywood Manufacturing	Replace [Work in Progress] sheet	New section
Chap. 11, Sect. 11.17	Lime Manufacturing	Replace entire	Minor revision
Chap. 12, Sect. 12.1	Primary Aluminum Production	Replace entire	Minor revision
Chap. 13, Sect. 13.2.1	Paved Roads	Replace entire	Major revision
Chap. 13, Sect. 13.2.6	Abrasive Blasting		New section
Chap. 14, Sect. 14.4	Enteric Fermentation - Greenhouse Gases		New section

Insert new Technical Report Data sheet.

This report has been reviewed by the Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, and has been approved for publication. Any mention of trade names or commercial products is not intended to constitute endorsement or recommendation for use.

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1.4 Natural Gas Combustion

1.4.1 General¹⁻²

Natural gas is one of the major combustion fuels used throughout the country. It is mainly used to generate industrial and utility electric power, produce industrial process steam and heat, and heat residential and commercial space. Natural gas consists of a high percentage of methane (generally above 85 percent) and varying amounts of ethane, propane, butane, and inerts (typically nitrogen, carbon dioxide, and helium). The average gross heating value of natural gas is approximately 1,020 British thermal units per standard cubic foot (Btu/scf), usually varying from 950 to 1,050 Btu/scf.

1.4.2 Firing Practices³⁻⁵

There are three major types of boilers used for natural gas combustion in commercial, industrial, and utility applications: watertube, firetube, and cast iron. Watertube boilers are designed to pass water through the inside of heat transfer tubes while the outside of the tubes is heated by direct contact with the hot combustion gases and through radiant heat transfer. The watertube design is the most common in utility and large industrial boilers. Watertube boilers are used for a variety of applications, ranging from providing large amounts of process steam, to providing hot water or steam for space heating, to generating high-temperature, high-pressure steam for producing electricity. Furthermore, watertube boilers can be distinguished either as field erected units or packaged units.

Field erected boilers are boilers that are constructed on site and comprise the larger sized watertube boilers. Generally, boilers with heat input levels greater than 100 MMBtu/hr, are field erected. Field erected units usually have multiple burners and, given the customized nature of their construction, also have greater operational flexibility and NO_x control options. Field erected units can also be further categorized as wall-fired or tangential-fired. Wall-fired units are characterized by multiple individual burners located on a single wall or on opposing walls of the furnace while tangential units have several rows of air and fuel nozzles located in each of the four corners of the boiler.

Package units are constructed off-site and shipped to the location where they are needed. While the heat input levels of packaged units may range up to 250 MMBtu/hr, the physical size of these units are constrained by shipping considerations and generally have heat input levels less than 100 MMBtu/hr. Packaged units are always wall-fired units with one or more individual burners. Given the size limitations imposed on packaged boilers, they have limited operational flexibility and cannot feasibly incorporate some NO_x control options.

Firetube boilers are designed such that the hot combustion gases flow through tubes, which heat the water circulating outside of the tubes. These boilers are used primarily for space heating systems, industrial process steam, and portable power boilers. Firetube boilers are almost exclusively packaged units. The two major types of firetube units are Scotch Marine boilers and the older firebox boilers. In cast iron boilers, as in firetube boilers, the hot gases are contained inside the tubes and the water being heated circulates outside the tubes. However, the units are constructed of cast iron rather than steel. Virtually all cast iron boilers are constructed as package boilers. These boilers are used to produce either low-pressure steam or hot water, and are most commonly used in small commercial applications.

Natural gas is also combusted in residential boilers and furnaces. Residential boilers and furnaces generally resemble firetube boilers with flue gas traveling through several channels or tubes with water or air circulated outside the channels or tubes.

1.4.3 Emissions³⁻⁴

The emissions from natural gas-fired boilers and furnaces include nitrogen oxides (NO_x), carbon monoxide (CO), and carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), volatile organic compounds (VOCs), trace amounts of sulfur dioxide (SO₂), and particulate matter (PM).

Nitrogen Oxides -

Nitrogen oxides formation occurs by three fundamentally different mechanisms. The principal mechanism of NO_x formation in natural gas combustion is thermal NO_x. The thermal NO_x mechanism occurs through the thermal dissociation and subsequent reaction of nitrogen (N₂) and oxygen (O₂) molecules in the combustion air. Most NO_x formed through the thermal NO_x mechanism occurs in the high temperature flame zone near the burners. The formation of thermal NO_x is affected by three furnace-zone factors: (1) oxygen concentration, (2) peak temperature, and (3) time of exposure at peak temperature. As these three factors increase, NO_x emission levels increase. The emission trends due to changes in these factors are fairly consistent for all types of natural gas-fired boilers and furnaces. Emission levels vary considerably with the type and size of combustor and with operating conditions (e.g., combustion air temperature, volumetric heat release rate, load, and excess oxygen level).

The second mechanism of NO_x formation, called prompt NO_x, occurs through early reactions of nitrogen molecules in the combustion air and hydrocarbon radicals from the fuel. Prompt NO_x reactions occur within the flame and are usually negligible when compared to the amount of NO_x formed through the thermal NO_x mechanism. However, prompt NO_x levels may become significant with ultra-low-NO_x burners.

The third mechanism of NO_x formation, called fuel NO_x, stems from the evolution and reaction of fuel-bound nitrogen compounds with oxygen. Due to the characteristically low fuel nitrogen content of natural gas, NO_x formation through the fuel NO_x mechanism is insignificant.

Carbon Monoxide -

The rate of CO emissions from boilers depends on the efficiency of natural gas combustion. Improperly tuned boilers and boilers operating at off-design levels decrease combustion efficiency resulting in increased CO emissions. In some cases, the addition of NO_x control systems such as low NO_x burners and flue gas recirculation (FGR) may also reduce combustion efficiency, resulting in higher CO emissions relative to uncontrolled boilers.

Volatile Organic Compounds -

The rate of VOC emissions from boilers and furnaces also depends on combustion efficiency. VOC emissions are minimized by combustion practices that promote high combustion temperatures, long residence times at those temperatures, and turbulent mixing of fuel and combustion air. Trace amounts of VOC species in the natural gas fuel (e.g., formaldehyde and benzene) may also contribute to VOC emissions if they are not completely combusted in the boiler.

Sulfur Oxides -

Emissions of SO₂ from natural gas-fired boilers are low because pipeline quality natural gas typically has sulfur levels of 2,000 grains per million cubic feet. However, sulfur-containing odorants are added to natural gas for detecting leaks, leading to small amounts of SO₂ emissions. Boilers combusting unprocessed natural gas may have higher SO₂ emissions due to higher levels of sulfur in the natural gas. For these units, a sulfur mass balance should be used to determine SO₂ emissions.

Particulate Matter -

Because natural gas is a gaseous fuel, filterable PM emissions are typically low. Particulate matter from natural gas combustion has been estimated to be less than 1 micrometer in size and has filterable and condensable fractions. Particulate matter in natural gas combustion are usually larger molecular weight hydrocarbons that are not fully combusted. Increased PM emissions may result from poor air/fuel mixing or maintenance problems.

Greenhouse Gases -⁶⁻¹¹

CO₂, CH₄, and N₂O emissions are all produced during natural gas combustion. In properly tuned boilers, nearly all of the fuel carbon (99.9 percent) in natural gas is converted to CO₂ during the combustion process. This conversion is relatively independent of boiler or combustor type. Fuel carbon not converted to CO₂ results in CH₄, CO, and/or VOC emissions and is due to incomplete combustion. Even in boilers operating with poor combustion efficiency, the amount of CH₄, CO, and VOC produced is insignificant compared to CO₂ levels.

Formation of N₂O during the combustion process is affected by two furnace-zone factors. N₂O emissions are minimized when combustion temperatures are kept high (above 1475°F) and excess oxygen is kept to a minimum (less than 1 percent).

Methane emissions are highest during low-temperature combustion or incomplete combustion, such as the start-up or shut-down cycle for boilers. Typically, conditions that favor formation of N₂O also favor emissions of methane.

1.4.4 Controls^{4,12}

NO_x Controls -

Currently, the two most prevalent combustion control techniques used to reduce NO_x emissions from natural gas-fired boilers are flue gas recirculation (FGR) and low NO_x burners. In an FGR system, a portion of the flue gas is recycled from the stack to the burner windbox. Upon entering the windbox, the recirculated gas is mixed with combustion air prior to being fed to the burner. The recycled flue gas consists of combustion products which act as inerts during combustion of the fuel/air mixture. The FGR system reduces NO_x emissions by two mechanisms. Primarily, the recirculated gas acts as a diluent to reduce combustion temperatures, thus suppressing the thermal NO_x mechanism. To a lesser extent, FGR also reduces NO_x formation by lowering the oxygen concentration in the primary flame zone. The amount of recirculated flue gas is a key operating parameter influencing NO_x emission rates for these systems. An FGR system is normally used in combination with specially designed low NO_x burners capable of sustaining a stable flame with the increased inert gas flow resulting from the use of FGR. When low NO_x burners and FGR are used in combination, these techniques are capable of reducing NO_x emissions by 60 to 90 percent.

Low NO_x burners reduce NO_x by accomplishing the combustion process in stages. Staging partially delays the combustion process, resulting in a cooler flame which suppresses thermal NO_x formation. The two most common types of low NO_x burners being applied to natural gas-fired boilers are staged air burners and staged fuel burners. NO_x emission reductions of 40 to 85 percent (relative to uncontrolled emission levels) have been observed with low NO_x burners.

Other combustion control techniques used to reduce NO_x emissions include staged combustion and gas reburning. In staged combustion (e.g., burners-out-of-service and overfire air), the degree of staging is a key operating parameter influencing NO_x emission rates. Gas reburning is similar to the use of overfire

in the use of combustion staging. However, gas reburning injects additional amounts of natural gas in the upper furnace, just before the overfire air ports, to provide increased reduction of NO_x to NO₂.

Two postcombustion technologies that may be applied to natural gas-fired boilers to reduce NO_x emissions are selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR). The SNCR system injects ammonia (NH₃) or urea into combustion flue gases (in a specific temperature zone) to reduce NO_x emission. The Alternative Control Techniques (ACT) document for NO_x emissions from utility boilers, maximum SNCR performance was estimated to range from 25 to 40 percent for natural gas-fired boilers.¹⁴ Performance data available from several natural gas fired utility boilers with SNCR show a 24 percent reduction in NO_x for applications on wall-fired boilers and a 13 percent reduction in NO_x for applications on tangential-fired boilers.¹³ In many situations, a boiler may have an SNCR system installed to trim NO_x emissions to meet permitted levels. In these cases, the SNCR system may not be operated to achieve maximum NO_x reduction. The SCR system involves injecting NH₃ into the flue gas in the presence of a catalyst to reduce NO_x emissions. No data were available on SCR performance on natural gas fired boilers at the time of this publication. However, the ACT Document for utility boilers estimates NO_x reduction efficiencies for SCR control ranging from 80 to 90 percent.¹⁴

Emission factors for natural gas combustion in boilers and furnaces are presented in Tables 1.4-1, 1.4-2, 1.4-3, and 1.4-4.¹³ Tables in this section present emission factors on a volume basis (lb/10⁶ scf). To convert to an energy basis (lb/MMBtu), divide by a heating value of 1,020 MMBtu/10⁶ scf. For the purposes of developing emission factors, natural gas combustors have been organized into three general categories: large wall-fired boilers with greater than 100 MMBtu/hr of heat input, boilers and residential furnaces with less than 100 MMBtu/hr of heat input, and tangential-fired boilers. Boilers within these categories share the same general design and operating characteristics and hence have similar emission characteristics when combusting natural gas.

Emission factors are rated from A to E to provide the user with an indication of how “good” the factor is, with “A” being excellent and “E” being poor. The criteria that are used to determine a rating for an emission factor can be found in the Emission Factor Documentation for AP-42 Section 1.4 and in the introduction to the AP-42 document.

1.4.5 Updates Since the Fifth Edition

The Fifth Edition was released in January 1995. Revisions to this section are summarized below. For further detail, consult the Emission Factor Documentation for this section. These and other documents can be found on the Emission Factor and Inventory Group (EFIG) home page (<http://www.epa.gov/oar/oaqps/efig>).

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- Text was revised concerning Firing Practices, Emissions, and Controls.
- All emission factors were updated based on 482 data points taken from 151 source tests. Many new emission factors have been added for speciated organic compounds, including hazardous air pollutants.

Table 1.4-1. EMISSION FACTORS FOR NITROGEN OXIDES (NO_x) AND CARBON MONOXIDE (CO)
FROM NATURAL GAS COMBUSTION^a

Combustor Type (MMBtu/hr Heat Input) [SCC]	NO _x ^b		CO	
	Emission Factor (lb/10 ⁶ scf)	Emission Factor Rating	Emission Factor (lb/10 ⁶ scf)	Emission Factor Rating
Large Wall-Fired Boilers (>100) [1-01-006-01, 1-02-006-01, 1-03-006-01]				
Uncontrolled (Pre-NSPS) ^c	280	A	84	B
Uncontrolled (Post-NSPS) ^c	190	A	84	B
Controlled - Low NO _x burners	140	A	84	B
Controlled - Flue gas recirculation	100	D	84	B
Small Boilers (<100) [1-01-006-02, 1-02-006-02, 1-03-006-02, 1-03-006-03]				
Uncontrolled	100	B	84	B
Controlled - Low NO _x burners	50	D	84	B
Controlled - Low NO _x burners/Flue gas recirculation	32	C	84	B
Tangential-Fired Boilers (All Sizes) [1-01-006-04]				
Uncontrolled	170	A	24	C
Controlled - Flue gas recirculation	76	D	98	D
Residential Furnaces (<0.3) [No SCC]				
Uncontrolled	94	B	40	B

^a Reference 13. Units are in pounds of pollutant per million standard cubic feet of natural gas fired. To convert from lb/10⁶ scf to kg/10⁶ m³, multiply by 16. Emission factors in this table may be converted to other natural gas heating value of 1,020 Btu/scf. To convert from lb/10⁶ scf to lb/MMBtu, divide by 1,020. The heating value to this average heating value. SCC = Source Classification Code. ND = no data. NA = not applicable.

^b Expressed as NO_x. For large and small wall fired boilers with SNCR control, apply a 24 percent reduction to the appropriate NO_x emission factor. For tangential-fired boilers with SNCR control, apply a 13 percent reduction to the appropriate NO_x emission factor.

^c NSPS=New Source Performance Standard as defined in 40 CFR 60 Subparts D and Db. Post-NSPS units are boilers with greater than 250 MMBtu/hr of heat input that commenced construction modification, or reconstruction after August 17, 1971, and units with heat input capacities between 100 and 250 MMBtu/hr that commenced construction modification, or reconstruction after June 19, 1984.

TABLE 1.4-2. EMISSION FACTORS FOR CRITERIA POLLUTANTS AND GREENHOUSE GASES FROM NATURAL GAS COMBUSTION^a

Pollutant	Emission Factor (lb/10 ⁶ scf)	Emission Factor Rating
CO ₂ ^b	120,000	A
Lead	0.0005	D
N ₂ O (Uncontrolled)	2.2	E
N ₂ O (Controlled-low-NO _x burner)	0.64	E
PM (Total) ^c	7.6	D
PM (Condensable) ^c	5.7	D
PM (Filterable) ^c	1.9	B
SO ₂ ^d	0.6	A
TOC	11	B
Methane	2.3	B
VOC	5.5	C

^a Reference 13. Units are in pounds of pollutant per million standard cubic feet of natural gas fired. Data are for all natural gas combustion sources. To convert from lb/10⁶ scf to kg/10⁶ m³, multiply by 16. To convert from lb/10⁶ scf to lb/MMBtu, divide by 1,020. The emission factors in this table may be converted to other natural gas heating values by multiplying the given emission factor by the ratio of the specified heating value to this average heating value. TOC = Total Organic Compounds. VOC = Volatile Organic Compounds.

^b Based on approximately 100% conversion of fuel carbon to CO₂. CO₂[lb/10⁶ scf] = (3.67) (CON) (C)(D), where CON = fractional conversion of fuel carbon to CO₂, C = carbon content of fuel by weight (0.76), and D = density of fuel, 4.2x10⁴ lb/10⁶ scf.

^c All PM (total, condensable, and filterable) is assumed to be less than 1.0 micrometer in diameter. Therefore, the PM emission factors presented here may be used to estimate PM₁₀, PM_{2.5} or PM₁ emissions. Total PM is the sum of the filterable PM and condensable PM. Condensable PM is the particulate matter collected using EPA Method 202 (or equivalent). Filterable PM is the particulate matter collected on, or prior to, the filter of an EPA Method 5 (or equivalent) sampling train.

^d Based on 100% conversion of fuel sulfur to SO₂. Assumes sulfur content is natural gas of 2,000 grains/10⁶ scf. The SO₂ emission factor in this table can be converted to other natural gas sulfur contents by multiplying the SO₂ emission factor by the ratio of the site-specific sulfur content (grains/10⁶ scf) to 2,000 grains/10⁶ scf.

TABLE 1.4-3. EMISSION FACTORS FOR SPECIATED ORGANIC COMPOUNDS FROM NATURAL GAS COMBUSTION^a

CAS No.	Pollutant	Emission Factor (lb/10 ⁶ scf)	Emission Factor Rating
91-57-6	2-Methylnaphthalene ^{b, c}	2.4E-05	D
56-49-5	3-Methylchloranthrene ^{b, c}	<1.8E-06	E
	7,12-Dimethylbenz(a)anthracene ^{b, c}	<1.6E-05	E
83-32-9	Acenaphthene ^{b, c}	<1.8E-06	E
203-96-8	Acenaphthylene ^{b, c}	<1.8E-06	E
120-12-7	Anthracene ^{b, c}	<2.4E-06	E
56-55-3	Benz(a)anthracene ^{b, c}	<1.8E-06	E
71-43-2	Benzene ^b	2.1E-03	B
50-32-8	Benzo(a)pyrene ^{b, c}	<1.2E-06	E
205-99-2	Benzo(b)fluoranthene ^{b, c}	<1.8E-06	E
191-24-2	Benzo(g,h,i)perylene ^{b, c}	<1.2E-06	E
205-82-3	Benzo(k)fluoranthene ^{b, c}	<1.8E-06	E
106-97-8	Butane	2.1E+00	E
218-01-9	Chrysene ^{b, c}	<1.8E-06	E
53-70-3	Dibenzo(a,h)anthracene ^{b, c}	<1.2E-06	E
25321-22-6	Dichlorobenzene ^b	1.2E-03	E
74-84-0	Ethane	3.1E+00	E
206-44-0	Fluoranthene ^{b, c}	3.0E-06	E
86-73-7	Fluorene ^{b, c}	2.8E-06	E
50-00-0	Formaldehyde ^b	7.5E-02	B
110-54-3	Hexane ^b	1.8E+00	E
193-39-5	Indeno(1,2,3-cd)pyrene ^{b, c}	<1.8E-06	E
91-20-3	Naphthalene ^b	6.1E-04	E
109-66-0	Pentane	2.6E+00	E
85-01-8	Phenanthrene ^{b, c}	1.7E-05	D

TABLE 1.4-3. EMISSION FACTORS FOR SPECIATED ORGANIC COMPOUNDS FROM
NATURAL GAS COMBUSTION (Continued)

CAS No.	Pollutant	Emission Factor (lb/10 ⁶ scf)	Emission Factor Rating
74-98-6	Propane	1.6E+00	E
129-00-0	Pyrene ^{b, c}	5.0E-06	E
108-88-3	Toluene ^b	3.4E-03	C

^a Reference 13. Units are in pounds of pollutant per million standard cubic feet of natural gas fired. Data are for all natural gas combustion sources. To convert from lb/10⁶ scf to kg/10⁶ m³, multiply by 16. To convert from lb/10⁶ scf to lb/MMBtu, divide by 1,020. Emission Factors preceded with a less-than symbol are based on method detection limits.

^b Hazardous Air Pollutant (HAP) as defined by Section 112(b) of the Clean Air Act.

^c HAP because it is Polycyclic Organic Matter (POM). POM is a HAP as defined by Section 112(b) of the Clean Air Act.

TABLE 1.4-4. EMISSION FACTORS FOR METALS FROM NATURAL GAS COMBUSTION^a

CAS No.	Pollutant	Emission Factor (lb/10 ⁶ scf)	Emission Factor Rating
7440-38-2	Arsenic ^b	2.0E-04	E
7440-39-3	Barium	4.4E-03	D
7440-41-7	Beryllium ^b	<1.2E-05	E
7440-43-9	Cadmium ^b	1.1E-03	D
7440-47-3	Chromium ^b	1.4E-03	D
7440-48-4	Cobalt ^b	8.4E-05	D
7440-50-8	Copper	8.5E-04	C
7439-96-5	Manganese ^b	3.8E-04	D
7439-97-6	Mercury ^b	2.6E-04	D
7439-98-7	Molybdenum	1.1E-03	D
7440-02-0	Nickel ^b	2.1E-03	C
7782-49-2	Selenium ^b	<2.4E-05	E
7440-62-2	Vanadium	2.3E-03	D
7440-66-6	Zinc	2.9E-02	E

^a Reference 13. Units are in pounds of pollutant per million standard cubic feet of natural gas fired. Data are for all natural gas combustion sources. Emission factors preceded by a less-than symbol are based on method detection limits. To convert from lb/10⁶ scf to kg/10⁶ m³, multiply by 16. To convert from lb/10⁶ scf to lb/MMBtu, divide by 1,020.

^b Hazardous Air Pollutant as defined by Section 112(b) of the Clean Air Act.

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11. *Emission Factor Documentation for AP-42 Section 1.4— Natural Gas Combustion*, Technical Support Division, Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1997.
12. *Alternate Control Techniques Document - NO_x Emissions from Utility Boilers* , EPA-453/R-94-023, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1994.

1.6 Wood Waste Combustion In Boilers

1.6.1 General¹⁻⁵

The burning of wood waste in boilers is mostly confined to those industries where it is available as a byproduct. It is burned both to obtain heat energy and to alleviate possible solid waste disposal problems. In boilers, wood waste is normally burned in the form of hogged wood, bark, sawdust, shavings, chips, mill rejects, sanderdust, or wood trim. Heating values for this waste range from about 4,000 to 5,000 British thermal units/pound (Btu/lb) of fuel on a wet, as-fired basis. The moisture content of as-fired wood is typically near 50 weight percent, but may vary from 5 to 75 weight percent depending on the waste type and storage operations.

Generally, bark is the major type of waste burned in pulp mills; either a mixture of wood and bark waste or wood waste alone is burned most frequently in the lumber, furniture, and plywood industries. As of 1980, there were approximately 1,600 wood-fired boilers operating in the U. S., with a total capacity of over 1.0×10^{11} Btu/hour.

1.6.2 Firing Practices⁵⁻⁷

Various boiler firing configurations are used for burning wood waste. One common type of boiler used in smaller operations is the Dutch oven. This unit is widely used because it can burn fuels with very high moisture content. Fuel is fed into the oven through an opening in the top of a refractory-lined furnace. The fuel accumulates in a cone-shaped pile on a flat or sloping grate. Combustion is accomplished in two stages: (1) drying and gasification, and (2) combustion of gaseous products. The first stage takes place in the primary furnace, which is separated from the secondary furnace chamber by a bridge wall. Combustion is completed in the secondary chamber before gases enter the boiler section. The large mass of refractory helps to stabilize combustion rates but also causes a slow response to fluctuating steam demand.

In another boiler type, the fuel cell oven, fuel is dropped onto suspended fixed grates and is fired in a pile. Unlike the Dutch oven, the refractory-lined fuel cell also uses combustion air preheating and positioning of secondary and tertiary air injection ports to improve boiler efficiency. Because of their overall design and operating similarities, however, fuel cell and Dutch oven boilers have comparable emission characteristics.

The firing method most commonly employed for wood-fired boilers with a steam generation rate larger than 100,000 lb/hr is the spreader stoker. In this boiler type, wood enters the furnace through a fuel chute and is spread either pneumatically or mechanically across the furnace, where small pieces of the fuel burn while in suspension. Simultaneously, larger pieces of fuel are spread in a thin, even bed on a stationary or moving grate. The burning is accomplished in three stages in a single chamber: (1) moisture evaporation; (2) distillation and burning of volatile matter; and (3) burning of fixed carbon. This type of boiler has a fast response to load changes, has improved combustion control, and can be operated with multiple fuels. Natural gas, oil, and/or coal, are often fired in spreader stoker boilers as auxiliary fuels. The fossil fuels are fired to maintain constant steam when the wood waste moisture content or mass rate fluctuates and/or to provide more steam than can be generated from the waste supply alone. Although spreader stokers are the most common stokers among larger wood-fired boilers, overfeed and underfeed stokers are also utilized for smaller units.

Another boiler type sometimes used for wood combustion is the suspension-fired boiler. This boiler differs from a spreader stoker in that small-sized fuel (normally less than 2 mm) is blown into the boiler and combusted by supporting it in air rather than on fixed grates. Rapid changes in combustion rate and, therefore, steam generation rate are possible because the finely divided fuel particles burn very quickly.

A recent innovation in wood firing is the fluidized bed combustion (FBC) boiler. A fluidized bed consists of inert particles through which air is blown so that the bed behaves as a fluid. Wood waste enters in the space above the bed and burns both in suspension and in the bed. Because of the large thermal mass represented by the hot inert bed particles, fluidized beds can handle fuels with moisture contents up to near 70 percent (total basis). Fluidized beds can also handle dirty fuels (up to 30 percent inert material). Wood fuel is pyrolyzed faster in a fluidized bed than on a grate due to its immediate contact with hot bed material. As a result, combustion is rapid and results in nearly complete combustion of the organic matter, thereby minimizing the emissions of unburned organic compounds.

1.6.3 Emissions And Controls⁶⁻¹¹

The major emission of concern from wood boilers is particulate matter (PM), although other pollutants, particularly carbon monoxide (CO), volatile organic compounds (VOC), and oxides of nitrogen (NO_x) may be emitted in significant quantities when certain types of wood waste are combusted or when operating conditions are poor. These emissions depend on a number of variables, including (1) the composition of the waste fuel burned, (2) furnace design and operating conditions, and (3) the degree of flyash reinjection employed.

1.6.3.1 Criteria Pollutants

The composition of wood waste and the characteristics of the resulting emissions depend largely on the industry from which the wood waste originates. Pulping operations, for example, produce great quantities of bark that may contain more than 70 weight percent moisture, sand, and other non-combustibles. As a result, bark boilers in pulp mills may emit considerable amounts of particulate matter to the atmosphere unless they are controlled. On the other hand, some operations, such as furniture manufacturing, generate a clean, dry wood waste (2 to 20 weight percent moisture) which produces relatively low particulate emission levels when properly burned. Still other operations, such as sawmills, burn a varying mixture of bark and wood waste that results in PM emissions somewhere between these two extremes. Additionally, NO_x emissions from bark boilers are typically low in comparison to NO_x emissions from sanderdust-fired boilers at urea formaldehyde process particleboard plants.

Furnace design and operating conditions are particularly important when firing wood waste. For example, because of the high moisture content that may be present in wood waste, a larger than usual area of refractory surface is often necessary to dry the fuel before combustion. In addition, sufficient secondary air must be supplied over the fuel bed to burn the volatiles that account for most of the combustible material in the waste. When proper drying conditions do not exist, or when secondary combustion is incomplete, the combustion temperature is lowered, and increased PM, CO, and organic compound emissions may result. Significant variations in fuel moisture content can cause short-term emissions to fluctuate.

Flyash reinjection, which is commonly used with larger boilers to improve fuel efficiency, has a considerable effect on PM emissions. Because a fraction of the collected flyash is reinjected into the boiler, the dust loading from the furnace and, consequently, from the collection device increase significantly per unit of wood waste burned. More recent boiler installations typically separate the collected particulate into

large and small fractions in sand classifiers. The larger particles, which are mostly carbon, are reinjected into the furnace. The smaller particles, mostly inorganic ash and sand, are sent to ash disposal.

1.6.3.2 Greenhouse Gases¹²⁻¹⁷

Carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emissions are all produced during wood waste combustion. Nearly all of the fuel carbon (99 percent) in wood waste is converted to CO₂ during the combustion process. This conversion is relatively independent of firing configuration. Although the formation of CO acts to reduce CO₂ emissions, the amount of CO produced is insignificant compared to the amount of CO₂ produced. The majority of the fuel carbon not converted to CO₂ is due to incomplete combustion and is entrained in the bottom ash. CO₂ emitted from this source may not increase total atmospheric CO₂, however, because emissions may be offset by the offtake of CO₂ by regrowing biomass.

Formation of N₂O during the combustion process is governed by a complex series of reactions and its formation is dependent upon many factors. Formation of N₂O is minimized when combustion temperatures are kept high (above 1475°F) and excess air is kept to a minimum (less than 1 percent). N₂O emissions for wood waste combustion are not significant except for fluidized bed combustion (FBC), where localized areas of lower temperatures in the fuel bed produce N₂O emissions an order of magnitude greater than emissions from stokers.

Methane emissions are highest during periods of low-temperature combustion or incomplete combustion, such as the start-up or shut-down cycle for boilers. Typically, conditions that favor formation of N₂O also favor emissions of CH₄.

1.6.4 Controls

Currently, the four most common control devices used to reduce PM emissions from wood-fired boilers are mechanical collectors, wet scrubbers, electrostatic precipitators (ESPs), and fabric filters. The use of multitube cyclone (or multiclone) mechanical collectors provides particulate control for many fuel-fired boilers. Often, two multiclones are used in series, allowing the first collector to remove the bulk of the dust and the second to remove smaller particles. The efficiency of this arrangement varies from 65 to 95 percent. The most widely used wet scrubbers for wood-fired boilers are venturi scrubbers. With gas-side pressure drops exceeding 15 inches of water, particulate collection efficiencies of 90 percent or greater have been reported for venturi scrubbers operating on wood-fired boilers.

Fabric filters (i. e., baghouses) and ESPs are employed when collection efficiencies above 95 percent are required. When applied to wood-fired boilers, ESPs are often used downstream of mechanical collector precleaners which remove larger-sized particles. Collection efficiencies of 93 to 99.8 percent for PM have been observed for ESPs operating on wood-fired boilers.

A variation of the ESP is the electrostatic gravel bed filter. In this device, PM in flue gases is removed by impaction with gravel media inside a packed bed; collection is augmented by an electrically charged grid within the bed. Particulate collection efficiencies are typically near 95 percent.

Fabric filters have had limited applications to wood-fired boilers. The principal drawback to fabric filtration, as perceived by potential users, is a fire danger arising from the collection of combustible carbonaceous fly ash. Steps can be taken to reduce this hazard, including the installation of a mechanical collector upstream of the fabric filter to remove large burning particles of fly ash (i. e., "sparklers"). Despite complications, fabric filters are generally preferred for boilers firing salt-laden wood. This fuel produces fine particulates with a high salt content. Fabric filters are capable of high fine particle collection efficiencies; in addition, the salt content of the particles has a quenching effect, thereby reducing fire

hazards. In two tests of fabric filters operating on salt-laden wood-fired boilers, particulate collection efficiencies were above 98 percent.

For stoker and FBC boilers, overfire air ports may be used to lower NO_x emissions by staging the combustion process. In those areas of the U. S. where NO_x emissions must be reduced to their lowest levels, the application of selective noncatalytic reduction (SNCR) to waste wood-fired boilers has been accomplished; the application of selective catalytic reduction (SCR) is being contemplated. Both systems are postcombustion NO_x reduction techniques in which ammonia (or urea) is injected into the flue gas to selectively reduce NO_x to nitrogen and water. In one application of SNCR to an industrial wood-fired boiler, NO_x reduction efficiencies varied between 35 and 75 percent as the ammonia-to-NO_x ratio increased from 0.4 to 3.2.

Emission factors and emission factor ratings for wood waste boilers are summarized in Tables 1.6-1, 1.6-2, 1.6-3, 1.6-4, and 1.6-5.¹⁸⁻¹⁹ Tables in this section present emission factors on a weight basis (lb/ton). To convert to an energy basis (lb/MMBtu), divide by a heating value of 9.0 MMBtu/ton. Emission factors are for uncontrolled combustors unless otherwise indicated. Cumulative particle size distribution data and associated emission factors are presented in Tables 1.6-6 and 1.6-7. Uncontrolled and controlled size-specific emission factors are plotted in Figure 1.6-1 and Figure 1.6-2. All emission factors presented are based on the feed rate of wet, as-fired wood with average properties of 50 weight percent moisture and 4500 Btu/lb higher heating values.

1.6.5 Updates Since the Fifth Edition

The Fifth Edition was released in January 1995. Revisions to this section since that date are summarized below. For further detail, consult the memoranda describing each supplement or the background report for this section. These and other documents can be found on the CHIEF electronic bulletin board (919-541-5742), or on the new EFIG home page (<http://www.epa.gov/oar/oaqps/efig/>).

Supplement A, February 1996

- Significant figures were added to some PM and PM-10 emission factors.
- In the table with NO_x and CO emission factors, text was added in the footnotes to clarify meaning.

Supplement B, October 1996

- SO_x, CH₄, N₂O, CO₂, speciated organics, and trace elements emission factors were corrected.
- Several HAP emission factors were updated.

Supplement D, February 1998

- Table 1.6-1, the PM-10 and one PM emission factors were revised to present two significant figures and the PM-10 emission factor for wood-fired boilers with mechanical collectors without flyash reinjection was revised to 2.6 lb/ton to reflect that these values are based on wood with 50% moisture. A typographical error in the wet scrubber emission factor for PM-10 was corrected.

- Table 1.6-2, the SO_x emission factors for all boiler categories were revised to 0.075 lb/ton to reflect that these factors are based on wood with 50% moisture.
- Tables 1.6-4 and 1.6-5 were re-titled to reflect that the speciated organic and trace element analysis presented in these tables are compiled from wood-fired boilers equipped with a variety of PM control technologies.

Supplement D, August 1998

- Table 1.6-4, the emission factor for trichlorotrifluoroethane was removed. The phenol emission factor was corrected to 1.47E-04; the phenanthrene factor was corrected to 5.02E-05; the chrysene factor was corrected to 4.52E-07; and, the polychlorinated dibenzo-p-furans factor was corrected to 2.9E-08.

Table 1.6-1. EMISSION FACTORS FOR PARTICULATE MATTER (PM), PARTICULATE MATTER LESS THAN 10 MICRONS (PM-10), AND LEAD (Pb) FROM WOOD WASTE COMBUSTION^a

Source Category (SCC)	PM ^b		PM-10 ^c		Pb ^d	
	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
Bark-fired boilers (1-01-009-01, 1-02-009-01, 1-02-009-04, 1-03-009-01)						
Uncontrolled	47	B	17	D	2.9 E-03	D
Mechanical collector with flyash reinjection without flyash reinjection	14 9.0	B B	11 3.2	D D	ND ND	NA NA
Wet scrubber	2.9	D	2.5	D	ND	NA
Wood/bark-fired boilers (1-01-009-02, 1-02-009-02, 1-02-009-05, 1-03-009-02)						
Uncontrolled	7.2	C	6.5	E	ND	NA
Mechanical collector with flyash reinjection without flyash reinjection	6.0 5.4	C C	5.5 1.7	E E	3.2 E-04 ^e 3.2 E-04 ^e	D D
Wet scrubber	0.48	D	0.47	E	3.5 E-04	D
Electrostatic precipitator	0.04	D	ND	NA	1.6 E-05	D
Wood-fired boilers (1-01-009-03, 1-02-009-03, 1-02-009-06, 1-03-009-03)						
Uncontrolled	8.8	C	ND	NA	ND	NA
Mechanical collector without flyash reinjection	4.2	C	2.6 ^f	D	3.1 E-04	D
Electrostatic precipitator	0.17	D	ND	NA	1.1 E-03	D

^a Units are lb of pollutant/ton of wood waste burned. To convert from lb/ton to kg/Mg, multiply by 0.5. To convert from lb/ton to lb/MMBtu, multiply by 0.11. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight % moisture and 4500 Btu/lb higher heating value. Before applying the factors to wood with moisture content other than 50%, or with a Btu content other than 4500 Btu/lb, multiply the factor by the appropriate ratio: (100-M)/50, where M is the percent moisture; (H/4500), where H is the Btu/lb. PM-10 = particulate matter less than 10 micrometers. SCC = Source Classification Code. ND = no data. NA = not applicable.

^b References 1,1,20-24.

^c References 1,21,25.

^d References 1,21-23,26.

^e Due to lead's relative volatility, it is assumed that flyash reinjection does not have a significant effect on lead emissions following mechanical collectors.

^f Based on one test in which 61% of emitted PM was less than 10 micrometer in size.

Table 1.6-2. EMISSION FACTORS FOR NITROGEN OXIDES (NO_x), SULFUR OXIDES (SO_x), AND CARBON MONOXIDE (CO) FROM WOOD WASTE COMBUSTION^a

Source Category (SCC)	NO _x ^b		SO _x ^c		CO ^d	
	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
Fuel cell/Dutch oven boiler (no SCC)	0.38 (0.0033 - 1.5)	C	0.075 (0.01 - 0.2)	B	6.6 (0.65 - 21)	C
Stoker boilers (no SCC)	1.5 (0.66 - 3.6)	C	0.075 (0.01 - 0.2)	B	13.6 (1.9 - 80)	C
FBC boilers (no SCC)	2.0	D	0.075 (0.01 - 0.2)	B	1.4 (0.47 - 2.4)	D

^a Units are lb of pollutant/ton of wood waste burned. To convert from lb/ton to kg/Mg, multiply by 0.5. To convert from lb/ton to lb/MMBtu, multiply by 0.11. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight % moisture and 4500 Btu/lb higher heating value. Before applying the factors to wood with moisture content other than 50%, or with a Btu content other than 4500 Btu/lb, multiply the factor by the appropriate ratio: (100-M)/50, where M is the percent moisture; (H/4500), where H is the Btu/lb. SCC = Source Classification Code. FBC = fluidized bed combustion.

^b References 20-22,27-28. NO_x formation is primarily a function of wood nitrogen content. Values in parentheses represent the range of emission factors.

^c Reference 29. Lower limit of the range (in parentheses) should be used for wood and higher values for bark.

^d References 11,20-22,27,30-32. Values in parentheses represent the range of emission factors.

Table 1.6-3. EMISSION FACTORS FOR TOTAL ORGANIC COMPOUNDS (TOC), METHANE (CH₄), NITROUS OXIDE (N₂O), AND CARBON DIOXIDE (CO₂) FROM WOOD WASTE COMBUSTION^a

Source Category (SCC)	TOC ^b		CH ₄ ^c		N ₂ O ^d		CO ₂ ^e	
	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING	Emission Factor (lb/ton)	EMISSION FACTOR RATING
Fuel cell/Dutch oven boilers (no SCC)	0.18	C	ND	NA	ND	NA	1900	B
Stoker boilers (no SCC)	0.22	C	0.1	E	0.04	D	2000	B
FBC boilers (no SCC)	ND	NA	ND	NA	0.2	E	1800	B

^a Units are lb of pollutant/ton of wood waste burned. To convert from lb/ton to kg/Mg, multiply by 0.5. To convert from lb/ton to lb/MMBtu, multiply by 0.11. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight % moisture and 4500 Btu/lb higher heating value. Before applying the factors to wood with moisture content other than 50%, or with a Btu content other than 4500 Btu/lb, multiply the factor by the appropriate ratio: (100-M)/50, where M is the percent moisture; (H/4500), where H is the Btu/lb. SCC = Source Classification Code. FBC = fluidized bed combustion. ND = no data. NA = not applicable.

^b References 11,22-23,27. Emissions measured as total hydrocarbons.

^c Reference 17.

^d References 14-15.

^e References 1,11,20-23,27,30-32.

Table 1.6-4. EMISSION FACTORS FOR SPECIATED ORGANIC COMPOUNDS FROM WOOD WASTE COMBUSTION WITH PM CONTROLS^a

Organic Compound ^b	Average Emission Factor (lb/ton)	EMISSION FACTOR RATING
Phenols ^{cc}	1.47 E-04 ^c	C
Acenaphthene ^{dd}	4.10 E-06 ^d	C
Fluorene ^{dd}	8.22 E-06 ^e	C
Phenanthrene ^{dd}	5.02 E-05 ^c	B
Anthracene	3.3 E-06 ^f	C
Fluoranthene ^{dd}	1.83 E-05 ^g	B
Benzo(a)anthracene ^{dd}	3.27 E-06 ^h	C
Benzo(k)fluoranthene ^{dd}	7.65 E-07 ⁱ	E
Benzo(b+k)fluoranthene ^{dd}	2.9 E-05 ^k	C
Benzofluoranthenes ^{dd}	1.08 E-06 ^{m,n}	E
Benzo(a)pyrene ^{dd}	6.75 E-08 ^{m,n}	E
Benzo(g,h,i)perylene ^{dd}	1.41 E-06 ^p	D
Chrysene ^{dd}	4.52 E-07 ^q	C
Indeno(1,2,3,c,d)pyrene ^{dd}	3.6 E-07 ^r	D
Polychlorinated dibenzo-p-dioxins	1.2 E-08 ^{k,s,i}	C
Polychlorinated dibenzo-p-furans	2.9E-08 ^{k,s,u}	C
Acenaphthylene ^{dd}	4.76 E-05 ^v	B
Methyl anthracene ^{dd}	1.4 E-04 ^m	D
Acrolein ^{dd}	4.0 E-06 ^m	D
Solicyladehyde	2.3 E-05 ^m	D
Benzaldehyde	1.2 E-05 ^m	D
Formaldehyde ^{dd}	8.2 E-03 ^w	B
Acetaldehyde ^{dd}	1.92 E-03 ^w	B
Benzene ^{dd}	9.95 E-03 ^x	B
Naphthalene ^{dd}	3.39 E-03 ^y	C
2,3,7,8-Tetrachlorodibenzo-p-dioxin ^{dd}	3.6 E-11 ^k	D
2-Chlorophenol ^{dd}	5.13 E-07 ^{m,n}	E
2,4-Dinitrophenol ^{dd}	4.23 E-06 ^{m,n}	E
Methane	1.12 E-02 ^z	D
4-Nitrophenol ^{dd}	2.97 E-06 ^m	E
Pyrene	1.67 E-05 ^{bb}	B

^a Units are lb of pollutant/ton of wood waste burned. To convert from lb/ton to kg/Mg, multiply by 0.5. To convert from lb/ton to lb/MMBtu, multiply by 0.11. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight % moisture and 4500 Btu/lb higher heating value. Before applying the factors to wood with moisture content other than 50%, or with a Btu content other than 4500 Btu/lb, multiply the factor by the appropriate ratio: (100-M)/50, where M is the percent moisture; (H/4500), where H is the Btu/lb. Source Classification Codes are 1-01-009-01/02/03, 1-02-009-01/02/03/04/05/06/07, and 1-03-009-01/02/03.

^b Pollutants in this table represent organic species measured for wood waste combustors equipped with PM controls (i.e., fabric filters, multi-cyclones, ESP, and wet scrubbers). Other organic species may also have been emitted but either were not measured or were present at concentrations below analytical limits.

^c References 32-35.

Table 1.6-4 (cont.).

- ^d References 34-39.
- ^e References 34-41.
- ^f References 34-39,41.
- ^g References 32-41.
- ^h References 34,37,39,40.
- ^j References 34,36.
- ^k References 11,19-23,26,31,42.
- ^m Based on data from one source test.
- ⁿ Reference 35.
- ^p References 35-36,39.
- ^q References 34-35,39-40.
- ^r References 35,39.
- ^s Emission factors are for total dioxins and furans, not toxic equivalents.
- ^t Excludes data from combustion of salt-laden wood. For salt-laden wood, emission factor is 1.3 E-06 lb/ton with a D rating.
- ^u Excludes data from combustion of salt-laden wood. For salt-laden wood, emission factor is 5.5 E-07 lb/ton with a D rating.
- ^v References 32,34-40.
- ^w References 32-41,43.
- ^x References 32-40,43.
- ^y References 32-34,37,40-41.
- ^z Reference 44.
- ^{aa} References 34,36-38.
- ^{bb} References 32,34-36,37-41.
- ^{cc} Emission factor value includes phenol, which is a hazardous air pollutant (HAP), plus substituted phenols which are not HAPs.
- ^{dd} Hazardous air pollutant.

Table 1.6-5. EMISSION FACTORS FOR TRACE ELEMENTS
FROM WOOD WASTE COMBUSTION WITH PM CONTROLS^a

Trace Element ^b	Average Emission Factor (lb/ton)	EMISSION FACTOR RATING
Chromium (VI)	4.6 E-05 ^c	D
Copper	3.73 E-04 ^d	B
Zinc	2.51 E-03 ^d	B
Barium	4.4 E-03 ^c	D
Potassium	7.8 E-01 ^c	D
Sodium	1.8 E-02 ^c	D
Iron	4.4 E-02 ^c	D
Lithium	7.0 E-05 ^c	D
Boron	8.0 E-04 ^c	D
Chlorine	7.8 E-03 ^c	D
Vanadium	1.2 E-04 ^c	D
Cobalt	1.3 E-04 ^c	D
Thorium	1.7 E-05 ^c	D
Tungsten	1.1 E-05 ^c	D
Dysprosium	1.3 E-05 ^c	D
Samarium	2.0 E-05 ^c	D
Neodymium	2.6 E-05 ^c	D
Praseodymium	3.0 E-05 ^c	D
Iodine	1.8 E-05 ^c	D
Tin	3.1 E-05 ^c	D
Molybdenum	1.9 E-04 ^c	D
Niobium	3.5 E-05 ^c	D
Zirconium	3.5 E-04 ^c	D
Yttrium	5.6 E-05 ^c	D
Rubidium	1.2 E-03 ^c	D
Bromine	3.9 E-04 ^c	D
Germanium	2.5 E-06 ^c	D
Arsenic	8.53 E-05 ^f	B
Cadmium	2.12 E-05 ^f	B
Chromium (Total)	1.56 E-04 ^g	B
Lead	4.45 E-04 ^d	B
Manganese	1.26 E-02 ^f	B
Mercury	5.15 E-06 ^h	C
Nickel	6.90 E-05 ^j	B
Selenium	4.59 E-05 ^{e,k}	E

^a Units are lb of pollutant/ton of wood waste burned. To convert from lb/ton to kg/Mg, multiply by 0.5. To convert from lb/ton to lb/MMBtu, multiply by 0.11. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight % moisture and 4500 Btu/lb higher heating value. Before applying the factors to wood with moisture content other than 50%, or with a Btu content other than 4500 Btu/lb, multiply the factor by the appropriate ratio: (100-M)/50, where M is the percent moisture; (H/4500), where H is the Btu/lb. Source Classification Codes are 1-010-09-01/02/03, 1-02-009-01/02/03/04/05/06/07, and 1-03-009-01/02/03.

^b Pollutants in this table represent metal species measured for wood waste combustors equipped with PM controls (i.e., fabric filters, multi-cyclones, ESP, and wet scrubbers). Other metal species may also have been emitted but were either not measured or were present at concentrations below analytical limits.

^c References 11,19-22.

^d References 32,34-41.

^e Based on data from one source test.

^f References 32,34-37,39,41.

^g References 32,34-39,41.

^h References 32,34-35,37.

^j References 32,34-37,40.

^k References 40.

Table 1.6-6. CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR BARK-FIRED SPREADER STOKER BOILERS^a

EMISSION FACTOR RATING: D

Particle Size ^b (μ m)	Cumulative Mass % \leq Stated Size				Cumulative Emission Factor (lb/ton)			
	Uncontrolled	Controlled			Uncontrolled	Controlled		
		Multiple Cyclone ^c	Multiple Cyclone ^c	Scrubber ^f		Multiple Cyclone ^c	Multiple Cyclone ^c	Scrubber ^f
15	42	90	40	92	20.2	12.6	3.6	2.64
10	35	79	36	87	16.8	11.0	3.24	2.50
6	28	64	30	78	13.4	9.0	2.7	2.24
2.5	21	40	19	56	10.0	5.6	1.72	1.62
1.25	15	26	14	29	7.2	3.6	1.26	0.84
1.00	13	21	11	23	6.2	3.0	1.0	0.66
0.625	9	15	8	14	4.4	2.2	0.72	0.40
Total	100	100	100	100	48	14	9.0	2.88

^a Reference 45. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight % moisture and 4500 Btu/lb higher heating value. Before applying the factors to wood with moisture content other than 50%, or with a Btu content other than 4500 Btu/lb, multiply the factor by the appropriate ratio: $(100-M)/50$, where M is the percent moisture; $(H/4500)$, where H is the Btu/lb. Source Classification Codes are 1-01-009-01, 1-02-009-01, 1-03-009-04, and 1-03-009-01.

^b Expressed as aerodynamic equivalent diameter.

^c Units are lb of pollutant/ton of wood waste burned. To convert from lb/ton to kg/Mg, multiply by 0.5. To convert from lb/ton to lb/MMBtu, multiply by 0.11.

^d With flyash reinjection.

^e Without flyash reinjection.

^f Assumed control efficiency for scrubber is 94%.

Table 1.6-7. CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR WOOD/BARK-FIRED BOILERS^a

EMISSION FACTOR RATING: E

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size					Cumulative Emission Factor ^c (lb/ton)				
	Uncontrolled ^d	Controlled			DEGF	Uncontrolled ^d	Controlled			DEGF ^g
		Multiple Cyclone ^e	Multiple Cyclone ^f	Scrubber ^g			Multiple Cyclone ^e	Multiple Cyclone ^f	Scrubber ^g	
15	94	96	35	98	77	6.77	5.76	1.90	0.431	0.246
10	90	91	32	98	74	6.48	5.46	1.72	0.432	0.236
6	86	80	27	98	69	6.20	4.80	1.46	0.432	0.220
2.5	76	54	16	98	65	5.47	3.24	0.86	0.432	0.208
1.25	69	30	8	96	61	4.97	1.80	0.44	0.422	0.196
1.00	67	24	6	95	58	4.82	1.44	0.32	0.418	0.186
0.625	ND	16	3	ND	51	ND	0.96	0.162	ND	0.164
Total	100	100	100	100	100	7.2	6.0	5.4	0.44	0.32

^a Reference 45. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight % moisture and 4500 Btu/lb higher heating value. Before applying the factors to wood with moisture content other than 50%, or with a Btu content other than 4500 Btu/lb, multiply the factor by the appropriate ratio: $(100-M)/50$, where M is the percent moisture; $(H/4500)$, where H is the Btu/lb. Source Classification Codes are 1-01-009-02, 1-02-009-02, 1-02-009-05, and 1-03-009-02. ND = no data. DEGF = dry electrostatic granular filter. Expressed as aerodynamic equivalent diameter.

^b Units are lb of pollutant/ton of wood bark burned. To convert from lb/ton to kg/Mg, multiply by 0.5. To convert from lb/ton to lb/MMBtu, multiply by 0.11.

^c From data on underfeed stokers. May also be used as size distribution for wood-fired boilers.

^d From data on spreader stokers with flyash reinjection.

^e From data on spreader stokers without flyash reinjection.

^f From data on Dutch ovens. Assumed control efficiency is 94%.

^g From data on Dutch ovens. Assumed control efficiency is 94%.

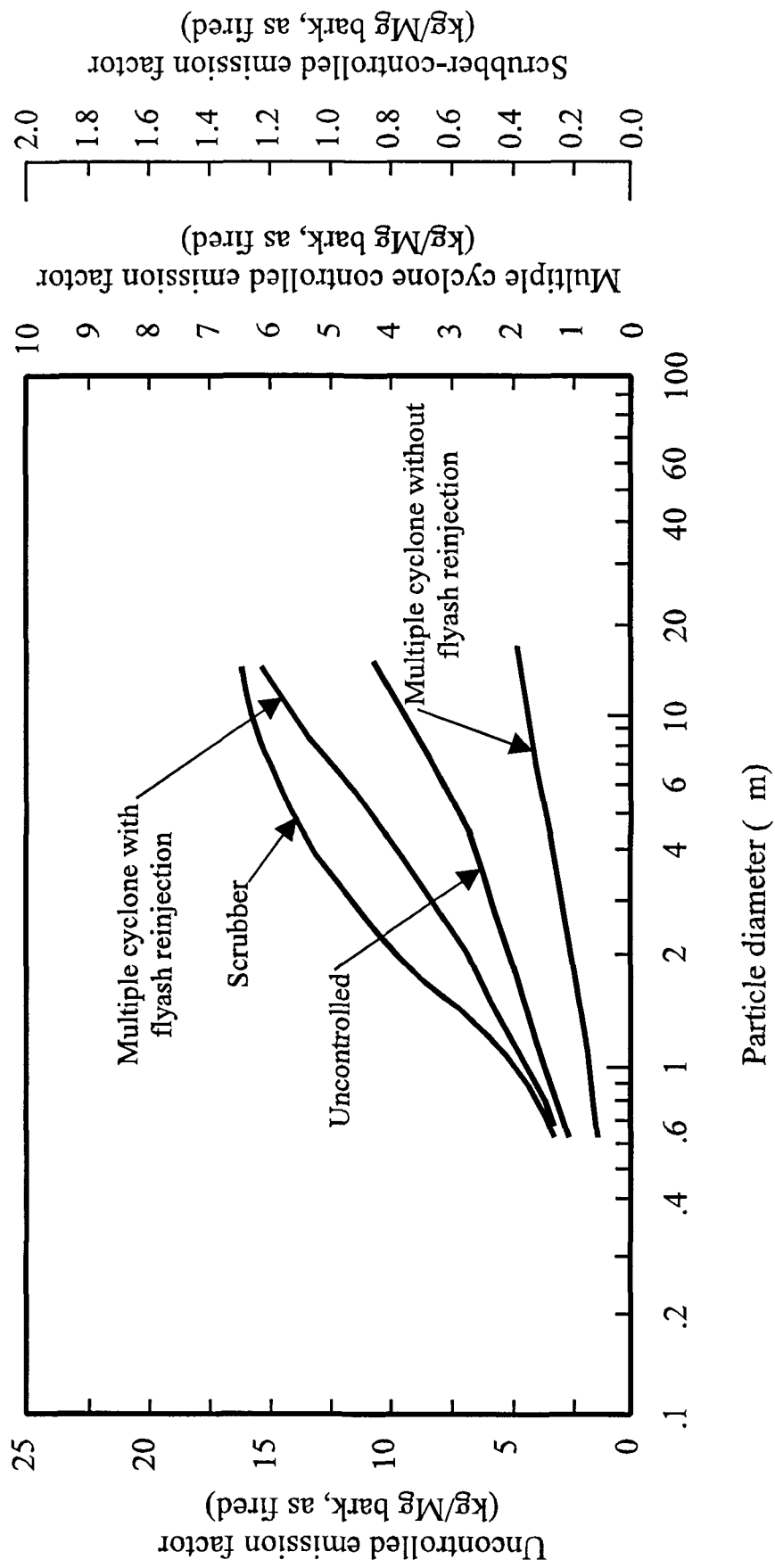


Figure 1.6-1. Cumulative size-specific particulate matter emission factors for bark-fired boilers.

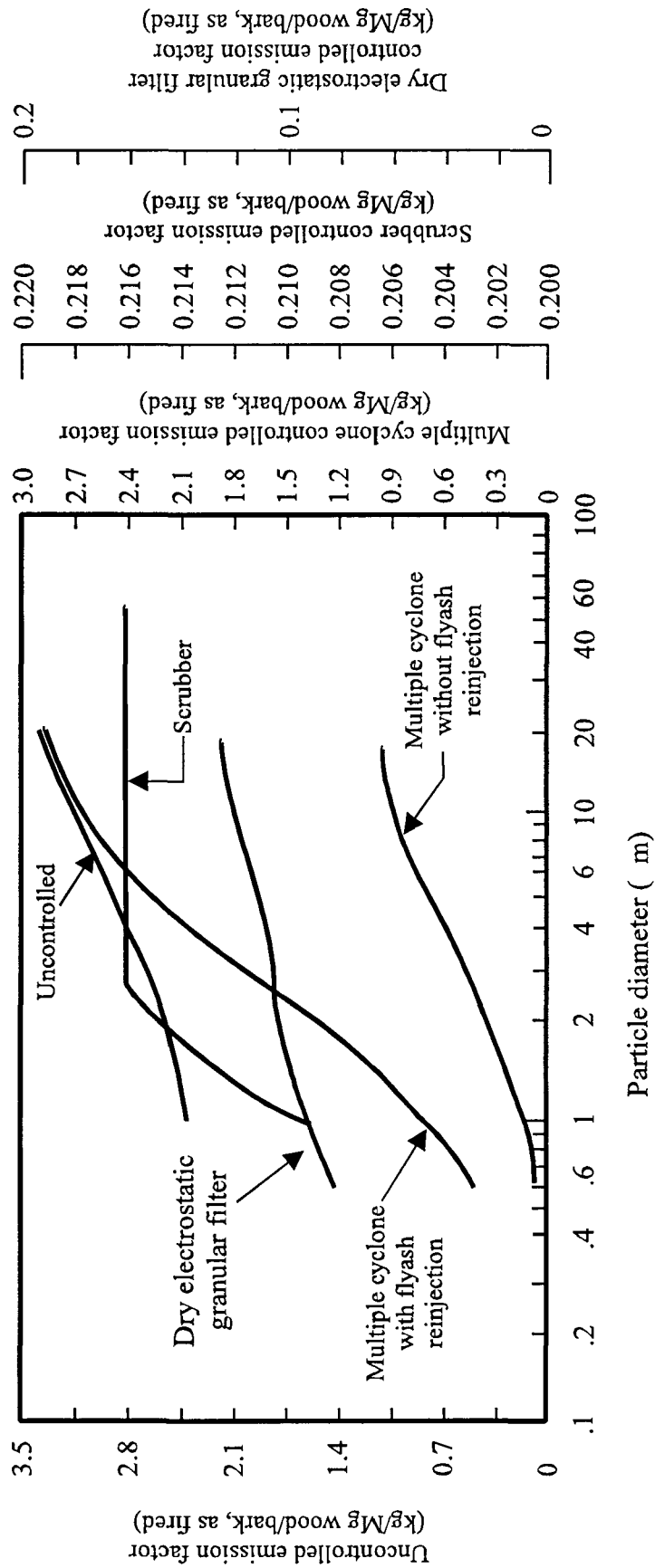


Figure 1.6-2. Cumulative size-specific particulate matter emission factors for wood/bark-fired boilers.

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2.4 Municipal Solid Waste Landfills

2.4.1 General¹⁻⁴

A municipal solid waste (MSW) landfill unit is a discrete area of land or an excavation that receives household waste, and that is not a land application unit, surface impoundment, injection well, or waste pile. An MSW landfill unit may also receive other types of wastes, such as commercial solid waste, nonhazardous sludge, and industrial solid waste. The municipal solid waste types potentially accepted by MSW landfills include (most landfills accept only a few of the following categories):

- MSW,
- Household hazardous waste,
- Municipal sludge,
- Municipal waste combustion ash,
- Infectious waste,
- Waste tires,
- Industrial non-hazardous waste,
- Conditionally exempt small quantity generator (CESQG) hazardous waste,
- Construction and demolition waste,
- Agricultural wastes,
- Oil and gas wastes, and
- Mining wastes.

In the United States, approximately 57 percent of solid waste is landfilled, 16 percent is incinerated, and 27 percent is recycled or composted. There were an estimated 2,500 active MSW landfills in the United States in 1995. These landfills were estimated to receive 189 million megagrams (Mg) (208 million tons) of waste annually, with 55 to 60 percent reported as household waste, and 35 to 45 percent reported as commercial waste.

2.4.2 Process Description^{2,5}

There are three major designs for municipal landfills. These are the area, trench, and ramp methods. All of these methods utilize a three step process, which includes spreading the waste, compacting the waste, and covering the waste with soil. The trench and ramp methods are not commonly used, and are not the preferred methods when liners and leachate collection systems are utilized or required by law. The area fill method involves placing waste on the ground surface or landfill liner, spreading it in layers, and compacting with heavy equipment. A daily soil cover is spread over the compacted waste. The trench method entails excavating trenches designed to receive a day's worth of waste. The soil from the excavation is often used for cover material and wind breaks. The ramp method is typically employed on sloping land, where waste is spread and compacted similar to the area method, however, the cover material obtained is generally from the front of the working face of the filling operation.

Modern landfill design often incorporates liners constructed of soil (i.e., recompacted clay), or synthetics (i.e., high density polyethylene), or both to provide an impermeable barrier to leachate (i.e., water that has passed through the landfill) and gas migration from the landfill.

2.4.3 Control Technology^{1,2,6}

The Resource Conservation and Recovery Act (RCRA) Subtitle D regulations promulgated on October 9, 1991 require that the concentration of methane generated by MSW landfills not exceed 25 percent of the lower explosive limit (LEL) in on-site structures, such as scale houses, or the LEL at the facility property boundary.

The New Source Performance Standards (NSPS) and Emission Guidelines for air emissions from MSW landfills for certain new and existing landfills were published in the Federal Register on March 1, 1996. The regulation requires that Best Demonstrated Technology (BDT) be used to reduce MSW landfill emissions from affected new and existing MSW landfills emitting greater than or equal to 50 Mg/yr (55 tons/yr) of non-methane organic compounds (NMOCs). The MSW landfills that are affected by the NSPS/Emission Guidelines are each new MSW landfill, and each existing MSW landfill that has accepted waste since November 8, 1987, or that has capacity available for future use. The NSPS/Emission Guidelines affect landfills with a design capacity of 2.5 million Mg (2.75 million tons) or more. Control systems require: (1) a well-designed and well-operated gas collection system, and (2) a control device capable of reducing NMOCs in the collected gas by 98 weight-percent.

Landfill gas (LFG) collection systems are either active or passive systems. Active collection systems provide a pressure gradient in order to extract LFG by use of mechanical blowers or compressors. Passive systems allow the natural pressure gradient created by the increase in pressure created by LFG generation within the landfill to mobilize the gas for collection.

LFG control and treatment options include (1) combustion of the LFG, and (2) purification of the LFG. Combustion techniques include techniques that do not recover energy (i.e., flares and thermal incinerators), and techniques that recover energy (i.e., gas turbines and internal combustion engines) and generate electricity from the combustion of the LFG. Boilers can also be employed to recover energy from LFG in the form of steam. Flares involve an open combustion process that requires oxygen for combustion, and can be open or enclosed. Thermal incinerators heat an organic chemical to a high enough temperature in the presence of sufficient oxygen to oxidize the chemical to carbon dioxide (CO₂) and water. Purification techniques can also be used to process raw landfill gas to pipeline quality natural gas by using adsorption, absorption, and membranes.

2.4.4 Emissions^{2,7}

Methane (CH₄) and CO₂ are the primary constituents of landfill gas, and are produced by microorganisms within the landfill under anaerobic conditions. Transformations of CH₄ and CO₂ are mediated by microbial populations that are adapted to the cycling of materials in anaerobic environments. Landfill gas generation, including rate and composition, proceeds through four phases. The first phase is aerobic [i.e., with oxygen (O₂) available] and the primary gas produced is CO₂. The second phase is characterized by O₂ depletion, resulting in an anaerobic environment, where large amounts of CO₂ and some hydrogen (H₂) are produced. In the third phase, CH₄ production begins, with an accompanying reduction in the amount of CO₂ produced. Nitrogen (N₂) content is initially high in landfill gas in the first phase, and declines sharply as the landfill proceeds through the second and third phases. In the fourth phase, gas production of CH₄, CO₂, and N₂ becomes fairly steady. The total time and phase duration of gas generation varies with landfill conditions (i.e., waste composition, design management, and anaerobic state).

Typically, LFG also contains a small amount of non-methane organic compounds (NMOC). This NMOC fraction often contains various organic hazardous air pollutants (HAP), greenhouse gases (GHG), and compounds associated with stratospheric ozone depletion. The NMOC fraction also contains volatile organic compounds (VOC). The weight fraction of VOC can be determined by subtracting the weight fractions of individual compounds that are non-photochemically reactive (i.e., negligibly-reactive organic compounds as defined in 40 CFR 51.100).

Other emissions associated with MSW landfills include combustion products from LFG control and utilization equipment (i.e., flares, engines, turbines, and boilers). These include carbon monoxide (CO), oxides of nitrogen (NO_x), sulfur dioxide (SO₂), hydrogen chloride (HCl), particulate matter (PM) and other combustion products (including HAPs). PM emissions can also be generated in the form of fugitive dust created by mobile sources (i.e., garbage trucks) traveling along paved and unpaved surfaces. The reader should consult AP-42 Volume I Sections 13.2.1 and 13.2.2 for information on estimating fugitive dust emissions from paved and unpaved roads.

The rate of emissions from a landfill is governed by gas production and transport mechanisms. Production mechanisms involve the production of the emission constituent in its vapor phase through vaporization, biological decomposition, or chemical reaction. Transport mechanisms involve the transportation of a volatile constituent in its vapor phase to the surface of the landfill, through the air boundary layer above the landfill, and into the atmosphere. The three major transport mechanisms that enable transport of a volatile constituent in its vapor phase are diffusion, convection, and displacement.

2.4.4.1 Uncontrolled Emissions — To estimate uncontrolled emissions of the various compounds present in landfill gas, total landfill gas emissions must first be estimated. Uncontrolled CH₄ emissions may be estimated for individual landfills by using a theoretical first-order kinetic model of methane production developed by the EPA.⁸ This model is known as the Landfill Air Emissions Estimation model, and can be accessed from the Office of Air Quality Planning and Standards Technology Transfer Network Website (OAQPS TTN Web) in the Clearinghouse for Inventories and Emission Factors (CHIEF) technical area (URL <http://www.epa.gov/ttn/chief>). The Landfill Air Emissions Estimation model equation is as follows:

$$Q_{CH_4} = L_o R (e^{-kc} - e^{-kt}) \quad (1)$$

where:

Q_{CH_4}	=	Methane generation rate at time t, m ³ /yr;
L_o	=	Methane generation potential, m ³ CH ₄ /Mg refuse;
R	=	Average annual refuse acceptance rate during active life, Mg/yr;
e	=	Base log, unitless;
k	=	Methane generation rate constant, yr ⁻¹ ;
c	=	Time since landfill closure, yrs (c = 0 for active landfills); and
t	=	Time since the initial refuse placement, yrs.

It should be noted that the model above was designed to estimate LFG generation and not LFG emissions to the atmosphere. Other fates may exist for the gas generated in a landfill, including capture and subsequent microbial degradation within the landfill's surface layer. Currently, there are no data that adequately address this fate. It is generally accepted that the bulk of the gas generated will be emitted through cracks or other openings in the landfill surface.

Site-specific landfill information is generally available for variables R , c , and t . When refuse acceptance rate information is scant or unknown, R can be determined by dividing the refuse in place by the age of the landfill. If a facility has documentation that a certain segment (cell) of a landfill received *only* nondegradable refuse, then the waste from this segment of the landfill can be excluded from the calculation of R . Nondegradable refuse includes concrete, brick, stone, glass, plaster, wallboard, piping, plastics, and metal objects. The average annual acceptance rate should only be estimated by this method when there is inadequate information available on the actual average acceptance rate. The time variable, t , includes the total number of years that the refuse has been in place (including the number of years that the landfill has accepted waste and, if applicable, has been closed).

Values for variables L_0 and k must be estimated. Estimation of the potential CH_4 generation capacity of refuse (L_0) is generally treated as a function of the moisture and organic content of the refuse. Estimation of the CH_4 generation constant (k) is a function of a variety of factors, including moisture, pH, temperature, and other environmental factors, and landfill operating conditions. Specific CH_4 generation constants can be computed by the use of EPA Method 2E (40 CFR Part 60 Appendix A).

The Landfill Air Emission Estimation model includes both regulatory default values and recommended AP-42 default values for L_0 and k . The regulatory defaults were developed for compliance purposes (NSPS/Emission Guideline). As a result, the model contains conservative L_0 and k default values in order to protect human health, to encompass a wide range of landfills, and to encourage the use of site-specific data. Therefore, different L_0 and k values may be appropriate in estimating landfill emissions for particular landfills and for use in an emissions inventory.

Recommended AP-42 defaults include a k value of 0.04/yr for areas receiving 25 inches or more of rain per year. A default k of 0.02/yr should be used in drier areas (<25 inches/yr). An L_0 value of 100 m^3/Mg (3,530 ft^3/ton) refuse is appropriate for most landfills. Although the recommended default k and L_0 are based upon the best fit to 21 different landfills, the predicted methane emissions ranged from 38 to 492% of actual, and had a relative standard deviation of 0.85. It should be emphasized that in order to comply with the NSPS/Emission Guideline, the regulatory defaults for k and L_0 must be applied as specified in the final rule.

When gas generation reaches steady state conditions, LFG consists of approximately 40 percent by volume CO_2 , 55 percent CH_4 , 5 percent N_2 (and other gases), and trace amounts of NMOCs. Therefore, the estimate derived for CH_4 generation using the Landfill Air Emissions Estimation model can also be used to represent CO_2 generation. Addition of the CH_4 and CO_2 emissions will yield an estimate of total landfill gas emissions. If site-specific information is available to suggest that the CH_4 content of landfill gas is not 55 percent, then the site-specific information should be used, and the CO_2 emission estimate should be adjusted accordingly.

Most of the NMOC emissions result from the volatilization of organic compounds contained in the landfilled waste. Small amounts may be created by biological processes and chemical reactions within the landfill. The current version of the Landfill Air Emissions Estimation model contains a proposed regulatory default value for total NMOC of 4,000 ppmv, expressed as hexane. However, available data show that there is a range of over 4,400 ppmv for total NMOC values from landfills. The proposed regulatory default value for NMOC concentration was developed for regulatory compliance purposes and to provide the most cost-effective default values on a national basis. For emissions inventory purposes, site-specific information should be taken into account when determining the total NMOC concentration. In the absence of site-specific information, a value of 2,420 ppmv as hexane is suggested for landfills known to have co-disposal of MSW and non-residential waste. If the landfill is known to contain only MSW or

have very little organic commercial/industrial wastes, then a total NMOC value of 595 ppmv as hexane should be used. In addition, as with the landfill model defaults, the regulatory default value for NMOC content must be used in order to comply with the NSPS/Emission Guideline.

If a site-specific total pollutant concentration is available (i.e., as measured by EPA Reference Method 25C), it must be corrected for air infiltration which can occur by two different mechanisms: LFG sample dilution, and air intrusion into the landfill. These corrections require site-specific data for the LFG CH₄, CO₂, nitrogen (N₂), and oxygen (O₂) content. If the ratio of N₂ to O₂ is less than or equal to 4.0 (as found in ambient air), then the total pollutant concentration is adjusted for sample dilution by assuming that CO₂ and CH₄ are the primary (100 percent) constituents of landfill gas, and the following equation is used:

$$C_P \text{ (ppmv) (corrected for air infiltration)} = \frac{C_P \text{ (ppmv)} (1 \times 10^6)}{C_{CO_2} \text{ (ppmv)} + C_{CH_4} \text{ (ppmv)}} \quad (2)$$

where:

- C_P = Concentration of pollutant P in landfill gas (i.e., NMOC as hexane), ppmv;
- C_{CO_2} = CO₂ concentration in landfill gas, ppmv;
- C_{CH_4} = CH₄ Concentration in landfill gas, ppmv; and
- 1×10^6 = Constant used to correct concentration of P to units of ppmv.

If the ratio of N₂ to O₂ concentrations (i.e., C_{N_2} , C_{O_2}) is greater than 4.0, then the total pollutant concentration should be adjusted for air intrusion into the landfill by using equation 2 and adding the concentration of N₂ (i.e., C_{N_2}) to the denominator. Values for C_{CO_2} , C_{CH_4} , C_{N_2} , C_{O_2} , can usually be found in the source test report for the particular landfill along with the total pollutant concentration data.

To estimate emissions of NMOC or other landfill gas constituents, the following equation should be used:

$$Q_P = 1.82 Q_{CH_4} * \frac{C_P}{(1 \times 10^6)} \quad (3)$$

where:

- Q_P = Emission rate of pollutant P (i.e. NMOC), m³/yr;
- Q_{CH_4} = CH₄ generation rate, m³/yr (from the Landfill Air Emissions Estimation model);
- C_P = Concentration of P in landfill gas, ppmv; and
- 1.82 = Multiplication factor (assumes that approximately 55 percent of landfill gas is CH₄ and 45 percent is CO₂, N₂, and other constituents).

Uncontrolled mass emissions per year of total NMOC (as hexane), CO₂, CH₄, and speciated organic and inorganic compounds can be estimated by the following equation:

$$UM_P = Q_P * \left[\frac{MW_P * 1 \text{ atm}}{(8.205 \times 10^{-5} \text{ m}^3\text{-atm/gmol-}^\circ\text{K})(1000\text{g/kg})(273 + T^\circ\text{K})} \right] \quad (4)$$

where:

UM_P = Uncontrolled mass emissions of pollutant P (i.e., NMOC), kg/yr;
 MW_P = Molecular weight of P, g/gmol (i.e., 86.18 for NMOC as hexane);
 Q_P = NMOC emission rate of P, m³/yr; and
 T = Temperature of landfill gas, °C.

This equation assumes that the operating pressure of the system is approximately 1 atmosphere. If the temperature of the landfill gas is not known, a temperature of 25°C (77°F) is recommended.

Uncontrolled default concentrations of speciated organics along with some inorganic compounds are presented in Table 2.4-1. These default concentrations have already been corrected for air infiltration and can be used as input parameters to equation 3 or the Landfill Air Emission Estimation model for estimating speciated emissions from landfills when site-specific data are not available. An analysis of the data, based on the co-disposal history (with non-residential wastes) of the individual landfills from which the concentration data were derived, indicates that for benzene, NMOC, and toluene, there is a difference in the uncontrolled concentrations. Table 2.4-2 presents the corrected concentrations for benzene, NMOC, and toluene to use based on the site's co-disposal history.

It is important to note that the compounds listed in Tables 2.4-1 and 2.4-2 are not the only compounds likely to be present in LFG. The listed compounds are those that were identified through a review of the available literature. The reader should be aware that additional compounds are likely present, such as those associated with consumer or industrial products. Given this information, extreme caution should be exercised in the use of the default VOC weight fractions and concentrations given at the bottom of Table 2.4-2. These default VOC values are heavily influenced by the ethane content of the LFG. Available data have shown that there is a range of over 1,500 ppmv in LFG ethane content among landfills.

2.4.4.2 Controlled Emissions — Emissions from landfills are typically controlled by installing a gas collection system, and combusting the collected gas through the use of internal combustion engines, flares, or turbines. Gas collection systems are not 100 percent efficient in collecting landfill gas, so emissions of CH₄ and NMOC at a landfill with a gas recovery system still occur. To estimate controlled emissions of CH₄, NMOC, and other constituents in landfill gas, the collection efficiency of the system must first be estimated. Reported collection efficiencies typically range from 60 to 85 percent, with an average of 75 percent most commonly assumed. Higher collection efficiencies may be achieved at some sites (i.e., those engineered to control gas emissions). If site-specific collection efficiencies are available (i.e., through a comprehensive surface sampling program), then they should be used instead of the 75 percent average.

Controlled emission estimates also need to take into account the control efficiency of the control device. Control efficiencies based on test data for the combustion of CH₄, NMOC, and some speciated organics with differing control devices are presented in Table 2.4-3. Emissions from the control devices need to be added to the uncollected emissions to estimate total controlled emissions.

Controlled CH₄, NMOC, and speciated emissions can be calculated with equation 5. It is assumed that the landfill gas collection and control system operates 100 percent of the time. Minor durations of system downtime associated with routine maintenance and repair (i.e., 5 to 7 percent) will not appreciably effect emission estimates. The first term in equation 5 accounts for emissions from uncollected landfill gas, while the second term accounts for emissions of the pollutant that were collected but not combusted in the control or utilization device:

$$CM_P = \left[UM_P * \left(1 - \frac{\eta_{col}}{100} \right) \right] + \left[UM_P * \frac{\eta_{col}}{100} * \left(1 - \frac{\eta_{cnt}}{100} \right) \right] \quad (5)$$

where:

- CM_P = Controlled mass emissions of pollutant P, kg/yr;
- UM_P = Uncontrolled mass emissions of P, kg/yr (from equation 4 or the Landfill Air Emissions Estimation Model);
- η_{col} = Collection efficiency of the landfill gas collection system, percent; and
- η_{cnt} = Control efficiency of the landfill gas control or utilization device, percent.

Emission factors for the secondary compounds, CO and NO_x, exiting the control device are presented in Tables 2.4-4 and 2.4-5. These emission factors should be used when equipment vendor guarantees are not available.

Controlled emissions of CO₂ and sulfur dioxide (SO₂) are best estimated using site-specific landfill gas constituent concentrations and mass balance methods.⁶⁸ If site-specific data are not available, the data in tables 2.4-1 through 2.4-3 can be used with the mass balance methods that follow.

Controlled CO₂ emissions include emissions from the CO₂ component of landfill gas (equivalent to uncontrolled emissions) and additional CO₂ formed during the combustion of landfill gas. The bulk of the CO₂ formed during landfill gas combustion comes from the combustion of the CH₄ fraction. Small quantities will be formed during the combustion of the NMOC fraction, however, this typically amounts to less than 1 percent of total CO₂ emissions by weight. Also, the formation of CO through incomplete combustion of landfill gas will result in small quantities of CO₂ not being formed. This contribution to the overall mass balance picture is also very small and does not have a significant impact on overall CO₂ emissions.⁶⁸

The following equation which assumes a 100 percent combustion efficiency for CH₄ can be used to estimate CO₂ emissions from controlled landfills:

$$CM_{CO_2} = UM_{CO_2} + \left[UM_{CH_4} * \frac{\eta_{col}}{100} * 2.75 \right] \quad (6)$$

where:

- CM_{CO₂} = Controlled mass emissions of CO₂, kg/yr;
- UM_{CO₂} = Uncontrolled mass emissions of CO₂, kg/yr (from equation 4 or the Landfill Air Emission Estimation Model);
- UM_{CH₄} = Uncontrolled mass emissions of CH₄, kg/yr (from equation 4 on the Landfill Air Emission Estimation Model);
- η_{col} = Efficiency of the landfill gas collection system, percent; and
- 2.75 = Ratio of the molecular weight of CO₂ to the molecular weight of CH₄.

To prepare estimates of SO₂ emissions, data on the concentration of reduced sulfur compounds within the landfill gas are needed. The best way to prepare this estimate is with site-specific information on the total reduced sulfur content of the landfill gas. Often these data are expressed in ppmv as sulfur (S). Equations 3 and 4 should be used first to determine the uncontrolled mass emission rate of reduced sulfur compounds as sulfur. Then, the following equation can be used to estimate SO₂ emissions:

$$CM_{SO_2} = UM_S * \frac{\eta_{col}}{100} * 2.0 \quad (7)$$

where:

CM_{SO_2}	=	Controlled mass emissions of SO ₂ , kg/yr;
UM_S	=	Uncontrolled mass emissions of reduced sulfur compounds as sulfur, kg/yr (from equations 3 and 4);
η_{col}	=	Efficiency of the landfill gas collection system, percent; and
2.0	=	Ratio of the molecular weight of SO ₂ to the molecular weight of S.

The next best method to estimate SO₂ concentrations, if site-specific data for total reduced sulfur compounds as sulfur are not available, is to use site-specific data for speciated reduced sulfur compound concentrations. These data can be converted to ppmv as S with equation 8. After the total reduced sulfur as S has been obtained from equation 8, then equations 3, 4, and 7 can be used to derive SO₂ emissions.

$$C_S = \sum_{i=1}^n C_P * S_P \quad (8)$$

where:

C_S	=	Concentration of total reduced sulfur compounds, ppmv as S (for use in equation 3);
C_P	=	Concentration of each reduced sulfur compound, ppmv;
S_P	=	Number of moles of S produced from the combustion of each reduced sulfur compound (i.e., 1 for sulfides, 2 for disulfides); and
n	=	Number of reduced sulfur compounds available for summation.

If no site-specific data are available, a value of 46.9 ppmv can be assumed for C_S (for use in equation 3). This value was obtained by using the default concentrations presented in Table 2.4-1 for reduced sulfur compounds and equation 8.

Hydrochloric acid [Hydrogen Chloride (HCl)] emissions are formed when chlorinated compounds in LFG are combusted in control equipment. The best methods to estimate emissions are mass balance methods that are analogous to those presented above for estimating SO₂ emissions. Hence, the best source of data to estimate HCl emissions is site-specific LFG data on total chloride [expressed in ppmv as the chloride ion (Cl⁻)]. If these data are not available, then total chloride can be estimated from data on individual chlorinated species using equation 9 below. However, emission estimates may be

underestimated, since not every chlorinated compound in the LFG will be represented in the laboratory report (i.e., only those that the analytical method specifies).

$$C_{Cl} = \sum_{i=1}^n C_P * Cl_P \quad (9)$$

where:

C_{Cl}	=	Concentration of total chloride, ppmv as Cl^- (for use in equation 3);
C_P	=	Concentration of each chlorinated compound, ppmv;
Cl_P	=	Number of moles of Cl^- produced from the combustion of each chlorinated compound (i.e., 3 for 1,1,1-trichloroethane); and
n	=	Number of chlorinated compounds available for summation.

After the total chloride concentration (C_{Cl}) has been estimated, equations 3 and 4 should be used to determine the total uncontrolled mass emission rate of chlorinated compounds as chloride ion (UM_{Cl}). This value is then used in equation 10 below to derive HCl emission estimates:

$$CM_{HCl} = UM_{Cl} * \frac{\eta_{col}}{100} * 1.03 * \left(1 - \frac{\eta_{cnt}}{100} \right) \quad (10)$$

where:

CM_{HCl}	=	Controlled mass emissions of HCl, kg/yr;
UM_{Cl}	=	Uncontrolled mass emissions of chlorinated compounds as chloride, kg/yr (from equations 3 and 4);
η_{col}	=	Efficiency of the landfill gas collection system, percent;
1.03	=	Ratio of the molecular weight of HCl to the molecular weight of Cl^- ; and
η_{cnt}	=	Control efficiency of the landfill gas control or utilization device, percent.

In estimating HCl emissions, it is assumed that all of the chloride ion from the combustion of chlorinated LFG constituents is converted to HCl. If an estimate of the control efficiency, η_{cnt} , is not available, then the high end of the control efficiency range for the equipment listed in Table 9 should be used. This assumption is recommended to assume that HCl emissions are not under-estimated.

If site-specific data on total chloride or speciated chlorinated compounds are not available, then a default value of 42.0 ppmv can be used for C_{Cl} . This value was derived from the default LFG constituent concentrations presented in Table 2.4-1. As mentioned above, use of this default may produce underestimates of HCl emissions since it is based only on those compounds for which analyses have been performed. The constituents listed in Table 2.4-1 are likely not all of the chlorinated compounds present in LFG.

The reader is referred to Sections 11.2-1 (Unpaved Roads, SCC 50100401), and 11-2.4 (Heavy Construction Operations) of Volume I, and Section II-7 (Construction Equipment) of Volume II, of the AP-42 document for determination of associated fugitive dust and exhaust emissions from these emission sources at MSW landfills.

2.4.5 Updates Since the Fifth Edition

The Fifth Edition was released in January 1995. This revision includes major revisions of the text and recommended emission factors contained in the section. The most significant revisions to this section since publication in the Fifth Edition are summarized below.

- The equations to calculate the CH₄, CO₂ and other constituents were simplified.
- The default L₀ and k were revised based upon an expanded base of gas generation data.
- The default ratio of CO₂ to CH₄ was revised based upon averages observed in available source test reports.
- The default concentrations of LFG constituents were revised based upon additional data.
- Additional control efficiencies were included and existing efficiencies were revised based upon additional emission test data.
- Revised and expanded the recommended emission factors for secondary compounds emitted from typical control devices.

Table 2.4-1. DEFAULT CONCENTRATIONS FOR LFG CONSTITUENTS^a

(SCC 50100402, 50300603)

Compound	Molecular Weight	Default Concentration (ppmv)	Emission Factor Rating
1,1,1-Trichloroethane (methyl chloroform) ^a	133.42	0.48	B
1,1,2,2-Tetrachloroethane ^a	167.85	1.11	C
1,1-Dichloroethane (ethylidene dichloride) ^a	98.95	2.35	B
1,1-Dichloroethene (vinylidene chloride) ^a	96.94	0.20	B
1,2-Dichloroethane (ethylene dichloride) ^a	98.96	0.41	B
1,2-Dichloropropane (propylene dichloride) ^a	112.98	0.18	D
2-Propanol (isopropyl alcohol)	60.11	50.1	E
Acetone	58.08	7.01	B
Acrylonitrile ^a	53.06	6.33	D
Bromodichloromethane	163.83	3.13	C
Butane	58.12	5.03	C
Carbon disulfide ^a	76.13	0.58	C
Carbon monoxide ^b	28.01	141	E
Carbon tetrachloride ^a	153.84	0.004	B
Carbonyl sulfide ^a	60.07	0.49	D
Chlorobenzene ^a	112.56	0.25	C
Chlorodifluoromethane	86.47	1.30	C
Chloroethane (ethyl chloride) ^a	64.52	1.25	B
Chloroform ^a	119.39	0.03	B
Chloromethane	50.49	1.21	B
Dichlorobenzene ^c	147	0.21	E
Dichlorodifluoromethane	120.91	15.7	A
Dichlorofluoromethane	102.92	2.62	D
Dichloromethane (methylene chloride) ^a	84.94	14.3	A
Dimethyl sulfide (methyl sulfide)	62.13	7.82	C
Ethane	30.07	889	C
Ethanol	46.08	27.2	E
Ethyl mercaptan (ethanethiol)	62.13	2.28	D
Ethylbenzene ^a	106.16	4.61	B
Ethylene dibromide	187.88	0.001	E
Fluorotrichloromethane	137.38	0.76	B
Hexane ^a	86.18	6.57	B
Hydrogen sulfide	34.08	35.5	B
Mercury (total) ^{a,d}	200.61	2.92x10 ⁻⁴	E

Table 2.4-1. (Concluded)

Compound	Molecular Weight	Default Concentration (ppmv)	Emission Factor Rating
Methyl ethyl ketone ^a	72.11	7.09	A
Methyl isobutyl ketone ^a	100.16	1.87	B
Methyl mercaptan	48.11	2.49	C
Pentane	72.15	3.29	C
Perchloroethylene (tetrachloroethylene) ^a	165.83	3.73	B
Propane	44.09	11.1	B
t-1,2-dichloroethene	96.94	2.84	B
Trichloroethylene (trichloroethene) ^a	131.38	2.82	B
Vinyl chloride ^a	62.50	7.34	B
Xylenes ^a	106.16	12.1	B

NOTE: This is not an all-inclusive list of potential LFG constituents, only those for which test data were available at multiple sites. References 10-67. Source Classification Codes in parentheses.

^a Hazardous Air Pollutants listed in Title III of the 1990 Clean Air Act Amendments.

^b Carbon monoxide is not a typical constituent of LFG, but does exist in instances involving landfill (underground) combustion. Therefore, this default value should be used with caution. Of 18 sites where CO was measured, only 2 showed detectable levels of CO.

^c Source tests did not indicate whether this compound was the para- or ortho- isomer. The para isomer is a Title III-listed HAP.

^d No data were available to speciate total Hg into the elemental and organic forms.

Table 2.4-2. DEFAULT CONCENTRATIONS OF BENZENE, NMOC, AND TOLUENE BASED ON WASTE DISPOSAL HISTORY^a

(SCC 50100402, 50300603)

Pollutant	Molecular Weight	Default Concentration (ppmv)	Emission Factor Rating
Benzene ^b	78.11		
Co-disposal		11.1	D
No or Unknown co-disposal		1.91	B
NMOC (as hexane) ^c	86.18		
Co-disposal		2420	D
No or Unknown co-disposal		595	B
Toluene ^b	92.13		
Co-disposal		165	D
No or Unknown co-disposal		39.3	A

^a References 10-54. Source Classification Codes in parentheses.

^b Hazardous Air Pollutants listed in Title III of the 1990 Clean Air Act Amendments.

^c For NSPS/Emission Guideline compliance purposes, the default concentration for NMOC as specified in the final rule must be used. For purposes not associated with NSPS/Emission Guideline compliance, the default VOC content at co-disposal sites = 85 percent by weight (2,060 ppmv as hexane); at No or Unknown sites = 39 percent by weight 235 ppmv as hexane).

Table 2.4-3. CONTROL EFFICIENCIES FOR LFG CONSTITUENTS^a

Control Device	Constituent ^b	Control Efficiency (%)		
		Typical	Range	Rating
Boiler/Steam Turbine (50100423)	NMOC	98.0	96-99+	D
	Halogenated Species	99.6	87-99+	D
	Non-Halogenated Species	99.8	67-99+	D
Flare ^c (50100410) (50300601)	NMOC	99.2	90-99+	B
	Halogenated Species	98.0	91-99+	C
	Non-Halogenated Species	99.7	38-99+	C
Gas Turbine (50100420)	NMOC	94.4	90-99+	E
	Halogenated Species	99.7	98-99+	E
	Non-Halogenated Species	98.2	97-99+	E
IC Engine (50100421)	NMOC	97.2	94-99+	E
	Halogenated Species	93.0	90-99+	E
	Non-Halogenated Species	86.1	25-99+	E

^a References 10-67. Source Classification Codes in parentheses.

^b Halogenated species are those containing atoms of chlorine, bromine, fluorine, or iodine. For any equipment, the control efficiency for mercury should be assumed to be 0. See section 2.4.4.2 for methods to estimate emissions of SO₂, CO₂, and HCl.

^c Where information on equipment was given in the reference, test data were taken from enclosed flares. Control efficiencies are assumed to be equally representative of open flares.

Table 2.4-4. (Metric Units) EMISSION FACTORS FOR SECONDARY COMPOUNDS
EXITING CONTROL DEVICES^a

Control Device	Pollutant ^b	Typical Rate, kg/hr/dscmm Methane	Emission Factor Rating
Flare ^c (50100410) (50300601)	Nitrogen dioxide	0.039	C
	Carbon monoxide	0.72	C
	Particulate matter	0.016	D
IC Engine (50100421)	Nitrogen dioxide	0.24	D
	Carbon monoxide	0.45	C
	Particulate matter	0.046	E
Boiler/Steam Turbine ^d (50100423)	Nitrogen dioxide	0.032	D
	Carbon monoxide	5.4×10^{-3}	E
	Particulate matter	7.9×10^{-3}	D
Gas Turbine (50100420)	Nitrogen dioxide	0.083	D
	Carbon monoxide	0.22	E
	Particulate matter	0.021	E

^a Source Classification Codes in parentheses.

^b No data on PM size distributions were available, however for other gas-fired combustion sources, most of the particulate matter is less than 2.5 microns in diameter. Hence, this emission factor can be used to provide estimates of PM-10 or PM-2.5 emissions. See section 2.4.4.2 for methods to estimate CO₂, SO₂, and HCl.

^c Where information on equipment was given in the reference, test data were taken from enclosed flares. Control efficiencies are assumed to be equally representative of open flares.

^d All source tests were conducted on boilers, however emission factors should also be representative of steam turbines. Emission factors are representative of boilers equipped with low-NO_x burners and flue gas recirculation. No data were available for uncontrolled NO_x emissions.

Table 2.4-5. (English Units) EMISSION RATES FOR SECONDARY COMPOUNDS
EXITING CONTROL DEVICES^a

Control Device	Pollutant ^b	Typical Rate, lb/hr/dscfm Methane	Emission Factor Rating
Flare ^c (50100410) (50300601)	Nitrogen dioxide	2.4×10^{-3}	C
	Carbon monoxide	0.045	C
	Particulate matter	1.0×10^{-3}	D
IC Engine (50100421)	Nitrogen dioxide	0.015	D
	Carbon monoxide	0.028	C
	Particulate matter	2.9×10^{-3}	E
Boiler/Steam Turbine ^d (50100423)	Nitrogen dioxide	2.0×10^{-3}	E
	Carbon monoxide	3.4×10^{-4}	E
	Particulate matter	4.9×10^{-4}	E
Gas Turbine (50100420)	Nitrogen dioxide	5.2×10^{-3}	D
	Carbon monoxide	0.014	D
	Particulate matter	1.3×10^{-3}	E

^a Source Classification Codes in parentheses.

^b Based on data for other combustion sources, most of the particulate matter will be less than 2.5 microns in diameter. Hence, this emission rate can be used to provide estimates of PM-10 or PM-2.5 emissions. See section 2.4.4.2 for methods to estimate CO₂, SO₂, and HCl.

^c Where information on equipment was given in the reference, test data were taken from enclosed flares. Control efficiencies are assumed to be equally representative of open flares.

^d All source tests were conducted on boilers, however emission factors should also be representative of steam turbines. Emission factors are representative of boilers equipped with low-NO_x burners and flue gas recirculation. No data were available for uncontrolled NO_x emissions.

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4.3 Waste Water Collection, Treatment And Storage

4.3.1 General

Many different industries generate waste water streams that contain organic compounds. Nearly all of these streams undergo collection, contaminant treatment, and/or storage operations before they are finally discharged into either a receiving body of water or a municipal treatment plant for further treatment. During some of these operations, the waste water is open to the atmosphere, and volatile organic compounds (VOC) may be emitted from the waste water into the air.

Industrial waste water operations can range from pretreatment to full-scale treatment processes. In a typical pretreatment facility, process and/or sanitary waste water and/or storm water runoff is collected, equalized, and/or neutralized and then discharged to a municipal waste water plant, also known as a publicly owned treatment works (POTWs), where it is then typically treated further by biodegradation.

In a full-scale treatment operation, the waste water must meet Federal and/or state quality standards before it is finally discharged into a receiving body of water. Figure 4.3-1 shows a generic example of collection, equalization, neutralization, and biotreatment of process waste water in a full-scale industrial treatment facility. If required, chlorine is added as a disinfectant. A storage basin contains the treated water until the winter months (usually January to May), when the facility is allowed to discharge to the receiving body of water. In the illustration, the receiving body of water is a slow-flowing stream. The facility is allowed to discharge in the rainy season when the facility waste water is diluted.

Figure 4.3-1 also presents a typical treatment system at a POTW waste water facility. Industrial waste water sent to POTWs may be treated or untreated. POTWs may also treat waste water from residential, institutional, and commercial facilities; from infiltration (water that enters the sewer system from the ground); and/or storm water runoff. These types of waste water generally do not contain VOCs. A POTW usually consists of a collection system, primary settling, biotreatment, secondary settling, and disinfection.

Collection, treatment, and storage systems are facility-specific. All facilities have some type of collection system, but the complexity will depend on the number and volume of waste water streams generated. As mentioned above, treatment and/or storage operations also vary in size and degree of treatment. The size and degree of treatment of waste water streams will depend on the volume and degree of contamination of the waste water and on the extent of contaminant removal desired.

4.3.1.1 Collection Systems -

There are many types of waste water collection systems. In general, a collection system is located at or near the point of waste water generation and is designed to receive 1 or more waste water streams and then to direct these streams to treatment and/or storage systems.

A typical industrial collection system may include drains, manholes, trenches, junction boxes, sumps, lift stations, and/or weirs. Waste water streams from different points throughout the industrial facility normally enter the collection system through individual drains or trenches connected to a main sewer line. The drains and trenches are usually open to the atmosphere. Junction boxes, sumps,

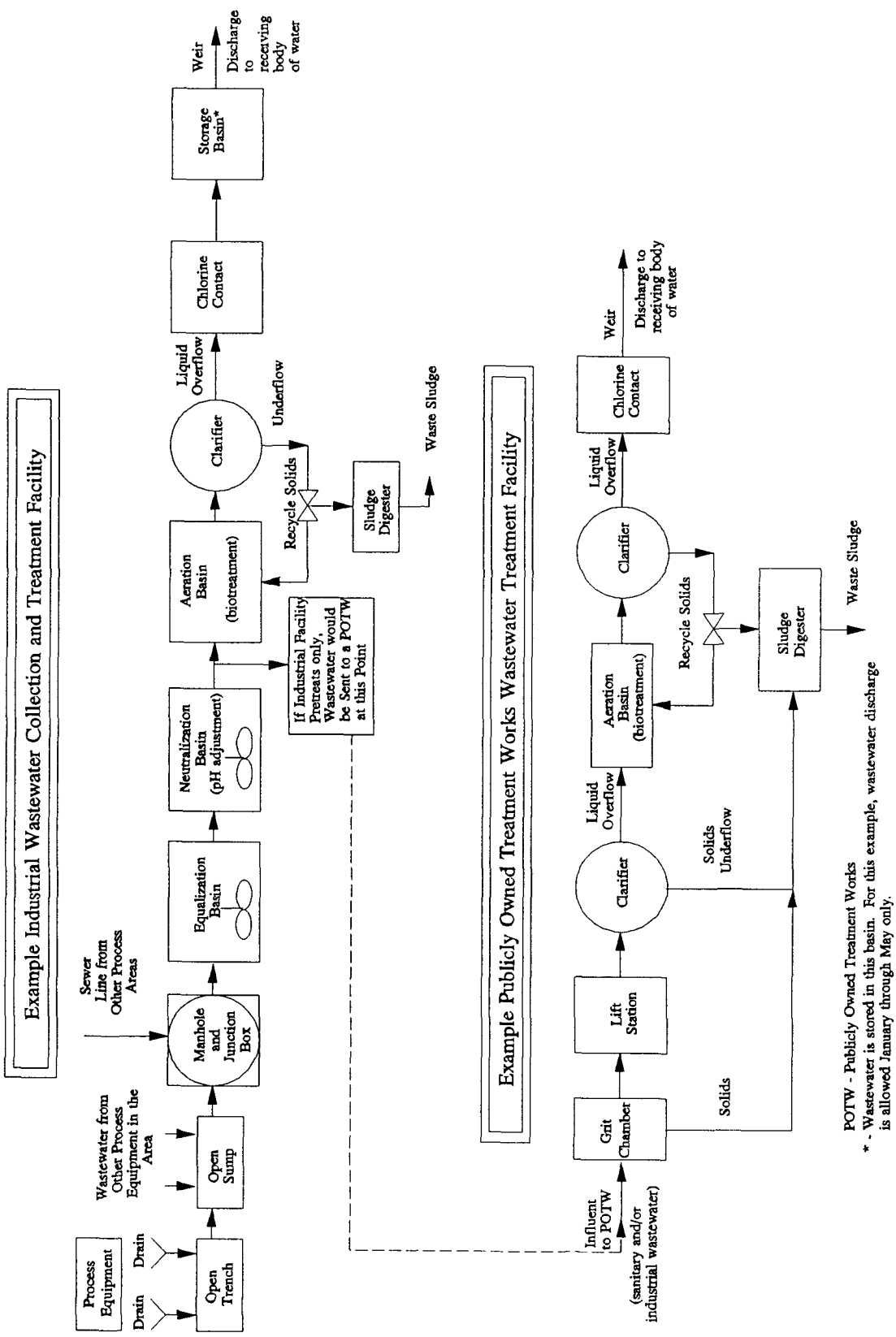


Figure 4.3.1. Typical waste water collection and treatment systems for industrial and municipal facilities.

trenches, lift stations, and weirs will be located at points requiring waste water transport from 1 area or treatment process to another.

A typical POTW facility collection system will contain a lift station, trenches, junction boxes, and manholes. Waste water is received into the POTW collection system through open sewer lines from all sources of influent waste water. As mentioned previously, these sources may convey sanitary, pretreated or untreated industrial, and/or storm water runoff waste water.

The following paragraphs briefly describe some of the most common types of waste water collection system components found in industrial and POTW facilities. Because the arrangement of collection system components is facility-specific, the order in which the collection system descriptions are presented is somewhat arbitrary.

Waste water streams normally are introduced into the collection system through individual or area drains, which can be open to the atmosphere or sealed to prevent waste water contact with the atmosphere. In industry, individual drains may be dedicated to a single source or piece of equipment. Area drains will serve several sources and are located centrally among the sources or pieces of equipment that they serve.

Manholes into sewer lines permit service, inspection, and cleaning of a line. They may be located where sewer lines intersect or where there is a significant change in direction, grade, or sewer line diameter.

Trenches can be used to transport industrial waste water from point of generation to collection units such as junction boxes and lift station, from 1 process area of an industrial facility to another, or from 1 treatment unit to another. POTWs also use trenches to transport waste water from 1 treatment unit to another. Trenches are likely to be either open or covered with a safety grating.

Junction boxes typically serve several process sewer lines, which meet at the junction box to combine multiple waste water streams into 1. Junction boxes normally are sized to suit the total flow rate of the entering streams.

Sumps are used typically for collection and equalization of waste water flow from trenches or sewer lines before treatment or storage. They are usually quiescent and open to the atmosphere.

Lift stations are usually the last collection unit before the treatment system, accepting waste water from 1 or several sewer lines. Their main function is to lift the collected waste water to a treatment and/or storage system, usually by pumping or by use of a hydraulic lift, such as a screw.

Weirs can act as open channel dams, or they can be used to discharge cleaner effluent from a settling basin, such as a clarifier. When used as a dam, the weir's face is normally aligned perpendicular to the bed and walls of the channel. Water from the channel usually flows over the weir and falls to the receiving body of water. In some cases, the water may pass through a notch or opening in the weir face. With this type of weir, flow rate through the channel can be measured. Weir height, generally the distance the water falls, is usually no more than 2 meters (6 feet). A typical clarifier weir is designed to allow settled waste water to overflow to the next treatment process. The weir is generally placed around the perimeter of the settling basin, but it can also be towards the middle. Clarifier weir height is usually only about 0.1 meters (4 inches).

4.3.1.2 Treatment And/Or Storage Systems -

These systems are designed to hold liquid wastes or waste water for treatment, storage, or disposal. They are usually composed of various types of earthen and/or concrete-lined basins, known as surface impoundments. Storage systems are used typically for accumulating waste water before its ultimate disposal, or for temporarily holding batch (intermittent) streams before treatment.

Treatment systems are divided into 3 categories: primary, secondary, or tertiary, depending on their design, operation, and application. In primary treatment systems, physical operations remove floatable and settleable solids. In secondary treatment systems, biological and chemical processes remove most of the organic matter in the waste water. In tertiary treatment systems, additional processes remove constituents not taken out by secondary treatment.

Examples of primary treatment include oil/water separators, primary clarification, equalization basins, and primary treatment tanks. The first process in an industrial waste water treatment plant is often the removal of heavier solids and lighter oils by means of oil/water separators. Oils are usually removed continuously with a skimming device, while solids can be removed with a sludge removal system.

In primary treatment, clarifiers are usually located near the beginning of the treatment process and are used to settle and remove settleable or suspended solids contained in the influent waste water. Figure 4.3-2 presents an example design of a clarifier. Clarifiers are generally cylindrical and are sized according to both the settling rate of the suspended solids and the thickening characteristics of the sludge. Floating scum is generally skimmed continuously from the top of the clarifier, while sludge is typically removed continuously from the bottom of the clarifier.

Equalization basins are used to reduce fluctuations in the waste water flow rate and organic content before the waste is sent to downstream treatment processes. Flow rate equalization results in a more uniform effluent quality in downstream settling units such as clarifiers. Biological treatment performance can also benefit from the damping of concentration and flow fluctuations, protecting biological processes from upset or failure from shock loadings of toxic or treatment-inhibiting compounds.

In primary treatment, tanks are generally used to alter the chemical or physical properties of the waste water by, for example, neutralization and the addition and dispersion of chemical nutrients. Neutralization can control the pH of the waste water by adding an acid or a base. It usually precedes biotreatment, so that the system is not upset by high or low pH values. Similarly, chemical nutrient addition/dispersion precedes biotreatment, to ensure that the biological organisms have sufficient nutrients.

An example of a secondary treatment process is biodegradation. Biological waste treatment usually is accomplished by aeration in basins with mechanical surface aerators or with a diffused air system. Mechanical surface aerators float on the water surface and rapidly mix the water. Aeration of the water is accomplished through splashing. Diffused air systems, on the other hand, aerate the water by bubbling oxygen through the water from the bottom of the tank or device. Figure 4.3-3 presents an example design of a mechanically aerated biological treatment basin. This type of basin is usually an earthen or concrete-lined pond and is used to treat large flow rates of waste water. Waste waters with high pollutant concentrations, and in particular high-flow sanitary waste waters, are typically treated using an activated sludge system where biotreatment is followed by secondary clarification. In this system, settled solids containing biomass are recycled from clarifier sludge to the biotreatment system. This creates a high biomass concentration and therefore allows biodegradation to occur over a shorter residence time. An example of a tertiary treatment process is nutrient

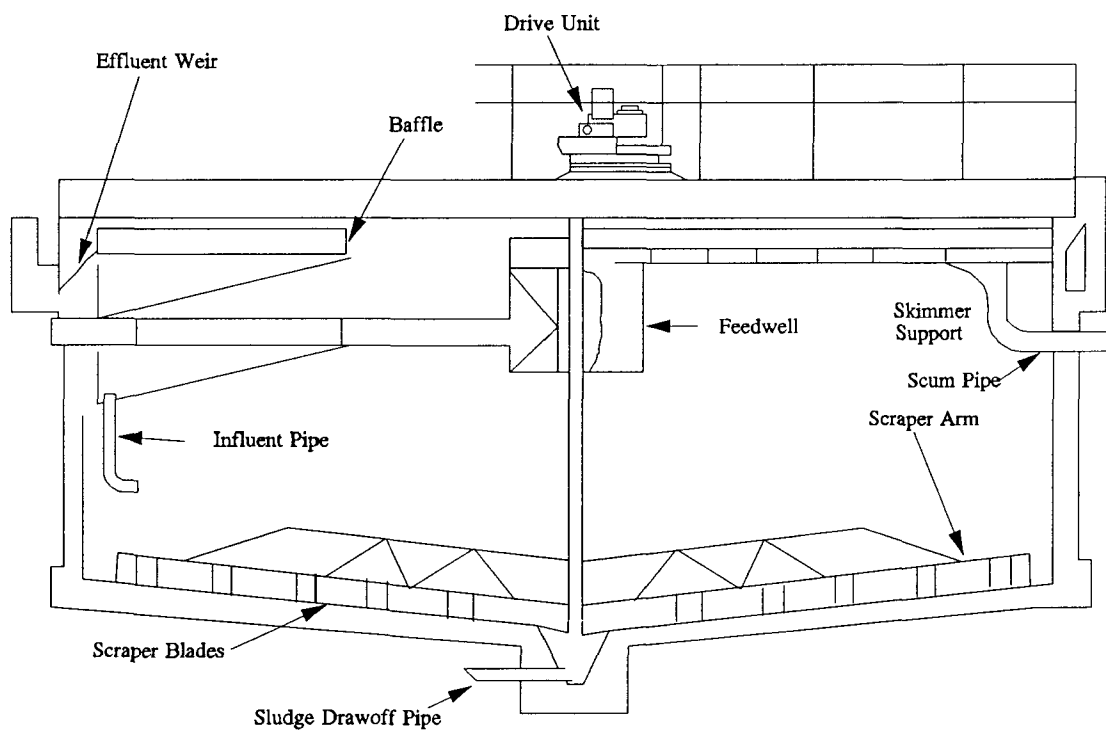


Figure 4.3-2. Example clarifier configuration.

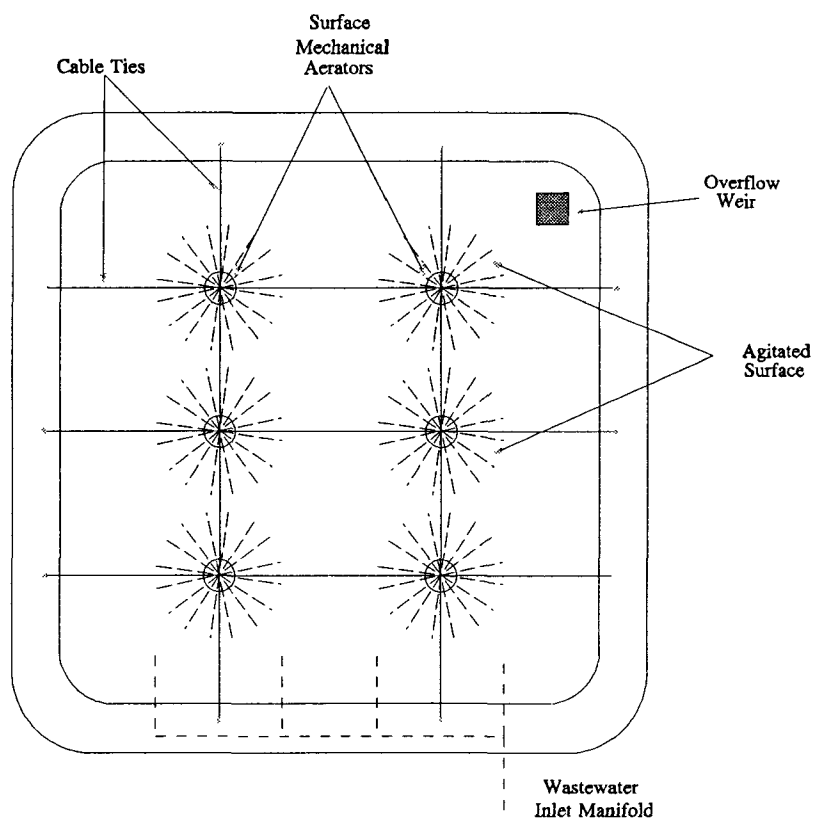


Figure 4.3-3. Example aerated biological treatment basin.

removal. Nitrogen and phosphorus are removed after biodegradation as a final treatment step before waste water is discharged to a receiving body of water.

4.3.1.3 Applications -

As previously mentioned, waste water collection, treatment, and storage are common in many industrial categories and in POTW. Most industrial facilities and POTW collect, contain, and treat waste water. However, some industries do not treat their waste water, but use storage systems for temporary waste water storage or for accumulation of waste water for ultimate disposal. For example, the Agricultural Industry does little waste water treatment but needs waste water storage systems, while the Oil and Gas Industry also has a need for waste water disposal systems.

The following are waste water treatment and storage applications identified by type of industry:

1. Mining And Milling Operations - Storage of various waste waters such as acid mine water, solvent wastes from solution mining, and leachate from disposed mining wastes. Treatment operations include settling, separation, washing, sorting of mineral products from tailings, and recovery of valuable minerals by precipitation.
2. Oil And Gas Industry - One of the largest sources of waste water. Operations treat brine produced during oil extraction and deep-well pressurizing operations, oil-water mixtures, gaseous fluids to be separated or stored during emergency conditions, and drill cuttings and drilling muds.
3. Textile And Leather Industry - Treatment and sludge disposal. Organic species treated or disposed of include dye carriers such as halogenated hydrocarbons and phenols. Heavy metals treated or disposed of include chromium, zinc, and copper. Tanning and finishing wastes may contain sulfides and nitrogenous compounds.
4. Chemical And Allied Products Industry - Process waste water treatment and storage, and sludge disposal. Waste constituents are process-specific and include organics and organic phosphates, fluoride, nitrogen compounds, and assorted trace metals.
5. Other Industries - Treatment and storage operations are found at petroleum refining, primary metals production, wood treating, and metal finishing facilities. Various industries store and/or treat air pollution scrubber sludge and dredging spoils sludge (i. e., settled solids removed from the floor of a surface impoundment).

4.3.2 Emissions

VOCs are emitted from waste water collection, treatment, and storage systems through volatilization of organic compounds at the liquid surface. Emissions can occur by diffusive or convective mechanisms, or both. Diffusion occurs when organic concentrations at the water surface are much higher than ambient concentrations. The organics volatilize, or diffuse into the air, in an attempt to reach equilibrium between aqueous and vapor phases. Convection occurs when air flows over the water surface, sweeping organic vapors from the water surface into the air. The rate of volatilization relates directly to the speed of the air flow over the water surface.

Other factors that can affect the rate of volatilization include waste water surface area, temperature, and turbulence; waste water retention time in the system(s); the depth of the waste water in the system(s); the concentration of organic compounds in the waste water and their physical

properties, such as volatility and diffusivity in water; the presence of a mechanism that inhibits volatilization, such as an oil film; or a competing mechanism, such as biodegradation.

The rate of volatilization can be determined by using mass transfer theory. Individual gas phase and liquid phase mass transfer coefficients (k_g and k_l , respectively) are used to estimate overall mass transfer coefficients (K , K_{oil} , and K_D) for each VOC.¹⁻² Figure 4.3-4 presents a flow diagram to assist in determining the appropriate emissions model for estimating VOC emissions from various types of waste water treatment, storage, and collection systems. Tables 4.3-1 and 4.3-2, respectively, present the emission model equations and definitions.

VOCs vary in their degree of volatility. The emission models presented in this section can be used for high-, medium-, and low-volatility organic compounds. The Henry's law constant (HLC) is often used as a measure of a compound's volatility, or the diffusion of organics into the air relative to diffusion through liquids. High-volatility VOCs are $HLC > 10^{-3}$ atm-m³/gmol; medium-volatility VOCs are $10^{-3} < HLC < 10^{-5}$ atm-m³/gmol; and low-volatility VOCs are $HLC < 10^{-5}$ atm-m³/gmol.¹

The design and arrangement of collection, treatment, and storage systems are facility-specific; therefore the most accurate waste water emissions estimate will come from actual tests of a facility (i. e., tracer studies or direct measurement of emissions from openings). If actual data are unavailable, the emission models provided in this section can be used.

Emission models should be given site-specific information whenever it is available. The most extensive characterization of an actual system will produce the most accurate estimates from an emissions model. In addition, when addressing systems involving biodegradation, the accuracy of the predicted rate of biodegradation is improved when site-specific compound biorates are input. Reference 3 contains information on a test method for measuring site-specific biorates, and Table 4.3-4 presents estimated biorates for approximately 150 compounds.

To estimate an emissions rate (N), the first step is to calculate individual gas phase and liquid phase mass transfer coefficients k_g and k_l . These individual coefficients are then used to calculate the overall mass transfer coefficient, K . Exceptions to this procedure are the calculation of overall mass transfer coefficients in the oil phase, K_{oil} , and the overall mass transfer coefficient for a weir, K_D . K_{oil} requires only k_g , and K_D does not require any individual mass transfer coefficients. The overall mass transfer coefficient is then used to calculate the emissions rates. The following discussion describes how to use Figure 4.3-4 to determine an emission rate. An example calculation is presented in Part 4.3.2.1 below.

Figure 4.3-4 is divided into 2 sections: waste water treatment and storage systems, and waste water collection systems. Waste water treatment and storage systems are further segmented into aerated/nonaerated systems, biologically active systems, oil film layer systems, and surface impoundment flowthrough or disposal. In flowthrough systems, waste water is treated and discharged to a POTW or a receiving body of water, such as a river or stream. All waste water collection systems are by definition flowthrough. Disposal systems, on the other hand, do not discharge any waste water.

Figure 4.3-4 includes information needed to estimate air emissions from junction boxes, lift stations, sumps, weirs, and clarifier weirs. Sumps are considered quiescent, but junction boxes, lift stations, and weirs are turbulent in nature. Junction boxes and lift stations are turbulent because incoming flow is normally above the water level in the component, which creates some splashing.

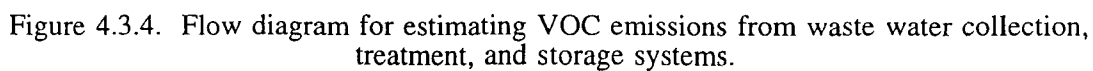


Table 4.3-1. MASS TRANSFER CORRELATIONS AND EMISSIONS EQUATIONS^a

Equation No.	Equation
<u>Individual liquid (k_ℓ) and gas (k_g) phase mass transfer coefficients</u>	
1	$k_\ell \text{ (m/s)} = (2.78 \times 10^{-6})(D_w/D_{\text{ether}})^{2/3}$ <p>For: $0 < U_{10} < 3.25 \text{ m/s}$ and all F/D ratios</p> $k_\ell \text{ (m/s)} = [(2.605 \times 10^{-9})(F/D) + (1.277 \times 10^{-7})](U_{10})^2(D_w/D_{\text{ether}})^{2/3}$ <p>For: $U_{10} > 3.25 \text{ m/s}$ and $14 < F/D < 51.2$</p> $k_\ell \text{ (m/s)} = (2.61 \times 10^{-7})(U_{10})^2(D_w/D_{\text{ether}})^{2/3}$ <p>For: $U_{10} > 3.25 \text{ m/s}$ and $F/D > 51.2$</p> $k_\ell \text{ (m/s)} = 1.0 \times 10^{-6} + 144 \times 10^{-4} (U^*)^{2.2} (Sc_L)^{-0.5}; U^* < 0.3$ $k_\ell \text{ (m/s)} = 1.0 \times 10^{-6} + 34.1 \times 10^{-4} U^* (Sc_L)^{-0.5}; U^* > 0.3$ <p>For: $U_{10} > 3.25 \text{ m/s}$ and $F/D < 14$</p> <p>where:</p> $U^* \text{ (m/s)} = (0.01)(U_{10})(6.1 + 0.63(U_{10}))^{0.5}$ $Sc_L = \mu_L/(\rho_L D_w)$ $F/D = 2(A/\pi)^{0.5}$
2	$k_g \text{ (m/s)} = (4.82 \times 10^{-3})(U_{10})^{0.78} (Sc_G)^{-0.67} (d_e)^{-0.11}$ <p>where:</p> $Sc_G = \mu_a/(\rho_a D_a)$ $d_e \text{ (m)} = 2(A/\pi)^{0.5}$
3	$k_\ell \text{ (m/s)} = [(8.22 \times 10^{-9})(J)(\text{POWR})(1.024)^{(T-20)}(O_\ell)(10^6) * (MW_L)/(V a_v \rho_L)](D_w/D_{O2,w})^{0.5}$ <p>where:</p> $\text{POWR (hp)} = (\text{total power to aerators})(V)$ $V a_v \text{ (ft}^2\text{)} = (\text{fraction of area agitated})(A)$
4	$k_g \text{ (m/s)} = (1.35 \times 10^{-7})(\text{Re})^{1.42} (P)^{0.4} (Sc_G)^{0.5} (\text{Fr})^{-0.21} (D_a \text{ MW}_a/d)$ <p>where:</p> $\text{Re} = d^2 w \rho_a / \mu_a$ $P = [(0.85)(\text{POWR})(550 \text{ ft-lb}_f/\text{s-hp})/N_I] g_c / (\rho_L (d^*)^5 w^3)$ $Sc_G = \mu_a / (\rho_a D_a)$ $\text{Fr} = (d^*) w^2 / g_c$
5	$k_\ell \text{ (m/s)} = (f_{\text{air},\ell})(Q)/[3600 \text{ s/min} (h_c)(\pi d_c)]$ <p>where:</p> $f_{\text{air},\ell} = 1 - 1/r$ $r = \exp [0.77(h_c)^{0.623} (Q/\pi d_c)^{0.66} (D_w/D_{O2,w})^{0.66}]$
6	$k_g \text{ (m/s)} = 0.001 + (0.0462(U^{**})(Sc_G)^{-0.67})$ <p>where:</p> $U^{**} \text{ (m/s)} = [6.1 + (0.63)(U_{10})]^{0.5} (U_{10}/100)$ $Sc_G = \mu_a / (\rho_a D_a)$

Table 4.3-1 (cont.).

Equation No.	Equation
<u>Overall mass transfer coefficients for water (K) and oil (K_{oil}) phases and for weirs (K_D)</u>	
7	$K = (k_\ell \text{ Keq } k_g) / (\text{Keq } k_g + k_\ell)$ <p>where:</p> $\text{Keq} = H/(RT)$
8	$K \text{ (m/s)} = \left[\frac{[\text{MW}_L / (k_{\ell} \rho_L * (100 \text{ cm/m})] + [\text{MW}_a / (k_g \rho_a H * 55,555 (100 \text{ cm/m}))]}{55,555 (100 \text{ cm/m})} \right]^{-1} \text{MW}_L / [(100 \text{ cm/m}) \rho_L]$
9	$K_{\text{oil}} = k_g \text{ Keq}_{\text{oil}}$ <p>where:</p> $\text{Keq}_{\text{oil}} = P^* \rho_a \text{MW}_{\text{oil}} / (\rho_{\text{oil}} \text{MW}_a P_o)$
10	$K_D = 0.16h (D_w / D_{O2,w})^{0.75}$
<u>Air emissions (N)</u>	
11	$N(\text{g/s}) = (1 - Ct/Co) V Co/t$ <p>where:</p> $Ct/Co = \exp[-K A t/V]$
12	$N(\text{g/s}) = K C_L A$ <p>where:</p> $C_L(\text{g/m}^3) = Q Co / (KA + Q)$
13	$N(\text{g/s}) = (1 - Ct/Co) V Co/t$ <p>where:</p> $Ct/Co = \exp[-(KA + \text{Keq} Q_a) t/V]$
14	$N(\text{g/s}) = (KA + Q_a \text{Keq}) C_L$ <p>where:</p> $C_L(\text{g/m}^3) = Q Co / (KA + Q + Q_a \text{Keq})$
15	$N(\text{g/s}) = (1 - Ct/Co) KA / (KA + K_{\text{max}} b_i V / K_s) V Co/t$ <p>where:</p> $Ct/Co = \exp[-K_{\text{max}} b_i t / K_s - K A t/V]$
16	$N(\text{g/s}) = K C_L A$ <p>where:</p> $C_L(\text{g/m}^3) = [-b + (b^2 - 4ac)^{0.5}] / (2a)$ <p>and:</p> $a = KA/Q + 1$ $b = K_s(KA/Q + 1) + K_{\text{max}} b_i V/Q - Co$ $c = -K_s Co$

Table 4.3-1 (cont.).

Equation No.	Equation
17	$N(g/s) = (1 - C_{t_{oil}}/C_{o_{oil}})V_{oil}C_{o_{oil}}/t$ <p>where:</p> $C_{t_{oil}}/C_{o_{oil}} = \exp[-K_{oil} t/D_{oil}]$ <p>and:</p> $C_{o_{oil}} = Kow Co/[1 - FO + FO(Kow)]$ $V_{oil} = (FO)(V)$ $D_{oil} = (FO)(V)/A$
18	$N(g/s) = K_{oil}C_{L,oil}A$ <p>where:</p> $C_{L,oil}(g/m^3) = Q_{oil}C_{o_{oil}}/(K_{oil}A + Q_{oil})$ <p>and:</p> $C_{o_{oil}} = Kow Co/[1 - FO + FO(Kow)]$ $Q_{oil} = (FO)(Q)$
19	$N(g/s) = (1 - Ct/Co)(KA + Q_aK_{eq})/(KA + Q_aK_{eq} + K_{max} b_i V/K_s) V Co/t$ <p>where:</p> $Ct/Co = \exp[-(KA + K_{eq}Q_a)t/V - K_{max} b_i t/K_s]$
20	$N(g/s) = (KA + Q_aK_{eq})C_L$ <p>where:</p> $C_L(g/m^3) = [-b + (b^2 - 4ac)^{0.5}]/(2a)$ <p>and:</p> $a = (KA + Q_aK_{eq})/Q + 1$ $b = K_s[(KA + Q_aK_{eq})/Q + 1] + K_{max} b_i V/Q - Co$ $c = -K_sCo$
21	$N(g/s) = (1 - \exp[-K_D])Q Co$
22	$N(g/s) = K_{oil}C_{L,oil}A$ <p>where:</p> $C_{L,oil}(g/m^3) = Q_{oil}(C_{o_{oil}}^*)/(K_{oil}A + Q_{oil})$ <p>and:</p> $C_{o_{oil}}^* = Co/FO$ $Q_{oil} = (FO)(Q)$
23	$N(g/s) = (1 - C_{t_{oil}}/C_{o_{oil}}^*)(V_{oil})(C_{o_{oil}}^*)/t$ <p>where:</p> $C_{t_{oil}}/C_{o_{oil}}^* = \exp[-K_{oil} t/D_{oil}]$ <p>and:</p> $C_{o_{oil}}^* = Co/FO$ $V_{oil} = (FO)(V)$ $D_{oil} = (FO)(V)/A$
24	$N(g/s) = (1 - \exp[-K \pi d_c h_c/Q])Q Co$

^a All parameters in numbered equations are defined in Table 4.3-2.

Table 4.3-2. PARAMETER DEFINITIONS FOR MASS TRANSFER CORRELATIONS AND EMISSIONS EQUATIONS

Parameter	Definition	Units	Code ^a
A	Waste water surface area	m ² or ft ²	A
b _i	Biomass concentration (total biological solids)	g/m ³	B
C _L	Concentration of constituent in the liquid phase	g/m ³	D
C _{L,oil}	Concentration of constituent in the oil phase	g/m ³	D
C _o	Initial concentration of constituent in the liquid phase	g/m ³	A
C _{o,oil}	Initial concentration of constituent in the oil phase considering mass transfer resistance between water and oil phases	g/m ³	D
C _{o,oil} [*]	Initial concentration of constituent in the oil phase considering no mass transfer resistance between water and oil phases	g/m ³	D
C _t	Concentration of constituent in the liquid phase at time = t	g/m ³	D
C _{t,oil}	Concentration of constituent in the oil phase at time = t	g/m ³	D
d	Impeller diameter	cm	B
D	Waste water depth	m or ft	A,B
d [*]	Impeller diameter	ft	B
D _a	Diffusivity of constituent in air	cm ² /s	C
d _c	Clarifier diameter	m	B
d _e	Effective diameter	m	D
D _{ether}	Diffusivity of ether in water	cm ² /s	(8.5x10 ⁻⁶) ^b
D _{O₂,w}	Diffusivity of oxygen in water	cm ² /s	(2.4x10 ⁻⁵) ^b
D _{oil}	Oil film thickness	m	B
D _w	Diffusivity of constituent in water	cm ² /s	C
f _{air,ℓ}	Fraction of constituent emitted to the air, considering zero gas resistance	dimensionless	D
F/D	Fetch to depth ratio, d _e /D	dimensionless	D
FO	Fraction of volume which is oil	dimensionless	B
Fr	Froude number	dimensionless	D
g _c	Gravitation constant (a conversion factor)	lb _m -ft/s ² -lb _f	32.17

Table 4.3-2 (cont.).

Parameter	Definition	Units	Code ^a
h	Weir height (distance from the waste water overflow to the receiving body of water)	ft	B
h_c	Clarifier weir height	m	B
H	Henry's law constant of constituent	atm-m ³ /gmol	C
J	Oxygen transfer rating of surface aerator	lb O ₂ /(hr-hp)	B
K	Overall mass transfer coefficient for transfer of constituent from liquid phase to gas phase	m/s	D
K_D	Volatilization-re-aeration theory mass transfer coefficient	dimensionless	D
K_{eq}	Equilibrium constant or partition coefficient (concentration in gas phase/concentration in liquid phase)	dimensionless	D
$K_{eq_{oil}}$	Equilibrium constant or partition coefficient (concentration in gas phase/concentration in oil phase)	dimensionless	D
k_g	Gas phase mass transfer coefficient	m/s	D
k_l	Liquid phase mass transfer coefficient	m/s	D
K_{max}	Maximum biorate constant	g/s-g biomass	A,C
K_{oil}	Overall mass transfer coefficient for transfer of constituent from oil phase to gas phase	m/s	D
K_{ow}	Octanol-water partition coefficient	dimensionless	C
K_s	Half saturation biorate constant	g/m ³	A,C
MW_a	Molecular weight of air	g/gmol	29
MW_{oil}	Molecular weight of oil	g/gmol	B
MW_L	Molecular weight of water	g/gmol	18
N	Emissions	g/s	D
N_I	Number of aerators	dimensionless	A,B
O_t	Oxygen transfer correction factor	dimensionless	B
P	Power number	dimensionless	D
P^*	Vapor pressure of the constituent	atm	C
P_o	Total pressure	atm	A
POWER	Total power to aerators	hp	B
Q	Volumetric flow rate	m ³ /s	A

Table 4.3-2 (cont.).

Parameter	Definition	Units	Code ^a
Q_a	Diffused air flow rate	m^3/s	B
Q_{oil}	Volumetric flow rate of oil	m^3/s	B
r	Deficit ratio (ratio of the difference between the constituent concentration at solubility and actual constituent concentration in the upstream and the downstream)	dimensionless	D
R	Universal gas constant	$atm \cdot m^3/gmol \cdot K$	8.21×10^{-5}
Re	Reynolds number	dimensionless	D
Sc_G	Schmidt number on gas side	dimensionless	D
Sc_L	Schmidt number on liquid side	dimensionless	D
T	Temperature of water	$^{\circ}C$ or Kelvin (K)	A
t	Residence time of disposal	s	A
U^*	Friction velocity	m/s	D
U^{**}	Friction velocity	m/s	D
U_{10}	Wind speed at 10 m above the liquid surface	m/s	B
V	Waste water volume	m^3 or ft^3	A
Va_v	Turbulent surface area	ft^2	B
V_{oil}	Volume of oil	m^3	B
w	Rotational speed of impeller	rad/s	B
ρ_a	Density of air	g/cm^3	$(1.2 \times 10^{-3})^b$
ρ_L	Density of water	g/cm^3 or lb/ft^3	1^b or 62.4^b
ρ_{oil}	Density of oil	g/m^3	B
μ_a	Viscosity of air	$g/cm \cdot s$	$(1.81 \times 10^{-4})^b$
μ_L	Viscosity of water	$g/cm \cdot s$	$(8.93 \times 10^{-3})^b$

^a Code:

A = Site-specific parameter.

B = Site-specific parameter. For default values, see Table 4.3-3.

C = Parameter can be obtained from literature. See Attachment 1 for a list of ~150 compound chemical properties at $T = 25^{\circ}C$ ($298^{\circ}K$).

D = Calculated value.

^b Reported values at $25^{\circ}C$ ($298^{\circ}K$).

Table 4.3-3. SITE-SPECIFIC DEFAULT PARAMETERS^a

Default Parameter ^b	Definition	Default Value
General		
T	Temperature of water	298°K
U ₁₀	Windspeed	4.47 m/s
Biotreatment Systems		
b _i	Biomass concentration (for biologically active systems)	
	Quiescent treatment systems	50 g/m ³
	Aerated treatment systems	300 g/m ³
	Activated sludge units	4000 g/m ³
POWR	Total power to aerators (for aerated treatment systems) (for activated sludge)	0.75 hp/1000 ft ³ (V) 2 hp/1000 ft ³ (V)
W	Rotational speed of impeller (for aerated treatment systems)	126 rad/s (1200 rpm)
d(d*)	Impeller diameter (for aerated treatment systems)	61 cm (2 ft)
Va _v	Turbulent surface area (for aerated treatment systems) (for activated sludge)	0.24 (A) 0.52 (A)
J	Oxygen transfer rating to surface aerator (for aerated treatment systems)	3 lb O ₂ /hp•hr
O _t	Oxygen transfer correction factor (for aerated treatment systems)	0.83
N _I	Number of aerators	POWR/75
Diffused Air Systems		
Q _a	Diffused air volumetric flow rate	0.0004(V) m ³ /s
Oil Film Layers		
MW _{oil}	Molecular weight of oil	282 g/gmol
D _{oil}	Depth of oil layer	0.001 (V/A) m
V _{oil}	Volume of oil	0.001 (V) m ³
Q _{oil}	Volumetric flow rate of oil	0.001 (Q) m ³ /s
ρ _{oil}	Density of oil	0.92 g/cm ³

Table 4.3-3 (cont.).

Default Parameter ^b	Definition	Default Value
FO	Fraction of volume which is oil ^c	0.001
Junction Boxes		
D	Depth of Junction Box	0.9 m
N _I	Number of aerators	1
Lift Station		
D	Depth of Lift Station	1.5 m
N _I	Number of aerators	1
Sump		
D	Depth of sump	5.9 m
Weirs		
d _c	Clarifier weir diameter ^d	28.5 m
h	Weir height	1.8 m
h _c	Clarifier weir height ^e	0.1 m

^a Reference 1.^b As defined in Table 4.3-2.^c Reference 4.^d Reference 2.^e Reference 5.

Waste water falls or overflows from weirs and creates splashing in the receiving body of water (both weir and clarifier weir models). Waste water from weirs can be aerated by directing it to fall over steps, usually only the weir model.

Assessing VOC emissions from drains, manholes, and trenches is also important in determining the total waste water facility emissions. As these sources can be open to the atmosphere and closest to the point of waste water generation (i. e., where water temperatures and pollutant concentrations are greatest), emissions can be significant. Currently, there are no well-established emission models for these collection system types. However, work is being performed to address this need.

Preliminary models of VOC emissions from waste collection system units have been developed.⁴ The emission equations presented in Reference 4 are used with standard collection system parameters to estimate the fraction of the constituents released as the waste water flows through each unit. The fractions released from several units are estimated for high-, medium-, and low-volatility compounds. The units used in the estimated fractions included open drains, manhole covers, open trench drains, and covered sumps.

The numbers in Figure 4.3-4 under the columns for k_l , k_g , K_{oil} , K_D , K , and N refer to the appropriate equations in Table 4.3-1.^a Definitions for all parameters in these equations are given in Table 4.3-2. Table 4.3-2 also supplies the units that must be used for each parameter, with codes to help locate input values. If the parameter is coded with the letter A, a site-specific value is required. Code B also requires a site-specific parameter, but defaults are available. These defaults are typical or average values and are presented by specific system in Table 4.3-3.

Code C means the parameter can be obtained from literature data. Table 4.3-4 contains a list of approximately 150 chemicals and their physical properties needed to calculate emissions from waste water, using the correlations presented in Table 4.3-1. All properties are at 25°C (77°F). A more extensive chemical properties data base is contained in Appendix C of Reference 1.) Parameters coded D are calculated values.

Calculating air emissions from waste water collection, treatment, and storage systems is a complex procedure, especially if several systems are present. Performing the calculations by hand may result in errors and will be time consuming. A personal computer program called the Surface Impoundment Modeling System (SIMS) is now available for estimating air emissions. The program is menu driven and can estimate air emissions from all surface impoundment models presented in Figure 4.3-4, individually or in series. The program requires for each collection, treatment, or storage system component, at a minimum, the waste water flow rate and component surface area. All other inputs are provided as default values. Any available site-specific information should be entered in place of these defaults, as the most fully characterized system will provide the most accurate emissions estimate.

The SIMS program with user's manual and background technical document can be obtained through state air pollution control agencies and through the U. S. Environmental Protection Agency's Control Technology Center in Research Triangle Park, NC, telephone (919) 541-0800. The user's manual and background technical document should be followed to produce meaningful results.

The SIMS program and user's manual also can be downloaded from EPA's Clearinghouse For Inventories and Emission Factors (CHIEF) electronic bulletin board (BB). The CHIEF BB is open to all persons involved in air emission inventories. To access this BB, one needs a computer, modem, and communication package capable of communicating at up to 14,400 baud, 8 data bits, 1 stop bit, and no parity (8-N-1). This BB is part of EPA's OAQPS Technology Transfer Network system and its telephone number is (919) 541-5742. First-time users must register before access is allowed.

Emissions estimates from SIMS are based on mass transfer models developed by Emissions Standards Division (ESD) during evaluations of TSDFs and VOC emissions from industrial waste water. As a part of the TSDF project, a Lotus[®] spreadsheet program called CHEMDAT7 was developed for estimating VOC emissions from waste water land treatment systems, open landfills, closed landfills, and waste storage piles, as well as from various types of surface impoundments. For more information about CHEMDAT7, contact the ESD's Chemicals And Petroleum Branch (MD 13), US EPA, Research Triangle Park, NC 27711.

^aAll emission model systems presented in Figure 4.3-4 imply a completely mixed or uniform waste water concentration system. Emission models for a plug flow system, or system in which there is no axial, or horizontal mixing, are too extensive to be covered in this document. (An example of plug flow might be a high waste water flow in a narrow channel.) For information on emission models of this type, see Reference 1.

4.3.2.1 Example Calculation -

An example industrial facility operates a flowthrough, mechanically aerated biological treatment impoundment that receives waste water contaminated with benzene at a concentration of 10.29 g/m^3 .

The following format is used for calculating benzene emissions from the treatment process:

- I. Determine which emission model to use
- II. User-supplied information
- III. Defaults
- IV. Pollutant physical property data and water, air, and other properties
- V. Calculate individual mass transfer coefficient
- VI. Calculate the overall mass transfer coefficients
- VII. Calculate VOC emissions

I. Determine Which Emission Model To Use — Following the flow diagram in Figure 4.3-4, the emission model for a treatment system that is aerated, but not by diffused air, is biologically active, and is a flowthrough system, contains the following equations:

Parameter	Definition	Equation Nos. from Table 4.3-1
K	Overall mass transfer coefficient, m/s	7
k_l	Individual liquid phase mass transfer coefficient, m/s	1,3
k_g	Individual gas phase mass transfer coefficient, m/s	2,4
N	VOC emissions, g/s	16

II. User-supplied Information — Once the correct emission model is determined, some site-specific parameters are required. As a minimum for this model, site-specific flow rate, waste water surface area and depth, and pollutant concentration should be provided. For this example, these parameters have the following values:

$$\begin{aligned}
 Q &= \text{Volumetric flow rate} = 0.0623 \text{ m}^3/\text{s} \\
 D &= \text{Waste water depth} = 1.97 \text{ m} \\
 A &= \text{Waste water surface area} = 17,652 \text{ m}^2 \\
 Co &= \text{Initial benzene concentration in the liquid phase} = 10.29 \text{ g/m}^3
 \end{aligned}$$

III. Defaults — Defaults for some emission model parameters are presented in Table 4.3-3. Generally, site-specific values should be used when available. For this facility, all available general and biotreatment system defaults from Table 4.3-3 were used:

$$\begin{aligned}
 U_{10} &= \text{Wind speed at 10 m above the liquid surface} = e = 4.47 \text{ m/s} \\
 T &= \text{Temperature of water} = 25^\circ\text{C} \text{ (} 298^\circ\text{K)} \\
 b_i &= \text{Biomass concentration for aerated treatment systems} = 300 \text{ g/m}^3 \\
 J &= \text{Oxygen transfer rating to surface aerator} = 3 \text{ lb O}_2/\text{hp-hr} \\
 \text{POWR} &= \text{Total power to aerators} = 0.75 \text{ hp/1,000 ft}^3 \text{ (V)} \\
 O_t &= \text{Oxygen transfer correction factor} = 0.83 \\
 Va_v &= \text{Turbulent surface area} = 0.24 \text{ (A)} \\
 d &= \text{Impeller diameter} = 61 \text{ cm}
 \end{aligned}$$

- d^* = Impeller diameter = 2 ft
 w = Rotational speed of impeller = 126 rad/s
 N_I = Number of aerators = POWR/75 hp

IV. Pollutant Physical Property Data, And Water, Air and Other Properties — For each pollutant, the specific physical properties needed by this model are listed in Table 4.3-4. Water, air, and other property values are given in Table 4.3-2.

A. Benzene (from Table 4.3-4)

- $D_{w,benzene}$ = Diffusivity of benzene in water = $9.8 \times 10^{-6} \text{ cm}^2/\text{s}$
 $D_{a,benzene}$ = Diffusivity of benzene in air = $0.088 \text{ cm}^2/\text{s}$
 $H_{benzene}$ = Henry's law constant for benzene = $0.0055 \text{ atm} \cdot \text{m}^3/\text{gmol}$
 $K_{max,benzene}$ = Maximum biorate constant for benzene = $5.28 \times 10^{-6} \text{ g/g-s}$
 $K_{s,benzene}$ = Half saturation biorate constant for benzene = 13.6 g/m^3

B. Water, Air, and Other Properties (from Table 4.3-3)

- ρ_a = Density of air = $1.2 \times 10^3 \text{ g/cm}^3$
 ρ_L = Density of water = 1 g/cm^3 ($62.4 \text{ lb}_m/\text{ft}^3$)
 μ_a = Viscosity of air = $1.81 \times 10^{-4} \text{ g/cm-s}$
 $D_{O_2,w}$ = Diffusivity of oxygen in water = $2.4 \times 10^{-5} \text{ cm}^2/\text{s}$
 D_{ether} = Diffusivity of ether in water = $8.5 \times 10^{-6} \text{ cm}^2/\text{s}$
 MW_L = Molecular weight of water = 18 g/gmol
 MW_a = Molecular weight of air = 29 g/gmol
 g_c = Gravitation constant = $32.17 \text{ lb}_m\text{-ft/lb}_f\text{-s}^2$
 R = Universal gas constant = $8.21 \times 10^{-5} \text{ atm-m}^3/\text{gmol}$

V. Calculate Individual Mass Transfer Coefficients — Because part of the impoundment is turbulent and part is quiescent, individual mass transfer coefficients are determined for both turbulent and quiescent areas of the surface impoundment.

Turbulent area of impoundment — Equations 3 and 4 from Table 4.3-1.

A. Calculate the individual liquid mass transfer coefficient, k_L :

$$k_L(\text{m/s}) = [(8.22 \times 10^{-9})(J)(\text{POWR})(1.024)^{(T-20)} * (O_L)(10^6)MW_L/(V_a v \rho_L)](D_w/D_{O_2,w})^{0.5}$$

The total power to the aerators, POWR, and the turbulent surface area, $V_a v$, are calculated separately [Note: some conversions are necessary]:

1. Calculate total power to aerators, POWR (Default presented in III):

$$\begin{aligned}
 \text{POWR (hp)} &= 0.75 \text{ hp}/1,000 \text{ ft}^3 \text{ (V)} \\
 V &= \text{waste water volume, m}^3 \\
 V \text{ (m}^3\text{)} &= (A)(D) = (17,652 \text{ m}^2)(1.97 \text{ m}) \\
 V &= 34,774 \text{ m}^3 \\
 \text{POWR} &= (0.75 \text{ hp}/1,000 \text{ ft}^3)(\text{ft}^3/0.028317 \text{ m}^3)(34,774 \text{ m}^3) \\
 &= 921 \text{ hp}
 \end{aligned}$$

2. Calculate turbulent surface area, $V_a v$ (default presented in III):

$$\begin{aligned}
 V_a v \text{ (ft}^2\text{)} &= 0.24 (A) \\
 &= 0.24(17,652 \text{ m}^2)(10.758 \text{ ft}^2/\text{m}^2) \\
 &= 45,576 \text{ ft}^2
 \end{aligned}$$

Now, calculate k_ℓ , using the above calculations and information from II, III, and IV:

$$\begin{aligned} k_\ell \text{ (m/s)} &= [(8.22 \times 10^{-9})(3 \text{ lb O}_2/\text{hp-hr})(921 \text{ hp}) * \\ &\quad (1.024)^{(25-20)}(0.83)(10^6)(18 \text{ g/gmol})/ \\ &\quad ((45,576 \text{ ft}^2)(1 \text{ g/cm}^3))] * \\ &\quad [(9.8 \times 10^{-6} \text{ cm}^2/\text{s})/(2.4 \times 10^{-5} \text{ cm}^2/\text{s})]^{0.5} \\ &= (0.00838)(0.639) \\ k_\ell &= 5.35 \times 10^{-3} \text{ m/s} \end{aligned}$$

B. Calculate the individual gas phase mass transfer coefficient, k_g :

$$k_g \text{ (m/s)} = (1.35 \times 10^{-7})(\text{Re})^{1.42}(\text{P})^{0.4}(\text{Sc}_G)^{0.5}(\text{Fr})^{-0.21}(\text{D}_a \text{ MW}_a/\text{d})$$

The Reynolds number, Re, power number, P, Schmidt number on the gas side, Sc_G , and Froude's number Fr, are calculated separately:

1. Calculate Reynolds number, Re:

$$\begin{aligned} \text{Re} &= d^2 w \rho_a / \mu_a \\ &= (61 \text{ cm})^2 (126 \text{ rad/s}) (1.2 \times 10^{-3} \text{ g/cm}^3) / (1.81 \times 10^{-4} \text{ g/cm-s}) \\ &= 3.1 \times 10^6 \end{aligned}$$

2. Calculate power number, P:

$$\begin{aligned} P &= [(0.85)(\text{POWER})(550 \text{ ft-lb}_f/\text{s-hp})/N_I] g_c / (\rho_L (d^*)^5 w^3) \\ N_I &= \text{POWER}/75 \text{ hp (default presented in III)} \\ P &= (0.85)(75 \text{ hp})(\text{POWER}/\text{POWER})(550 \text{ ft-lb}_f/\text{s-hp}) * \\ &\quad (32.17 \text{ lb}_m\text{-ft/lb}_f\text{-s}^2) / [(62.4 \text{ lb}_m/\text{ft}^3)(2 \text{ ft})^5 (126 \text{ rad/s})^3] \\ &= 2.8 \times 10^{-4} \end{aligned}$$

3. Calculate Schmidt number on the gas side, Sc_G :

$$\begin{aligned} \text{Sc}_G &= \mu_a / (\rho_a D_a) \\ &= (1.81 \times 10^{-4} \text{ g/cm-s}) / [(1.2 \times 10^{-3} \text{ g/cm}^3)(0.088 \text{ cm}^2/\text{s})] \\ &= 1.71 \end{aligned}$$

4. Calculate Froude number, Fr:

$$\begin{aligned} \text{Fr} &= (d^*) w^2 / g_c \\ &= (2 \text{ ft})(126 \text{ rad/s})^2 / (32.17 \text{ lb}_m\text{-ft/lb}_f\text{-s}^2) \\ &= 990 \end{aligned}$$

Now, calculate k_g using the above calculations and information from II, III, and IV:

$$\begin{aligned} k_g \text{ (m/s)} &= (1.35 \times 10^{-7})(3.1 \times 10^6)^{1.42}(2.8 \times 10^{-4})^{0.4}(1.71)^{0.5} * \\ &\quad (990)^{-0.21}(0.088 \text{ cm}^2/\text{s})(29 \text{ g/gmol})/(61 \text{ cm}) \\ &= 0.109 \text{ m/s} \end{aligned}$$

Quiescent surface area of impoundment — Equations 1 and 2 from Table 4.3-1

A. Calculate the individual liquid phase mass transfer coefficient, k_ℓ :

$$\begin{aligned} F/D &= 2(A/\pi)^{0.5}/D \\ &= 2(17,652 \text{ m}^2/\pi)^{0.5}/(1.97 \text{ m}) \\ &= 76.1 \\ U_{10} &= 4.47 \text{ m/s} \end{aligned}$$

For $U_{10} > 3.25$ m/s and $F/D > 51.2$ use the following:

$$\begin{aligned} k_l \text{ (m/s)} &= (2.61 \times 10^{-7})(U_{10})^2(D_w/D_{\text{ether}})^{2/3} \\ &= (2.61 \times 10^{-7})(4.47 \text{ m/s})^2[(9.8 \times 10^{-6} \text{ cm}^2/\text{s}) / \\ &\quad (8.5 \times 10^{-6} \text{ cm}^2/\text{s})]^{2/3} \\ &= 5.74 \times 10^{-6} \text{ m/s} \end{aligned}$$

B. Calculate the individual gas phase mass transfer coefficient, k_g :

$$k_g = (4.82 \times 10^{-3})(U_{10})^{0.78}(Sc_G)^{-0.67}(d_e)^{-0.11}$$

The Schmidt number on the gas side, Sc_G , and the effective diameter, d_e , are calculated separately:

1. Calculate the Schmidt number on the gas side, Sc_G :

$$Sc_G = \mu_a/(\rho_a D_a) = 1.71 \text{ (same as for turbulent impoundments)}$$

2. Calculate the effective diameter, d_e :

$$\begin{aligned} d_e \text{ (m)} &= 2(A/\pi)^{0.5} \\ &= 2(17,652 \text{ m}^2/\pi)^{0.5} \\ &= 149.9 \text{ m} \\ k_g \text{ (m/s)} &= (4.82 \times 10^{-3})(4.47 \text{ m/s})^{0.78} (1.71)^{-0.67} (149.9 \text{ m})^{-0.11} \\ &= 6.24 \times 10^{-3} \text{ m/s} \end{aligned}$$

VI. Calculate The Overall Mass Transfer Coefficient — Because part of the impoundment is turbulent and part is quiescent, the overall mass transfer coefficient is determined as an area-weighted average of the turbulent and quiescent overall mass transfer coefficients. (Equation 7 from Table 4.3-1).

Overall mass transfer coefficient for the turbulent surface area of impoundment, K_T

$$\begin{aligned} K_T \text{ (m/s)} &= (k_l Keq k_g)/(Keq k_g + k_l) \\ Keq &= H/RT \\ &= (0.0055 \text{ atm-m}^3/\text{gmol})/[(8.21 \times 10^{-5} \text{ atm-m}^3/\text{gmol-}^\circ\text{K})(298^\circ\text{K})] \\ &= 0.225 \\ K_T \text{ (m/s)} &= (5.35 \times 10^{-3} \text{ m/s})(0.225)(0.109)/[(0.109 \text{ m/s})(0.225) + \\ &\quad (5.35 \times 10^{-6} \text{ m/s})] \\ K_T &= 4.39 \times 10^{-3} \text{ m/s} \end{aligned}$$

Overall mass transfer coefficient for the quiescent surface area of impoundment, K_Q

$$\begin{aligned} K_Q \text{ (m/s)} &= (k_l Keq k_g)/(Keq k_g + k_l) \\ &= (5.74 \times 10^{-6} \text{ m/s})(0.225)(6.24 \times 10^{-3} \text{ m/s}) / \\ &\quad [(6.24 \times 10^{-3} \text{ m/s})(0.225) + (5.74 \times 10^{-6} \text{ m/s})] \\ &= 5.72 \times 10^{-6} \text{ m/s} \end{aligned}$$

Overall mass transfer coefficient, K , weighted by turbulent and quiescent surface areas, A_T and A_Q

$$\begin{aligned} K \text{ (m/s)} &= (K_T A_T + K_Q A_Q)/A \\ A_T &= 0.24(A) \text{ (Default value presented in III: } A_T = V a_v) \\ A_Q &= (1 - 0.24)A \\ K \text{ (m/s)} &= [(4.39 \times 10^{-3} \text{ m/s})(0.24 A) + (5.72 \times 10^{-6} \text{ m/s})(1 - 0.24)A]/A \\ &= 1.06 \times 10^{-3} \text{ m/s} \end{aligned}$$

VII. Calculate VOC Emissions For An Aerated Biological Flowthrough Impoundment — Equation 16 from Table 4.3-1:

$$N \text{ (g/s)} = K C_L A$$

where:

$$C_L \text{ (g/m}^3\text{)} = [-b + (b^2 - 4ac)^{0.5}]/(2a)$$

and:

$$a = KA/Q + 1$$

$$b = K_s(KA/Q + 1) + K_{max} b_i V/Q - C_o$$

$$c = -K_s C_o$$

Calculate a, b, c, and the concentration of benzene in the liquid phase, C_L , separately:

1. Calculate a:

$$\begin{aligned} a &= (KA/Q + 1) = [(1.06 \times 10^{-3} \text{ m/s})(17,652 \text{ m}^2)/(0.0623 \text{ m}^3/\text{s})] + 1 \\ &= 301.3 \end{aligned}$$

2. Calculate b ($V = 34,774 \text{ m}^3$ from IV):

$$\begin{aligned} b &= K_s(KA/Q + 1) + K_{max} b_i V/Q - C_o \\ &= (13.6 \text{ g/m}^3)[(1.06 \times 10^{-3} \text{ m/s})(17,652 \text{ m}^2)/(0.0623 \text{ m}^3/\text{s})] + \\ &\quad [(5.28 \times 10^{-6} \text{ g/g-s})(300 \text{ g/m}^3)(34,774 \text{ m}^3)/(0.0623 \text{ m}^3/\text{s})] - 10.29 \text{ g/m}^3 \\ &= 4,084.6 + 884.1 - 10.29 \\ &= 4,958.46 \text{ g/m}^3 \end{aligned}$$

3. Calculate c:

$$\begin{aligned} c &= -K_s C_o \\ &= -(13.6 \text{ g/m}^3)(10.29 \text{ g/m}^3) \\ &= -139.94 \end{aligned}$$

4. Calculate the concentration of benzene in the liquid phase, C_L , from a, b, and c above:

$$\begin{aligned} C_L \text{ (g/m}^3\text{)} &= [-b + (b^2 - 4ac)^{0.5}]/(2a) \\ &= [(4,958.46 \text{ g/m}^3) + [(4,958.46 \text{ g/m}^3)^2 - \\ &\quad [4(301.3)(-139.94)]]^{0.5}]/(2(301.3)) \\ &= 0.0282 \text{ g/m}^3 \end{aligned}$$

Now calculate N with the above calculations and information from II and V:

$$\begin{aligned} N \text{ (g/s)} &= K A C_L \\ &= (1.06 \times 10^{-3} \text{ m/s})(17,652 \text{ m}^2)(0.0282 \text{ g/m}^3) \\ &= 0.52 \text{ g/s} \end{aligned}$$

4.3.3 Controls

The types of control technology generally used in reducing VOC emissions from waste water include: steam stripping or air stripping, carbon adsorption (liquid phase), chemical oxidation, membrane separation, liquid-liquid extraction, and biotreatment (aerobic or anaerobic). For efficient control, all control elements should be placed as close as possible to the point of waste water generation, with all collection, treatment, and storage systems ahead of the control technology being covered to suppress emissions. Tightly covered, well-maintained collection systems can suppress

emissions by 95 to 99 percent. However, if there is explosion potential, the components should be vented to a control device such as an incinerator or carbon adsorber.

The following are brief descriptions of the control technology listed above and of any secondary controls that may need to be considered for fugitive air emissions.

Steam stripping is the fractional distillation of waste water to remove volatile organic constituents, with the basic operating principle being the direct contact of steam with waste water. The steam provides the heat of vaporization for the more volatile organic constituents. Removal efficiencies vary with volatility and solubility of the organic impurities. For highly volatile compounds (HLC greater than 10^{-3} atm-m³/gmol), average VOC removal ranges from 95 to 99 percent. For medium-volatility compounds (HLC between 10^{-5} and 10^{-3} atm-m³/gmol), average removal ranges from 90 to 95 percent. For low-volatility compounds (HLC $<10^{-5}$ atm-m³/gmol), average removal ranges from less than 50 to 90 percent.

Air stripping involves the contact of waste water and air to strip out volatile organic constituents. By forcing large volumes of air through contaminated water, the surface area of water in contact with air is greatly increased, resulting in an increase in the transfer rate of the organic compounds into the vapor phase. Removal efficiencies vary with volatility and solubility of organic impurities. For highly volatile compounds, average removal ranges from 90 to 99 percent; for medium- to low-volatility compounds, removal ranges from less than 50 to 90 percent.

Steam stripping and air stripping controls most often are vented to a secondary control, such as a combustion device or gas phase carbon adsorber. Combustion devices may include incinerators, boilers, and flares. Vent gases of high fuel value can be used as an alternate fuel. Typically, vent gas is combined with other fuels such as natural gas and fuel oil. If the fuel value is very low, vent gases can be heated and combined with combustion air. It is important to note that organics such as chlorinated hydrocarbons can emit toxic pollutants when combusted.

Secondary control by gas phase carbon adsorption processes takes advantage of compound affinities for activated carbon. The types of gas phase carbon adsorption systems most commonly used to control VOC are fixed-bed carbon adsorbers and carbon canisters. Fixed-bed carbon adsorbers are used to control continuous organic gas streams with flow rates ranging from 30 to over 3000 m³/min. Canisters are much simpler and smaller than fixed-bed systems and are usually installed to control gas flows of less than 3 m³/min.⁴ Removal efficiencies depend highly on the type of compound being removed. Pollutant-specific activated carbon is usually required. Average removal efficiency ranges from 90 to 99 percent.

Like gas phase carbon adsorption, liquid phase carbon adsorption takes advantage of compound affinities for activated carbon. Activated carbon is an excellent adsorbent, because of its large surface area and because it is usually in granular or powdered form for easy handling. Two types of liquid phase carbon adsorption are the fixed-bed and moving-bed systems. The fixed-bed system is used primarily for low-flow waste water streams with contact times around 15 minutes, and it is a batch operation (i. e., once the carbon is spent, the system is taken off line). Moving-bed carbon adsorption systems operate continuously with waste water typically being introduced from the bottom of the column and regenerated carbon from the top (countercurrent flow). Spent carbon is continuously removed from the bottom of the bed. Liquid phase carbon adsorption is usually used for low concentrations of nonvolatile components and for high concentrations of nondegradable compounds.⁵ Removal efficiencies depend on whether the compound is adsorbed on activated carbon. Average removal efficiency ranges from 90 to 99 percent.

Chemical oxidation involves a chemical reaction between the organic compound and an oxidant such as ozone, hydrogen peroxide, permanganate, or chlorine dioxide. Ozone is usually added to the waste water through an ultraviolet-ozone reactor. Permanganate and chlorine dioxide are added directly into the waste water. It is important to note that adding chlorine dioxide can form chlorinated hydrocarbons in a side reaction. The applicability of this technique depends on the reactivity of the individual organic compound.

Two types of membrane separation processes are ultrafiltration and reverse osmosis. Ultrafiltration is primarily a physical sieving process driven by a pressure gradient across the membrane. This process separates organic compounds with molecular weights greater than 2000, depending on the size of the membrane pore. Reverse osmosis is the process by which a solvent is forced across a semipermeable membrane because of an osmotic pressure gradient. Selectivity is, therefore, based on osmotic diffusion properties of the compound and on the molecular diameter of the compound and membrane pores.⁴

Liquid-liquid extraction as a separation technique involves differences in solubility of compounds in various solvents. Contacting a solution containing the desired compound with a solvent in which the compound has a greater solubility may remove the compound from the solution. This technology is often used for product and process solvent recovery. Through distillation, the target compound is usually recovered, and the solvent reused.

Biotreatment is the aerobic or anaerobic chemical breakdown of organic chemicals by microorganisms. Removal of organics by biodegradation is highly dependent on the compound's biodegradability, its volatility, and its ability to be adsorbed onto solids. Removal efficiencies range from almost zero to 100 percent. In general, highly volatile compounds such as chlorinated hydrocarbons and aromatics will biodegrade very little because of their high-volatility, while alcohols and other compounds soluble in water, as well as low-volatility compounds, can be almost totally biodegraded in an acclimated system. In the acclimated biotreatment system, the microorganisms easily convert available organics into biological cells, or biomass. This often requires a mixed culture of organisms, where each organism utilizes the food source most suitable to its metabolism. The organisms will starve and the organics will not be biodegraded if a system is not acclimated, i. e., the organisms cannot metabolize the available food source.

4.3.4 Glossary Of Terms

Basin -	an earthen or concrete-lined depression used to hold liquid.
Completely mixed -	having the same characteristics and quality throughout or at all times.
Disposal -	the act of permanent storage. Flow of liquid into, but not out of a device.
Drain -	a device used for the collection of liquid. It may be open to the atmosphere or be equipped with a seal to prevent emissions of vapors.
Flowthrough -	having a continuous flow into and out of a device.
Plug flow -	having characteristics and quality not uniform throughout. These will change in the direction the fluid flows, but not perpendicular to the direction of flow (i. e., no axial movement)

- Storage - any device to accept and retain a fluid for the purpose of future discharge. Discontinuity of flow of liquid into and out of a device.
- Treatment - the act of improving fluid properties by physical means. The removal of undesirable impurities from a fluid.
- VOC - volatile organic compounds, referring to all organic compounds except the following, which have been shown not to be photochemically reactive: methane, ethane, trichlorotrifluoroethane, methylene chloride, 1,1,1-trichloroethane, trichlorofluoromethane, dichlorodifluoromethane, chlorodifluoromethane, trifluoromethane, dichlorotetrafluoroethane, and chloropentafluoroethane.

Table 4.3-4. SIMS CHEMICAL PROPERTY DATA FILE (PART 1)

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m ³ /mol)	Diffusivity Of Chemical In Water At 25°C (cm ² /s)	Diffusivity Of Chemical In Air At 25°C (cm ² /s)
ACETALDEHYDE	75-07-0	44.00	760	0.000095	0.0000141	0.124
ACETIC ACID	64-19-7	60.05	15.4	0.0627	0.000012	0.113
ACETIC ANHYDRIDE	108-24-7	102.09	5.29	0.00000591	0.00000933	0.235
ACETONE	67-64-1	58.00	266	0.000025	0.0000114	0.124
ACETONITRILE	75-05-8	41.03	90	0.0000058	0.0000166	0.128
ACROLEIN	107-02-8	56.10	244.2	0.0000566	0.0000122	0.105
ACRYLAMIDE	79-06-1	71.09	0.012	0.00000000052	0.0000106	0.097
ACRYLIC ACID	79-10-7	72.10	5.2	0.0000001	0.0000106	0.098
ACRYLONITRILE	107-13-1	53.10	114	0.000088	0.0000134	0.122
ADIPIC ACID	124-04-9	146.14	0.0000225	0.00000000005	0.00000684	0.0659
ALLYL ALCOHOL	107-18-6	58.10	23.3	0.000018	0.0000114	0.114
AMINOPHENOL(-O)	95-55-6	109.12	0.511	0.00000367	0.00000864	0.0774
AMINOPHENOL(-P)	123-30-8	109.12	0.893	0.0000197	0.00000239	0.0774
AMMONIA	7664-41-7	17.03	7470	0.000328	0.0000693	0.259
AMYL ACETATE(-N)	628-37-8	130.18	5.42	0.000464	0.0000012	0.064
ANILINE	62-53-3	93.10	1	0.0000026	0.0000083	0.07
BENZENE	71-43-2	78.10	95.2	0.0055	0.0000098	0.088
BENZO(A)ANTHRACENE	56-55-3	228.30	0.00000015	0.00000000138	0.000009	0.051
BENZO(A)PYRENE	50-32-8	252.30	0.00568	0.00000000138	0.000009	0.043

Table 4.3-4 (Part 1) (cont.).

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m ³ /mol)	Diffusivity Of Chemical In Water At 25°C (cm ² /s)	Diffusivity Of Chemical In Air At 25°C (cm ² /s)
CRESYLIC ACID	1319-77-3	108.00	0.3	0.0000017	0.0000083	0.074
CROTONALDEHYDE	4170-30-0	70.09	30	0.00000154	0.0000102	0.0903
CUMENE (ISOPROPYLBENZENE)	98-82-8	120.20	4.6	0.0146	0.0000071	0.065
CYCLOHEXANE	110-82-7	84.20	100	0.0137	0.0000091	0.0839
CYCLOHEXANOL	108-93-0	100.20	1.22	0.00000447	0.00000831	0.214
CYCLOHEXANONE	108-94-1	98.20	4.8	0.00000413	0.00000862	0.0784
DI-N-OCTYL PHTHALATE	117-84-0	390.62	0	0.137	0.0000041	0.0409
DIBUTYL PHTHALATE	84-74-2	278.30	0.00001	0.00000028	0.0000079	0.0438
DICHLORO(-2)BUTENE(1,4)	764-41-0	125.00	2.87	0.000259	0.00000812	0.0725
DICHLOROBENZENE(1,2) (-O)	95-50-1	147.00	1.5	0.00194	0.0000079	0.069
DICHLOROBENZENE(1,3) (-M)	541-73-1	147.00	2.28	0.00361	0.0000079	0.069
DICHLOROBENZENE(1,4) (-P)	106-46-7	147.00	1.2	0.0016	0.0000079	0.069
DICHLORODIFLUOROMETHANE	75-71-8	120.92	5000	0.401	0.00001	0.0001
DICHLOROETHANE(1,1)	75-34-3	99.00	234	0.00554	0.0000105	0.0914
DICHLOROETHANE(1,2)	107-06-2	99.00	80	0.0012	0.0000099	0.104
DICHLOROETHYLENE(1,2)	156-54-2	96.94	200	0.0319	0.000011	0.0935
DICHLOROPHENOL(2,4)	120-83-2	163.01	0.1	0.0000048	0.0000076	0.0709
DICHLOROPHENOXYACETIC ACID(2,4)	94-75-7	221.00	290	0.0621	0.00000649	0.0588
DICHLOROPROPANE(1,2)	78-87-5	112.99	40	0.0023	0.0000087	0.0782
DIETHYL (N,N) ANILIN	91-66-7	149.23	0.00283	0.0000000574	0.00000587	0.0513

Table 4.3-4 (Part 1) (cont.).

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m ³ /mol)	Diffusivity Of Chemical In Water At 25°C (cm ² /s)	Diffusivity Of Chemical In Air At 25°C (cm ² /s)
DIETHYL PHTHALATE	84-66-2	222.00	0.003589	0.0111	0.0000058	0.0542
DIMETHYL FORMAMIDE	68-12-2	73.09	4	0.0000192	0.0000103	0.0939
DIMETHYL HYDRAZINE(1,1)	57-14-7	60.10	157	0.000124	0.0000109	0.106
DIMETHYL PHTHALATE	131-11-3	194.20	0.000187	0.00000215	0.0000063	0.0568
DIMETHYLBENZ(A)ANTHRACENE	57-97-6	256.33	0	0.00000000027	0.00000498	0.0461
DIMETHYLPHENOL(2,4)	105-67-9	122.16	0.0573	0.000921	0.0000084	0.0712
DINITROBENZENE (-M)	99-65-0	168.10	0.05	0.000022	0.00000764	0.279
DINITROTOLUENE(2,4)	121-14-2	182.10	0.0051	0.00000407	0.00000706	0.203
DIOXANE(1,4)	123-91-1	88.20	37	0.0000231	0.0000102	0.229
DIOXIN	NOCAS2	322.00	0	0.0000812	0.0000056	0.104
DIPHENYLAMINE	122-39-4	169.20	0.00375	0.00000278	0.00000631	0.058
EPICHLOROHYDRIN	106-89-8	92.50	17	0.0000323	0.0000098	0.086
ETHANOL	64-17-5	46.10	50	0.0000303	0.000013	0.123
ETHANOLAMINE(MONO-)	141-43-5	61.09	0.4	0.000000322	0.0000114	0.107
ETHYL ACRYLATE	140-88-5	100.00	40	0.00035	0.0000086	0.077
ETHYL CHLORIDE	75-00-3	64.52	1200	0.014	0.0000115	0.271
ETHYL-(2)PROPYL-(3) ACROLEIN	645-62-5	92.50	17	0.0000323	0.0000098	0.086
ETHYLACETATE	141-78-6	88.10	100	0.000128	0.00000966	0.0732
ETHYLBENZENE	100-41-4	106.20	10	0.00644	0.0000078	0.075
ETHYLENEOXIDE	75-21-8	44.00	1250	0.000142	0.0000145	0.104

Table 4.3-4 (Part 1) (cont.).

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m ³ /mol)	Diffusivity Of Chemical In Water At 25°C (cm ² /s)	Diffusivity Of Chemical In Air At 25°C (cm ² /s)
ETHYLETHER	60-29-7	74.10	520	0.00068	0.0000093	0.074
FORMALDEHYDE	50-00-0	30.00	3500	0.0000576	0.0000198	0.178
FORMIC ACID	64-18-6	46.00	42	0.0000007	0.00000137	0.079
FREONS	NOCAS3	120.92	5000	0.401	0.00001	0.104
FURAN	110-00-9	68.08	596	0.00534	0.0000122	0.104
FURFURAL	96-01-1	96.09	2	0.0000811	0.0000104	0.0872
HEPTANE (ISO)	142-82-5	100.21	66	1.836	0.00000711	0.187
HEXACHLOROBENZENE	118-74-1	284.80	1	0.00068	0.00000591	0.0542
HEXACHLOROBUTADIENE	87-68-3	260.80	0.15	0.0256	0.0000062	0.0561
HEXACHLOROCYCLOPENTADIENE	77-47-4	272.80	0.081	0.016	0.00000616	0.0561
HEXACHLOROETHANE	67-72-1	237.00	0.65	0.00000249	0.0000068	0.00249
HEXANE(-N)	100-54-3	86.20	150	0.122	0.00000777	0.2
HEXANOL(-1)	111-27-3	102.18	0.812	0.0000182	0.00000753	0.059
HYDROCYANIC ACID	74-90-8	27.00	726	0.000000465	0.0000182	0.197
HYDROFLUORIC ACID	7664-39-3	20.00	900	0.000237	0.000033	0.388
HYDROGEN SULFIDE	7783-06-4	34.10	15200	0.023	0.0000161	0.176
ISOPHORONE	78-59-1	138.21	0.439	0.00000576	0.00000676	0.0623
METHANOL	67-56-1	32.00	114	0.0000027	0.0000164	0.15
METHYL ACETATE	79-20-9	74.10	235	0.000102	0.00001	0.104
METHYL CHLORIDE	74-87-3	50.50	3830	0.00814	0.0000065	0.126

Table 4.3-4 (Part 1) (cont.).

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m ³ /mol)	Diffusivity Of Chemical In Water At 25°C (cm ² /s)	Diffusivity Of Chemical In Air At 25°C (cm ² /s)
METHYL ETHYL KETONE	78-93-3	72.10	100	0.0000435	0.0000098	0.0808
METHYL ISOBUTYL KETONE	108-10-1	100.20	15.7	0.0000495	0.0000078	0.075
METHYL METHACRYLATE	80-62-6	100.10	39	0.000066	0.0000086	0.077
METHYL STYRENE (ALPHA)	98-83-9	118.00	0.076	0.00591	0.0000114	0.264
METHYLENE CHLORIDE	75-09-2	85.00	438	0.00319	0.0000117	0.101
MORPHOLINE	110-91-8	87.12	10	0.0000573	0.0000096	0.091
NAPHTHALENE	91-20-3	128.20	0.23	0.00118	0.0000075	0.059
NITROANILINE(-O)	88-74-4	138.14	0.003	0.0000005	0.000008	0.073
NITROBENZENE	98-95-3	123.10	0.3	0.0000131	0.0000086	0.076
PENTACHLOROBENZENE	608-93-5	250.34	0.0046	0.0073	0.0000063	0.057
PENTACHLOROETHANE	76-01-7	202.30	4.4	0.021	0.0000073	0.066
PENTACHLOROPHENOL	87-86-5	266.40	0.00099	0.0000028	0.0000061	0.056
PHENOL	108-95-2	94.10	0.34	0.000000454	0.0000091	0.082
PHOSGENE	75-44-5	98.92	1390	0.171	0.00000112	0.108
PHTHALIC ACID	100-21-0	166.14	121	0.0132	0.0000068	0.064
PHTHALIC ANHYDRIDE	85-44-9	148.10	0.0015	0.0000009	0.0000086	0.071
PICOLINE(-2)	108-99-6	93.12	10.4	0.000127	0.0000096	0.075
POLYCHLORINATED BIPHENYLS	1336-36-3	290.00	0.00185	0.0004	0.00001	0.104
PROPANOL (ISO)	71-23-8	60.09	42.8	0.00015	0.0000104	0.098
PROPIONALDEHYDE	123-38-6	58.08	300	0.00115	0.0000114	0.102

Table 4.3-4 (Part 1) (cont.).

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m ³ /mol)	Diffusivity Of Chemical In Water At 25°C (cm ² /s)	Diffusivity Of Chemical In Air At 25°C (cm ² /s)
PROPYLENE GLYCOL	57-55-6	76.11	0.3	0.0000015	0.0000102	0.093
PROPYLENE OXIDE	75-66-9	58.10	525	0.00134	0.00001	0.104
PYRIDINE	110-86-1	79.10	20	0.0000236	0.0000076	0.091
RESORCINOL	108-46-3	110.11	0.00026	0.0000000188	0.0000087	0.078
STYRENE	100-42-5	104.20	7.3	0.00261	0.000008	0.071
TETRACHLOROETHANE(1,1,1,2)	630-20-6	167.85	6.5	0.002	0.0000079	0.071
TETRACHLOROETHANE(1,1,2,2)	79-34-5	167.85	6.5	0.00038	0.0000079	0.071
TETRACHLOROETHYLENE	127-18-4	165.83	19	0.029	0.0000082	0.072
TETRAHYDROFURAN	109-99-9	72.12	72.1	0.000049	0.0000105	0.098
TOLUENE	109-88-3	92.40	30	0.00668	0.0000086	0.087
TOLUENE DIISOCYANATE(2,4)	584-84-9	174.16	0.08	0.0000083	0.0000062	0.061
TRICHLORO(1,1,2)TRIFLUOROETHANE	76-13-1	187.38	300	0.435	0.0000082	0.078
TRICHLOROBENZENE(1,2,4)	120-82-1	181.50	0.18	0.00142	0.0000077	0.0676
TRICHLOROBUTANE(1,2,3)	NOCAS5	161.46	4.39	4.66	0.0000072	0.066
TRICHLOROETHANE(1,1,1)	71-55-6	133.40	123	0.00492	0.0000088	0.078
TRICHLOROETHANE(1,1,2)	79-00-5	133.40	25	0.000742	0.0000088	0.078
TRICHLOROETHYLENE	79-01-6	131.40	75	0.0091	0.0000091	0.079
TRICHLOROFLUOROMETHANE	75-69-4	137.40	796	0.0583	0.0000097	0.087
TRICHLOROPHENOL(2,4,6)	88-06-2	197.46	0.0073	0.0000177	0.0000075	0.0661
TRICHLOROPROPANE(1,1,1)	NOCAS6	147.43	3.1	0.029	0.0000079	0.071

Table 4.3-4 (Part 1) (cont.).

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m ³ /mol)	Diffusivity Of Chemical In Water At 25°C (cm ² /s)	Diffusivity Of Chemical In Air At 25°C (cm ² /s)
TRICHLOROPROPANE(1,2,3)	96-18-4	147.43	3	0.028	0.0000079	0.071
UREA	57-13-6	60.06	6.69	0.000264	0.0000137	0.122
VINYL ACETATE	108-05-4	86.09	115	0.00062	0.0000092	0.085
VINYL CHLORIDE	75-01-4	62.50	2660	0.086	0.0000123	0.106
VINYLDENE CHLORIDE	75-35-4	97.00	591	0.015	0.0000104	0.09
XYLENE(-M)	1330-20-7	106.17	8	0.0052	0.0000078	0.07
XYLENE(-O)	95-47-6	106.17	7	0.00527	0.00001	0.087

Table 4.3-4. SIMS CHEMICAL PROPERTY DATA FILE (PART 2)

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m ³)	Octanol-Water Partition Coefficient At 25°C
ACETALDEHYDE	8.005	1600.017	291.809	0.0000228944	419.0542	2.69153
ACETIC ACID	7.387	1533.313	222.309	0.0000038889	14.2857	0.48978
ACETIC ANHYDRIDE	7.149	1444.718	199.817	0.0000026944	1.9323	1
ACETONE	7.117	1210.595	229.664	0.0000003611	1.1304	0.57544
ACETONITRILE	7.119	1314.4	230	0.000000425	152.6014	0.45709
ACROLEIN	2.39	0	0	0.0000021667	22.9412	0.81283
ACRYLAMIDE	11.2932	3939.877	273.16	0.000000425	56.2388	6.32182
ACRYLIC ACID	5.652	648.629	154.683	0.0000026944	54.7819	2.04174
ACRYLONITRILE	7.038	1232.53	222.47	0.000005	24	0.12023
ADIPIC ACID	0	0	0	0.0000026944	66.9943	1.20226
ALLYL ALCOHOL	0	0	0	0.0000048872	3.9241	1.47911
AMINOPHENOL(-O)	0	0	0	0.00000425	68.1356	3.81533
AMINOPHENOL(-P)	-3.357	699.157	-331.343	0.00000425	68.1356	3.81533
AMMONIA	7.5547	1002.711	247.885	0.00000425	15.3	1
AMYL ACETATE(-N)	0	0	0	0.0000026944	16.1142	51.10801
ANILINE	7.32	1731.515	206.049	0.0000019722	.3381	7.94328
BENZENE	6.905	1211.033	220.79	0.0000052778	13.5714	141.25375
BENZO(A)ANTHRACENE	6.9824	2426.6	156.6	0.0000086389	1.7006	407380.2778
BENZO(A)PYRENE	9.2455	3724.363	273.16	0.0000086389	1.2303	954992.58602

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m ³)	Octanol-Water Partition Coefficient At 25°C
BENZYL CHLORIDE	0	0	0	0.0000049306	17.5674	199.52623
BIS(2-CHLOROETHYL)ETHER	0	0	0	0.0000029889	20.0021	38.01894
BIS(2-CHLOROISOPROPYL)ETHER	0	0	0	0.0000029889	8.3382	380.1894
BIS(2-ETHYLHEXYL)PHTHALATE	0	0	0	0.0000002139	2.2	199526.2315
BROMOFORM	0	0	0	0.0000029889	10.653	199.52623
BROMOMETHANE	0	0	0	0.0000029889	30.4422	12.58925
BUTADIENE-(1,3)	6.849	930.546	238.854	0.0000042534	15.3	74.32347
BUTANOL (ISO)	7.4743	1314.19	186.55	0.0000021667	70.9091	5.62341
BUTANOL-(1)	7.4768	1362.39	178.77	0.0000021667	70.9091	5.62341
BUTYL BENZYL PHTHALATE	0	0	0	0.0000086389	14.1364	60255.95861
CARBON DISULFIDE	6.942	1169.11	241.59	0.0000042534	5.8175	1
CARBON TETRACHLORIDE	6.934	1242.43	230	0.0000004167	1	524.80746
CHLORO(-P)CRESOL(-M)	0	0	0	0.0000029889	5.2902	1258.92541
CHLOROACETALDEHYDE	0	0	0	0.0000029889	49.838	3.4405
CHLOROBENZENE	6.978	1431.05	217.55	0.0000001083	.039	316.22777
CHLOROFORM	6.493	929.44	196.03	0.0000008167	3.7215	91.20108
CHLORONAPHTHALENE-(2)	0	0	0	0.0000029889	2.167	13182.56739
CHLOROPRENE	6.161	783.45	179.7	0.0000029968	6.3412	1
CRESOL(-M)	7.508	1856.36	199.07	0.0000064472	1.3653	93.32543
CRESOL(-O)	6.911	1435.5	165.16	0.0000063278	1.34	95.49926

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m ³)	Octanol-Water Partition Coefficient At 25°C
CRESOL(-P)	7.035	1511.08	161.85	0.0000064472	1.3653	87.09636
CRESYLIC ACID	0	0	0	0.0000041667	15	1
CROTONALDEHYDE	0	0	0	0.0000026944	27.6285	12.36833
CUMENE (ISOPROPYLBENZENE)	6.963	1460.793	207.78	0.0000086458	16.5426	1
CYCLOHEXANE	6.841	1201.53	222.65	0.0000042534	15.3	338.0687
CYCLOHEXANOL	6.255	912.87	109.13	0.0000026944	18.0816	37.74314
CYCLOHEXANONE	7.8492	2137.192	273.16	0.0000031917	41.8921	6.45654
DI-N-OCTYL PHTHALATE	0	0	0	0.000000083	0.02	141253.7
DIBUTYLPHTHALATE	6.639	1744.2	113.59	0.0000001111	0.4	158489.31925
DICHLORO(-2)BUTENE(1,4)	0	0	0	0.0000029889	9.8973	242.1542
DICHLOROBENZENE(1,2) (-O)	.176	0	0	0.0000006944	4.3103	2398.83292
DICHLOROBENZENE(1,3) (-M)	0	0	0	0.0000017778	2.7826	2398.83292
DICHLOROBENZENE(1,4) (-P)	.079	0	0	0.0000017778	2.7826	2454.70892
DICHLORODIFLUOROMETHANE	0	0	0	0.0000029889	12.0413	144.54398
DICHLOROETHANE(1,1)	0	0	0	0.0000029889	4.6783	61.6595
DICHLOROETHANE(1,2)	7.025	1272.3	222.9	0.0000005833	2.1429	61.6595
DICHLOROETHYLENE(1,2)	6.965	1141.9	231.9	0.0000029889	6.3294	1
DICHLOROPHENOL(2,4)	0	0	0	0.0000069444	7.5758	562.34133
DICHLOROPHENOXYYACETIC ACID(2,4)	0	0	0	0.0000029889	14.8934	82.61445

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m ³)	Octanol-Water Partition Coefficient At 25°C
DICHLOROPROPANE(1,2)	6.98	1380.1	22.8	0.0000047222	12.1429	1
DIETHYL (N,N) ANILIN	7.466	1993.57	218.5	0.00000425	27.0047	43.57596
DIETHYL PHTHALATE	0	0	0	0.000000753	1.28	1412.537
DIMETHYL FORMAMIDE	6.928	1400.87	196.43	0.00000425	15.3	1
DIMETHYL HYDRAZINE(1,1)	7.408	1305.91	225.53	0.00000425	15.3	1
DIMETHYL PHTHALATE	4.522	700.31	51.42	0.0000006111	0.7097	74.13102
DIMETHYLBENZ(A)ANTHRACENE	0	0	0	0.0000086389	0.3377	28680056.33087
DIMETHYLPHENOL(2,4)	0	0	0	0.0000029722	2.2766	263.0268
DINITROBENZENE (-M)	4.337	229.2	-137	0.00000425	29.9146	33.28818
DINITROTOLUENE(2,4)	5.798	1118	61.8	0.00000425	19.5233	102.3293
DIOXANE(1,4)	7.431	1554.68	240.34	0.0000026944	24.7001	16.60956
DIOXIN	12.88	6465.5	273	0.0000029968	6.3412	1
DIPHENYLAMINE	0	0	0	0.0000052778	8.4103	1659.58691
EPICHLOROHYDRIN	8.2294	2086.816	273.16	0.0000029968	6.3412	1.07152
ETHANOL	8.321	1718.21	237.52	0.0000024444	9.7778	0.47863
ETHANOLAMINE(MONO-)	7.456	1577.67	173.37	0.00000425	223.0321	0.16865
ETHYL ACRYLATE	7.9645	1897.011	273.16	0.0000026944	39.4119	4.85667
ETHYL CHLORIDE	6.986	1030.01	238.61	0.0000029889	22.8074	26.91535
ETHYL-(2)PROPYL-(3) ACROLEIN	0	0	0	0.00000425	15.3	1

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m ³)	Octanol-Water Partition Coefficient At 25°C
ETHYLACETATE	7.101	1244.95	217.88	0.0000048833	17.58	1
ETHYLBENZENE	6.975	1424.255	213.21	0.0000018889	3.2381	1412.53754
ETHYLENEOXIDE	7.128	1054.54	237.76	0.0000011667	4.6154	0.50003
ETHYLETHER	6.92	1064.07	228.8	0.0000026944	17.1206	43.57596
FORMALDEHYDE	7.195	970.6	244.1	0.0000013889	20	87.09636
FORMIC ACID	7.581	1699.2	260.7	0.0000026944	161.3977	0.1191
FREONS	0	0	0	0.0000029968	6.3412	1
FURAN	6.975	1060.87	227.74	0.0000026944	14.1936	71.37186
FURFURAL	6.575	1198.7	162.8	0.0000026944	18.0602	37.86047
HEPTANE (ISO)	6.8994	1331.53	212.41	0.0000042534	15.3	1453.372
HEXACHLOROBENZENE	0	0	0	0.0000029889	0.6651	295120.92267
HEXACHLOROBUTADIENE	0.824	0	0	0.000003	6.3412	5495.408
HEXACHLOROCYCLOPENTADIENE	0	0	0	0.0000029968	0.3412	9772.372
HEXACHLOROETHANE	0	0	0	0.0000029889	3.3876	4068.32838
HEXANE(-N)	6.876	1171.17	224.41	0.0000042534	15.3	534.0845
HEXANOL(-1)	7.86	1761.26	196.66	0.0000026944	15.2068	59.52851
HYDROCYANIC ACID	7.528	1329.5	260.4	0.0000026944	1.9323	1
HYDROFLUORIC ACID	7.217	1268.37	273.87	0.0000026944	1.9323	1
HYDROGEN SULFIDE	7.614	885.319	250.25	0.0000029889	6.3294	1
ISOPHORONE	0	0	0	0.00000425	25.6067	50.11872

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m ³)	Octanol-Water Partition Coefficient At 25°C
METHANOL	7.897	1474.08	229.13	0.000005	90	0.19953
METHYL ACETATE	7.065	1157.63	219.73	0.0000055194	159.2466	0.81283
METHYL CHLORIDE	7.093	948.58	249.34	0.0000029889	14.855	83.17638
METHYL ETHYL KETONE	6.9742	1209.6	216	0.0000005556	10	1.90546
METHYL ISOBUTYL KETONE	6.672	1168.4	191.9	0.0000002056	1.6383	23.98833
METHYL METHACRYLATE	8.409	2050.5	274.4	0.0000026944	109.2342	0.33221
METHYL STYRENE (ALPHA)	6.923	1486.88	202.4	0.000008639	11.12438	2907.589
METHYLENE CHLORIDE	7.409	1325.9	252.6	0.0000061111	54.5762	17.78279
MORPHOLINE	7.7181	1745.8	235	0.00000425	291.9847	0.08318
NAPHTHALENE	7.01	1733.71	201.86	0.0000117972	42.47	1
NITROANILINE(-O)	8.868	336.5	273.16	0.00000425	22.8535	67.6083
NITROBENZENE	7.115	1746.6	201.8	0.0000030556	4.7826	69.1831
PENTACHLOROBENZENE	0	0	0	0.0000029889	0.4307	925887.02902
PENTACHLOROETHANE	6.74	1378	197	0.0000029889	0.4307	925887.02902
PENTACHLOROPHENOL	0	0	0	0.0000361111	38.2353	102329.29923
PHENOL	7.133	1516.79	174.95	0.0000269444	7.4615	28.84032
PHOSGENE	6.842	941.25	230	0.00000425	70.8664	3.4405
PHTHALIC ACID	0	0	0	0.0000026944	34.983	6.64623
PHTHALIC ANHYDRIDE	8.022	2868.5	273.16	0.0000048872	3.9241	0.23988
PICOLINE(-2)	7.032	1415.73	211.63	0.00000425	44.8286	11.48154

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m ³)	Octanol-Water Partition Coefficient At 25°C
POLYCHLORINATED BIPHENYLS	0	0	0	0.000005278	20	1
PROPANOL (ISO)	8.117	1580.92	219.61	0.0000041667	200	0.69183
PROPIONALDEHYDE	16.2315	2659.02	-44.15	0.0000026944	39.2284	4.91668
PROPYLENE GLYCOL	8.2082	2085.9	203.5396	0.0000026944	109.3574	0.33141
PROPYLENE OXIDE	8.2768	1656.884	273.16	0.0000048872	3.9241	1
PYRIDINE	7.041	1373.8	214.98	0.0000097306	146.9139	4.46684
RESORCINOL	6.9243	1884.547	186.0596	0.0000026944	35.6809	6.30957
STYRENE	7.14	1574.51	224.09	0.0000086389	282.7273	1445.43977
TETRACHLOROETHANE(1,1,1,2)	6.898	1365.88	209.74	0.0000029889	6.3294	1
TETRACHLOROETHANE(1,1,2,2)	6.631	1228.1	179.9	0.0000017222	9.1176	363.07805
TETRACHLOROETHYLENE	6.98	1386.92	217.53	0.0000017222	9.1176	398.10717
TETRAHYDROFURAN	6.995	1202.29	226.25	0.0000026944	20.3702	27.58221
TOLUENE	6.954	1344.8	219.48	0.0000204111	30.6167	489.77882
TOLUENE DIISOCYANATE(2,4)	0	0	0	0.00000425	15.3	1
TRICHLORO(1,1,2)TRIFLUOROETHANE	6.88	1099.9	227.5	0.0000029889	3.3876	4068.32838
TRICHLOROBENZENE(1,2,4)	0	0	0	0.0000029889	2.4495	9549.92586
TRICHLOROBUTANE(1,2,3)	0	0	0	0.0000029968	6.3412	1450901.06626
TRICHLOROETHANE(1,1,1)	8.643	2136.6	302.8	0.0000009722	4.7297	309.02954
TRICHLOROETHANE(1,1,2)	6.951	1314.41	209.2	0.0000009722	4.7297	1

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass)	Half Saturation Constant (g/m ³)	Octanol-Water Partition Coefficient At 25°C
TRICHLOROETHYLENE	6.518	1018.6	192.7	0.0000010833	4.4318	194.98446
TRICHLOROFLUOROMETHANE	6.884	1043.004	236.88	0.000003	6.3412	338.8441
TRICHLOROPHENOL(2,4,6)	0	0	0	0.00000425	58.8462	4897.78819
TRICHLOROPROPANE(1,1,1)	0	0	0	0.0000029889	10.7719	193.7827
TRICHLOROPROPANE(1,2,3)	6.903	788.2	243.23	0.0000029889	10.7719	193.7827
UREA	0	0	0	0.00000425	4.8169	4068.32838
VINYL ACETATE	7.21	1296.13	226.66	0.0000026944	31.8363	8.51722
VINYL CHLORIDE	3.425	0	0	0.000003	6.3412	1.14815
VINYLDENE CHLORIDE	6.972	1099.4	237.2	0.0000029968	6.3412	1
XYLENE(-M)	7.009	1426.266	215.11	0.0000086389	14.0094	1584.89319
XYLENE(-O)	6.998	1474.679	213.69	0.0000113306	22.8569	891.25094

4.3.5 Waste Water—Greenhouse Gases

Greenhouse gases are emitted from both domestic and industrial waste water treatment operations. When biological processes such as suspended-growth and attached-growth units operate in anaerobic conditions with high biochemical oxygen demand (BOD) loading, the dominant greenhouse gas emitted is methane (CH_4), though lesser quantities of carbon dioxide (CO_2) and nitrous oxide (N_2O) may also be emitted. Methane generated from waste water treatment plants may also be collected and utilized as a source of energy, or flared. An anaerobic process is any treatment process that operates in the absence of oxygen. The chemical reactions that occur in anaerobic conditions are mitigated by biological activities, such that they are affected by many different factors (i.e., BOD loading, oxygen concentration, phosphorus and nitrogen levels, temperature, redox potential, and retention time) which may significantly impact emissions.

4.3.5.1 Domestic Waste Water Treatment Processes -

Publicly owned treatment works (POTWs) are treatment facilities that treat waste water from residences and businesses of a defined community. Aerobic treatment, which is rapid and relatively low in odor, is used by a majority of POTWs in the U.S. The most common aerobic treatment process is activated sludge, where raw waste water is mixed with a sludge of living aerobic microorganisms (the sludge is activated in a mechanically aerated tank). The microorganisms rapidly adsorb and biologically oxidize the organic solids suspended in the waste water, producing CO_2 .⁶ POTWs use a wide range of chemical and biological processes. A POTW usually consists of a number of aerobic, anaerobic, and physical processes.⁷ Those facilities that use biological processes under anaerobic conditions with high BOD loading emit CH_4 , and, to a lesser extent, N_2O and CO_2 . None of the data currently available on N_2O and CO_2 emissions are useful for developing emission factors for this source. Emissions of CO_2 from this source as well as other biogenic sources are part of the carbon cycle, and as such are typically not included in greenhouse gas emission inventories. To estimate uncontrolled CH_4 emissions from a typical waste water treatment plant, the following equation can be used:

$$(P) * \left(\frac{\text{lb BOD}_5}{\text{capita/day}} \right) * \left(\frac{365 \text{ days}}{\text{yr}} \right) * \left(\frac{0.22 \text{ lb CH}_4}{\text{lb BOD}_5} \right) * \left(\frac{\text{Fraction Anaerobically Digested}}{\text{Fraction Anaerobically Digested}} \right) = \frac{\text{lb CH}_4}{\text{yr}} \quad (1)$$

where:

P is the population of the community served by the POTW.

Note: To convert from lb CH_4 /yr to kg CH_4 /yr, multiply by 0.454.

BOD_5 is a standardized measurement for BOD. This 5-day BOD test is a measure of the "strength" of the waste water; waste water with a high BOD_5 is considered "strong." The BOD_5 - CH_4 conversion (0.22 lb CH_4 /lb BOD_5) is taken from Metcalf & Eddy⁸ and Orlich.⁹ The domestic BOD loading rate (lb BOD_5 /capita/day) varies from one population group to the next, usually ranging from 0.10 to 0.17 lb, with a typical value of 0.13 lb BOD_5 /capita/day.¹⁰ To obtain the exact domestic BOD loading rate for a specific community, contact the local waste water treatment plant operator for that community. It has been hypothesized that emission factors based on chemical oxygen demand (COD) are more accurate than those based on BOD.¹¹ Research is currently being conducted by the U. S. EPA relevant to this hypothesis.

The fraction of the domestic waste water treated anaerobically is calculated by considering which treatment processes are anaerobic and what percent of the total hydraulic retention time the waste water spends in these treatment processes. This fraction is dependent on the treatment processes used and the operating conditions of a specific plant. This information can also be provided by contacting local waste water treatment plant operators. If treatment activity data are not available from local wastewater treatment plant operators, a default value of 15 percent of domestic water treated anaerobically may also be used.¹² A default value of 15 percent is also recommended in the Intergovernmental Panel on Climate Change (IPCC) *Greenhouse Gas Inventory Reference Manual*.¹³

If a BOD₅ value of 0.13 lb BOD₅ is assumed, the IPCC assumption is used that 15 percent of waste water is anaerobically digested, and none of the gas is recovered for energy or flared, then equation 1 reduces to the following equation:

$$(P) * \left(1.56 \frac{\text{lb CH}_4}{\text{capita/yr}} \right) = \text{lb} \frac{\text{CH}_4}{\text{yr}} \quad (2)$$

4.3.5.2 Industrial Waste Water Treatment Processes -

An industrial waste water system uses unit processes similar to those found in POTWs. Such a treatment system may discharge into a water body or may pretreat the waste water for discharge into a sewer system leading to a POTW. To estimate uncontrolled CH₄ methane emissions from a typical industrial waste water treatment plant the following equation can be used:

$$(Q_I) * \left(\frac{\text{lb BOD}_5}{\text{ft}^3 \text{ wastewater}} \right) * \left(\frac{0.22 \text{ lb CH}_4}{\text{lb BOD}_5} \right) * \left(\frac{\text{Fraction Anaerobically Digested}}{\text{Fraction Anaerobically Digested}} \right) * \left(365 \frac{\text{days}}{\text{yr}} \right) = \frac{\text{lb CH}_4}{\text{yr}} \quad (3)$$

where:

Q_I = daily waste water flow (ft³/day).

Flow rates for individual industrial waste water treatment facilities (Q_I) can be provided by the operator of the industrial waste water treatment plant or by reviewing a facility's National Pollution Discharge Elimination System (NPDES) discharge permit.

Industrial BOD loading rates (lb BOD₅/ft³ waste water) vary depending upon the source of the waste water contamination. Some contaminants have very high BOD₅, such as contaminants in food and beverage manufacturers' waste water. Table 4.3-5 provides a list of typical industrial BOD loading rates for major industrial sources. To obtain the exact BOD loading rate for a specific facility, contact the facility's waste water treatment plant operator or review the facility's NPDES discharge permit.

The fraction of the industrial waste water treated anaerobically is dependent on the treatment processes used in specific plants. The composition of an industrial waste stream is more diverse than municipal wastewater. The difference makes it very difficult to provide a default fraction of anaerobically treated wastewater that would be representative of facilities in a specific inventory area. This information can also be provided by contacting individual waste water treatment plant operators.

4.3.5.3 Controls

Waste water treatment plant operators (domestic as well as industrial) can also provide information on gas recovery and utilization. If a gas recovery system is in place, uncontrolled CH₄ emissions estimates should be adjusted based on operator estimates of the efficiency of the gas collection system and the destruction of the collected gas. For more information on control efficiencies, see Section 4.3.3.

4.3.6 Updates Since the Fifth Edition

The Fifth Edition was released in January 1995. In February 1998, this section was revised by the addition of 4.3.5 which addresses Greenhouse Gas emissions. The revisions made in February 1998 are to be included in Supplement D.

Table 4.3-5. BIOCHEMICAL OXYGEN DEMAND (BOD) ESTIMATES FOR VARIOUS INDUSTRIAL WASTE WATERS

Industry	BOD ₅ (lb/ft ³) ^a	Reference Number	Range
Fertilizer	0.04	14	0.03-0.05 ^b
Food and beverages			
Beer	5.31	15	4.99-5.62 ^c
Beet sugar	0.41	15, 16	0.34-0.47 ^c
Butter	0.19	17	
Cane sugar	0.08	15	0.07-0.09 ^c
Cereals	0.06	18	
Cheese	1.9	17	
Fruits and vegetables ^d	40.27	15	Average of BOD values for processing 35 different fruits and vegetables. The BOD values ranged from 4.370 to 1747.979 lbs/ft ³ . For the BOD ₅ value it was assumed that biodegradation was high such that the BOD ₅ value was considered to be 75% of the BOD value.
Meats	1.3	19	--
Milk	7.6	15	6.24-8.93 ^c
Wine	8.43	15	7.49-9.36 ^c
Iron and steel	0.04	14	0.03-0.05 ^b
Non-ferrous metals	0.04	14	0.03-0.05 ^b
Petroleum refining (Petrochemical)	0.25	14	Average of values reported in Carmichael and Strzepek (1987).
Pharmaceutical	0.08	14	0.07-0.09 ^c
Pulp and paper	0.17	14, 20	0.14-0.19
Rubber	0.04	14	0.03-0.05 ^b
Textiles	0.04	14	0.03-0.05 ^c

^a To convert lb/ft³ to kg/m³ multiply by 16.0185.

^b A BOD₅ value was not provided in the literature. The range of BOD₅ values was derived from the ultimate BOD value from the textile industry, which should have a similar, relatively small value. BOD₅ is 55 to 75 percent of ultimate BOD, depending on the biodegradability of the waste stream. The midpoint of the extrapolated range is presented in the second column as BOD₅.

^c A range of values is given for BOD₅ because a specific BOD₅ value was not provided in the literature. The range of BOD₅ values was derived from the ultimate BOD value from the literature. BOD₅ is 55 to 75 percent of ultimate BOD, depending on the biodegradability of the waste stream. If the waste stream contains a large amount of material that does not biodegrade easily, then a value closer to the lower value should be used. If the waste stream contains a large amount of material that does biodegrade easily, then a value closer to the higher value should be used. If it is unclear how biodegradable the material is, and BOD₅ data for a specific facility is not available, then a value at the midpoint of the range should be used. The midpoint of the range is presented in the second column as BOD₅.

^d For a more complete list of BOD₅ values see reference 15.

References For Section 4.3

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2. *Waste Water Treatment Compound Property Processor Air Emissions Estimator (WATER 7)*, U. S. Environmental Protection Agency, Research Triangle Park, NC, available early 1992.
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7.1 Organic Liquid Storage Tanks

7.1.1 Process Description¹⁻²

Storage vessels containing organic liquids can be found in many industries, including (1) petroleum producing and refining, (2) petrochemical and chemical manufacturing, (3) bulk storage and transfer operations, and (4) other industries consuming or producing organic liquids. Organic liquids in the petroleum industry, usually called petroleum liquids, generally are mixtures of hydrocarbons having dissimilar true vapor pressures (for example, gasoline and crude oil). Organic liquids in the chemical industry, usually called volatile organic liquids, are composed of pure chemicals or mixtures of chemicals with similar true vapor pressures (for example, benzene or a mixture of isopropyl and butyl alcohols).

Six basic tank designs are used for organic liquid storage vessels: fixed roof (vertical and horizontal), external floating roof, domed external (or covered) floating roof, internal floating roof, variable vapor space, and pressure (low and high). A brief description of each tank is provided below. Loss mechanisms associated with each type of tank are provided in Section 7.1.2.

The emission estimating equations presented in Section 7.1 were developed by the American Petroleum Institute (API). API retains the copyright to these equations. API has granted permission for the nonexclusive; noncommercial distribution of this material to governmental and regulatory agencies. However, API reserves its rights regarding all commercial duplication and distribution of its material. Therefore, the material presented in Section 7.1 is available for public use, but the material cannot be sold without written permission from the American Petroleum Institute and the U. S. Environmental Protection Agency.

7.1.1.1 Fixed Roof Tanks –

A typical vertical fixed roof tank is shown in Figure 7.1-1. This type of tank consists of a cylindrical steel shell with a permanently affixed roof, which may vary in design from cone- or dome-shaped to flat. Losses from fixed roof tanks are caused by changes in temperature, pressure, and liquid level.

Fixed roof tanks are either freely vented or equipped with a pressure/vacuum vent. The latter allows the tanks to operate at a slight internal pressure or vacuum to prevent the release of vapors during very small changes in temperature, pressure, or liquid level. Of current tank designs, the fixed roof tank is the least expensive to construct and is generally considered the minimum acceptable equipment for storing organic liquids.

Horizontal fixed roof tanks are constructed for both above-ground and underground service and are usually constructed of steel, steel with a fiberglass overlay, or fiberglass-reinforced polyester. Horizontal tanks are generally small storage tanks with capacities of less than 40,000 gallons. Horizontal tanks are constructed such that the length of the tank is not greater than six times the diameter to ensure structural integrity. Horizontal tanks are usually equipped with pressure-vacuum vents, gauge hatches and sample wells, and manholes to provide access to these tanks. In addition, underground tanks may be cathodically protected to prevent corrosion of the tank shell. Cathodic protection is accomplished by placing sacrificial anodes in the tank that are connected to an impressed current system or by using galvanic anodes in the tank. However, internal cathodic protection against

corrosion is no longer widely used in the petroleum industry, due to corrosion inhibitors that are now found in most refined petroleum products.

The potential emission sources for above-ground horizontal tanks are the same as those for vertical fixed roof tanks. Emissions from underground storage tanks are associated mainly with changes in the liquid level in the tank. Losses due to changes in temperature or barometric pressure are minimal for underground tanks because the surrounding earth limits the diurnal temperature change, and changes in the barometric pressure result in only small losses.

7.1.1.2 External Floating Roof Tanks –

A typical external floating roof tank (EFRT) consists of an open-topped cylindrical steel shell equipped with a roof that floats on the surface of the stored liquid. The floating roof consists of a deck, fittings, and rim seal system. Floating decks that are currently in use are constructed of welded steel plate and are of two general types: pontoon or double-deck. Pontoon-type and double-deck-type external floating roof tanks are shown in Figures 7.1-2 and 7.1-3, respectively. With all types of external floating roof tanks, the roof rises and falls with the liquid level in the tank. External floating decks are equipped with a rim seal system, which is attached to the deck perimeter and contacts the tank wall. The purpose of the floating roof and rim seal system is to reduce evaporative loss of the stored liquid. Some annular space remains between the seal system and the tank wall. The seal system slides against the tank wall as the roof is raised and lowered. The floating deck is also equipped with fittings that penetrate the deck and serve operational functions. The external floating roof design is such that evaporative losses from the stored liquid are limited to losses from the rim seal system and deck fittings (standing storage loss) and any exposed liquid on the tank walls (withdrawal loss).

7.1.1.3 Internal Floating Roof Tanks –

An internal floating roof tank (IFRT) has both a permanent fixed roof and a floating roof inside. There are two basic types of internal floating roof tanks: tanks in which the fixed roof is supported by vertical columns within the tank, and tanks with a self-supporting fixed roof and no internal support columns. Fixed roof tanks that have been retrofitted to use a floating roof are typically of the first type. External floating roof tanks that have been converted to internal floating roof tanks typically have a self-supporting roof. Newly constructed internal floating roof tanks may be of either type. The deck in internal floating roof tanks rises and falls with the liquid level and either floats directly on the liquid surface (contact deck) or rests on pontoons several inches above the liquid surface (noncontact deck). The majority of aluminum internal floating roofs currently in service have noncontact decks. A typical internal floating roof tank is shown in Figure 7.1-4.

Contact decks can be (1) aluminum sandwich panels that are bolted together, with a honeycomb aluminum core floating in contact with the liquid; (2) pan steel decks floating in contact with the liquid, with or without pontoons; and (3) resin-coated, fiberglass reinforced polyester (FRP), buoyant panels floating in contact with the liquid. The majority of internal contact floating decks currently in service are aluminum sandwich panel-type or pan steel-type. The FRP decks are less common. The panels of pan steel decks are usually welded together.

Noncontact decks are the most common type currently in use. Typical noncontact decks are constructed of an aluminum deck and an aluminum grid framework supported above the liquid surface by tubular aluminum pontoons or some other buoyant structure. The noncontact decks usually have bolted deck seams. Installing a floating roof minimizes evaporative losses of the stored liquid. Both contact and noncontact decks incorporate rim seals and deck fittings for the same purposes previously described for external floating roof tanks. Evaporative losses from floating roofs may come from deck

fittings, nonwelded deck seams, and the annular space between the deck and tank wall. In addition, these tanks are freely vented by circulation vents at the top of the fixed roof. The vents minimize the possibility of organic vapor accumulation in the tank vapor space in concentrations approaching the flammable range. An internal floating roof tank not freely vented is considered a pressure tank. Emission estimation methods for such tanks are not provided in AP-42.

7.1.1.4 Domed External Floating Roof Tanks –

Domed external (or covered) floating roof tanks have the heavier type of deck used in external floating roof tanks as well as a fixed roof at the top of the shell like internal floating roof tanks. Domed external floating roof tanks usually result from retrofitting an external floating roof tank with a fixed roof. This type of tank is very similar to an internal floating roof tank with a welded deck and a self supporting fixed roof. A typical domed external floating roof tank is shown in Figure 7.1-5.

As with the internal floating roof tanks, the function of the fixed roof is not to act as a vapor barrier, but to block the wind. The type of fixed roof most commonly used is a self supporting aluminum dome roof, which is of bolted construction. Like the internal floating roof tanks, these tanks are freely vented by circulation vents at the top of the fixed roof. The deck fittings and rim seals, however, are identical to those on external floating roof tanks. In the event that the floating deck is replaced with the lighter IFRT-type deck, the tank would then be considered an internal floating roof tank.

7.1.1.5 Variable Vapor Space Tanks –

Variable vapor space tanks are equipped with expandable vapor reservoirs to accommodate vapor volume fluctuations attributable to temperature and barometric pressure changes. Although variable vapor space tanks are sometimes used independently, they are normally connected to the vapor spaces of one or more fixed roof tanks. The two most common types of variable vapor space tanks are lifter roof tanks and flexible diaphragm tanks.

Lifter roof tanks have a telescoping roof that fits loosely around the outside of the main tank wall. The space between the roof and the wall is closed by either a wet seal, which is a trough filled with liquid, or a dry seal, which uses a flexible coated fabric.

Flexible diaphragm tanks use flexible membranes to provide expandable volume. They may be either separate gasholder units or integral units mounted atop fixed roof tanks.

Variable vapor space tank losses occur during tank filling when vapor is displaced by liquid. Loss of vapor occurs only when the tank's vapor storage capacity is exceeded.

7.1.1.6 Pressure Tanks –

Two classes of pressure tanks are in general use: low pressure (2.5 to 15 psig) and high pressure (higher than 15 psig). Pressure tanks generally are used for storing organic liquids and gases with high vapor pressures and are found in many sizes and shapes, depending on the operating pressure of the tank. Pressure tanks are equipped with a pressure/vacuum vent that is set to prevent venting loss from boiling and breathing loss from daily temperature or barometric pressure changes. High-pressure storage tanks can be operated so that virtually no evaporative or working losses occur. In low-pressure tanks, working losses can occur with atmospheric venting of the tank during filling operations. No appropriate correlations are available to estimate vapor losses from pressure tanks.

7.1.2 Emission Mechanisms And Control

Emissions from organic liquids in storage occur because of evaporative loss of the liquid during its storage and as a result of changes in the liquid level. The emission sources vary with tank design, as does the relative contribution of each type of emission source. Emissions from fixed roof tanks are a result of evaporative losses during storage (known as breathing losses or standing storage losses) and evaporative losses during filling and emptying operations (known as working losses). External and internal floating roof tanks are emission sources because of evaporative losses that occur during standing storage and withdrawal of liquid from the tank. Standing storage losses are a result of evaporative losses through rim seals, deck fittings, and/or deck seams. The loss mechanisms for fixed roof and external and internal floating roof tanks are described in more detail in this section. Variable vapor space tanks are also emission sources because of evaporative losses that result during filling operations. The loss mechanism for variable vapor space tanks is also described in this section. Emissions occur from pressure tanks, as well. However, loss mechanisms from these sources are not described in this section.

7.1.2.1 Fixed Roof Tanks –

The two significant types of emissions from fixed roof tanks are storage and working losses. Storage loss is the expulsion of vapor from a tank through vapor expansion and contraction, which are the results of changes in temperature and barometric pressure. This loss occurs without any liquid level change in the tank.

The combined loss from filling and emptying is called working loss. Evaporation during filling operations is a result of an increase in the liquid level in the tank. As the liquid level increases, the pressure inside the tank exceeds the relief pressure and vapors are expelled from the tank. Evaporative loss during emptying occurs when air drawn into the tank during liquid removal becomes saturated with organic vapor and expands, thus exceeding the capacity of the vapor space.

Fixed roof tank emissions vary as a function of vessel capacity, vapor pressure of the stored liquid, utilization rate of the tank, and atmospheric conditions at the tank location.

Several methods are used to control emissions from fixed roof tanks. Emissions from fixed roof tanks can be controlled by installing an internal floating roof and seals to minimize evaporation of the product being stored. The control efficiency of this method ranges from 60 to 99 percent, depending on the type of roof and seals installed and on the type of organic liquid stored.

Vapor balancing is another means of emission control. Vapor balancing is probably most common in the filling of tanks at gasoline stations. As the storage tank is filled, the vapors expelled from the storage tank are directed to the emptying gasoline tanker truck. The truck then transports the vapors to a centralized station where a vapor recovery or control system is used to control emissions. Vapor balancing can have control efficiencies as high as 90 to 98 percent if the vapors are subjected to vapor recovery or control. If the truck vents the vapor to the atmosphere instead of to a recovery or control system, no control is achieved.

Vapor recovery systems collect emissions from storage vessels and convert them to liquid product. Several vapor recovery procedures may be used, including vapor/liquid absorption, vapor compression, vapor cooling, vapor/solid adsorption, or a combination of these. The overall control efficiencies of vapor recovery systems are as high as 90 to 98 percent, depending on the methods used, the design of the unit, the composition of vapors recovered, and the mechanical condition of the system.

In a typical thermal oxidation system, the air/vapor mixture is injected through a burner manifold into the combustion area of an incinerator. Control efficiencies for this system can range from 96 to 99 percent.

7.1.2.2 Floating Roof Tanks²⁻⁷ –

Total emissions from floating roof tanks are the sum of withdrawal losses and standing storage losses. Withdrawal losses occur as the liquid level, and thus the floating roof, is lowered. Some liquid remains on the inner tank wall surface and evaporates. For an internal floating roof tank that has a column supported fixed roof, some liquid also clings to the columns and evaporates. Evaporative loss occurs until the tank is filled and the exposed surfaces are again covered. Standing storage losses from floating roof tanks include rim seal and deck fitting losses, and for internal floating roof tanks also include deck seam losses for constructions other than welded decks. Other potential standing storage loss mechanisms include breathing losses as a result of temperature and pressure changes.

Rim seal losses can occur through many complex mechanisms, but for external floating roof tanks, the majority of rim seal vapor losses have been found to be wind induced. No dominant wind loss mechanism has been identified for internal floating roof or domed external floating roof tank rim seal losses. Losses can also occur due to permeation of the rim seal material by the vapor or via a wicking effect of the liquid, but permeation of the rim seal material generally does not occur if the correct seal fabric is used. Testing has indicated that breathing, solubility, and wicking loss mechanisms are small in comparison to the wind-induced loss. The rim seal factors presented in this section incorporate all types of losses.

The rim seal system is used to allow the floating roof to rise and fall within the tank as the liquid level changes. The rim seal system also helps to fill the annular space between the rim and the tank shell and therefore minimize evaporative losses from this area. A rim seal system may consist of just a primary seal or a primary and a secondary seal, which is mounted above the primary seal. Examples of primary and secondary seal configurations are shown in Figures 7.1-6, 7.1-7, and 7.1-8.

The primary seal serves as a vapor conservation device by closing the annular space between the edge of the floating deck and the tank wall. Three basic types of primary seals are used on external floating roofs: mechanical (metallic) shoe, resilient filled (nonmetallic), and flexible wiper seals. Some primary seals on external floating roof tanks are protected by a weather shield. Weather shields may be of metallic, elastomeric, or composite construction and provide the primary seal with longer life by protecting the primary seal fabric from deterioration due to exposure to weather, debris, and sunlight. Internal floating roofs typically incorporate one of two types of flexible, product-resistant seals: resilient foam-filled seals or wiper seals. Mechanical shoe seals, resilient filled seals, and wiper seals are discussed below.

A mechanical shoe seal uses a light-gauge metallic band as the sliding contact with the shell of the tank, as shown in Figure 7.1-7. The band is formed as a series of sheets (shoes) which are joined together to form a ring, and are held against the tank shell by a mechanical device. The shoes are normally 3 to 5 feet deep, providing a potentially large contact area with the tank shell. Expansion and contraction of the ring can be provided for as the ring passes over shell irregularities or rivets by jointing narrow pieces of fabric into the ring or by crimping the shoes at intervals. The bottoms of the shoes extend below the liquid surface to confine the rim vapor space between the shoe and the floating deck.

The rim vapor space, which is bounded by the shoe, the rim of the floating deck, and the liquid surface, is sealed from the atmosphere by bolting or clamping a coated fabric, called the primary seal fabric, that extends from the shoe to the rim to form an "envelope". Two locations are used for attaching the primary seal fabric. The fabric is most commonly attached to the top of the shoe and the rim of the floating deck. To reduce the rim vapor space, the fabric can be attached to the shoe and the floating deck rim near the liquid surface. Rim vents can be used to relieve any excess pressure or vacuum in the vapor space.

A resilient filled seal can be mounted to eliminate the vapor space between the rim seal and liquid surface (liquid mounted) or to allow a vapor space between the rim seal and the liquid surface (vapor mounted). Both configurations are shown in Figures 7.1-6 and 7.1-7. Resilient filled seals work because of the expansion and contraction of a resilient material to maintain contact with the tank shell while accommodating varying annular rim space widths. These rim seals allow the roof to move up and down freely, without binding.

Resilient filled seals typically consist of a core of open-cell foam encapsulated in a coated fabric. The seals are attached to a mounting on the deck perimeter and extend around the deck circumference. Polyurethane-coated nylon fabric and polyurethane foam are commonly used materials. For emission control, it is important that the attachment of the seal to the deck and the radial seal joints be vapor-tight and that the seal be in substantial contact with the tank shell.

Wiper seals generally consist of a continuous annular blade of flexible material fastened to a mounting bracket on the deck perimeter that spans the annular rim space and contacts the tank shell. This type of seal is depicted in Figure 7.1-6. New tanks with wiper seals may have dual wipers, one mounted above the other. The mounting is such that the blade is flexed, and its elasticity provides a sealing pressure against the tank shell.

Wiper seals are vapor mounted; a vapor space exists between the liquid stock and the bottom of the seal. For emission control, it is important that the mounting be vapor-tight, that the seal extend around the circumference of the deck and that the blade be in substantial contact with the tank shell. Two types of materials are commonly used to make the wipers. One type consists of a cellular, elastomeric material tapered in cross section with the thicker portion at the mounting. Rubber is a commonly used material; urethane and cellular plastic are also available. All radial joints in the blade are joined. The second type of material that can be used is a foam core wrapped with a coated fabric. Polyurethane on nylon fabric and polyurethane foam are common materials. The core provides the flexibility and support, while the fabric provides the vapor barrier and wear surface.

A secondary seal may be used to provide some additional evaporative loss control over that achieved by the primary seal. Secondary seals can be either flexible wiper seals or resilient filled seals. For external floating roof tanks, two configurations of secondary seals are available: shoe mounted and rim mounted, as shown in Figure 7.1-8. Rim mounted secondary seals are more effective in reducing losses than shoe mounted secondary seals because they cover the entire rim vapor space. For internal floating roof tanks, the secondary seal is mounted to an extended vertical rim plate, above the primary seal, as shown in Figure 7.1-8. However, for some floating roof tanks, using a secondary seal further limits the tank's operating capacity due to the need to keep the seal from interfering with fixed roof rafters or to keep the secondary seal in contact with the tank shell when the tank is filled.

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The deck fitting losses from floating roof tanks can be explained by the same mechanisms as the rim seal losses. However, the relative contribution of each mechanism is not known. The deck fitting losses identified in this section account for the combined effect of all of the mechanisms.

Numerous fittings pass through or are attached to floating roof decks to accommodate structural support components or allow for operational functions. Internal floating roof deck fittings are typically of different configuration than those for external floating roof decks. Rather than having tall housings to avoid rainwater entry, internal floating roof deck fittings tend to have lower profile housings to minimize the potential for the fitting to contact the fixed roof when the tank is filled. Deck fittings can be a source of evaporative loss when they require openings in the deck. The most common components that require openings in the deck are described below.

1. Access hatches. An access hatch is an opening in the deck with a peripheral vertical well that is large enough to provide passage for workers and materials through the deck for construction or servicing. Attached to the opening is a removable cover that may be bolted and/or gasketed to reduce evaporative loss. On internal floating roof tanks with noncontact decks, the well should extend down into the liquid to seal off the vapor space below the noncontact deck. A typical access hatch is shown in Figure 7.1-9.

2. Gauge-floats. A gauge-float is used to indicate the level of liquid within the tank. The float rests on the liquid surface and is housed inside a well that is closed by a cover. The cover may be bolted and/or gasketed to reduce evaporation loss. As with other similar deck penetrations, the well extends down into the liquid on noncontact decks in internal floating roof tanks. A typical gauge-float and well are shown in Figure 7.1-9.

3. Gauge-hatch/sample ports. A gauge-hatch/sample port consists of a pipe sleeve equipped with a self-closing gasketed cover (to reduce evaporative losses) and allows hand-gauging or sampling of the stored liquid. The gauge-hatch/sample port is usually located beneath the gauger's platform, which is mounted on top of the tank shell. A cord may be attached to the self-closing gasketed cover so that the cover can be opened from the platform. A typical gauge-hatch/sample port is shown in Figure 7.1-9.

4. Rim vents. Rim vents are used on tanks equipped with a seal design that creates a vapor pocket in the seal and rim area, such as a mechanical shoe seal. A typical rim vent is shown in Figure 7.1-10. The vent is used to release any excess pressure or vacuum that is present in the vapor space bounded by the primary-seal shoe and the floating roof rim and the primary seal fabric and the liquid level. Rim vents usually consist of weighted pallets that rest on a gasketed cover.

5. Deck drains. Currently two types of deck drains are in use (closed and open deck drains) to remove rainwater from the floating deck. Open deck drains can be either flush or overflow drains. Both types consist of a pipe that extends below the deck to allow the rainwater to drain into the stored liquid. Only open deck drains are subject to evaporative loss. Flush drains are flush with the deck surface. Overflow drains are elevated above the deck surface. Typical overflow and flush deck drains are shown in Figure 7.1-10. Overflow drains are used to limit the maximum amount of rainwater that can accumulate on the floating deck, providing emergency drainage of rainwater if necessary. Closed deck drains carry rainwater from the surface of the deck through a flexible hose or some other type of piping system that runs through the stored liquid prior to exiting the tank. The rainwater does not come in contact with the liquid, so no evaporative losses result. Overflow drains are usually used in conjunction with a closed drain system to carry rainwater outside the tank.

6. Deck legs. Deck legs are used to prevent damage to fittings underneath the deck and to allow for tank cleaning or repair, by holding the deck at a predetermined distance off the tank bottom. These supports consist of adjustable or fixed legs attached to the floating deck or hangers suspended from the fixed roof. For adjustable legs or hangers, the load-carrying element passes through a well or sleeve into the deck. With noncontact decks, the well should extend into the liquid. Evaporative losses may occur in the annulus between the deck leg and its sleeve. A typical deck leg is shown in Figure 7.1-10.

7. Unslotted guidepoles and wells. A guidepole is an antirotational device that is fixed to the top and bottom of the tank, passing through a well in the floating roof. The guidepole is used to prevent adverse movement of the roof and thus damage to deck fittings and the rim seal system. In some cases, an unslotted guidepole is used for gauging purposes, but there is a potential for differences in the pressure, level, and composition of the liquid inside and outside of the guidepole. A typical guidepole and well are shown in Figure 7.1-11.

8. Slotted (perforated) guidepoles and wells. The function of the slotted guidepole is similar to the unslotted guidepole but also has additional features. Perforated guidepoles can be either slotted or drilled hole guidepoles. A typical slotted guidepole and well are shown in Figure 7.1-11. As shown in this figure, the guide pole is slotted to allow stored liquid to enter. The same can be accomplished with drilled holes. The liquid entering the guidepole is well mixed, having the same composition as the remainder of the stored liquid, and is at the same liquid level as the liquid in the tank. Representative samples can therefore be collected from the slotted or drilled hole guidepole. However, evaporative loss from the guidepole can be reduced by modifying the guidepole or well or by placing a float inside the guidepole. Guidepoles are also referred to as gauge poles, gauge pipes, or stilling wells.

9. Vacuum breakers. A vacuum breaker equalizes the pressure of the vapor space across the deck as the deck is either being landed on or floated off its legs. A typical vacuum breaker is shown in Figure 7.1-10. As depicted in this figure, the vacuum breaker consists of a well with a cover. Attached to the underside of the cover is a guided leg long enough to contact the tank bottom as the floating deck approaches. When in contact with the tank bottom, the guided leg mechanically opens the breaker by lifting the cover off the well; otherwise, the cover closes the well. The closure may be gasketed or ungasketed. Because the purpose of the vacuum breaker is to allow the free exchange of air and/or vapor, the well does not extend appreciably below the deck.

Fittings used only on internal floating roof tanks include column wells, ladder wells, and stub drains.

1. Columns and wells. The most common fixed-roof designs are normally supported from inside the tank by means of vertical columns, which necessarily penetrate an internal floating deck. (Some fixed roofs are entirely self-supporting and, therefore, have no support columns.) Column wells are similar to unslotted guide pole wells on external floating roofs. Columns are made of pipe with circular cross sections or of structural shapes with irregular cross sections (built-up). The number of columns varies with tank diameter, from a minimum of 1 to over 50 for very large diameter tanks. A typical fixed roof support column and well are shown in Figure 7.1-9.

The columns pass through deck openings via peripheral vertical wells. With noncontact decks, the well should extend down into the liquid stock. Generally, a closure device exists between the top of the well and the column. Several proprietary designs exist for this closure, including sliding covers and fabric sleeves, which must accommodate the movements of the deck relative to the column as the

liquid level changes. A sliding cover rests on the upper rim of the column well (which is normally fixed to the deck) and bridges the gap or space between the column well and the column. The cover, which has a cutout, or opening, around the column slides vertically relative to the column as the deck raises and lowers. At the same time, the cover slides horizontally relative to the rim of the well. A gasket around the rim of the well reduces emissions from this fitting. A flexible fabric sleeve seal between the rim of the well and the column (with a cutout or opening, to allow vertical motion of the seal relative to the columns) similarly accommodates limited horizontal motion of the deck relative to the column.

2. Ladders and wells. Some tanks are equipped with internal ladders that extend from a manhole in the fixed roof to the tank bottom. The deck opening through which the ladder passes is constructed with similar design details and considerations to deck openings for column wells, as previously discussed. A typical ladder well is shown in Figure 7.1-12.

3. Stub drains. Bolted internal floating roof decks are typically equipped with stub drains to allow any stored product that may be on the deck surface to drain back to the underside of the deck. The drains are attached so that they are flush with the upper deck. Stub drains are approximately 1 inch in diameter and extend down into the product on noncontact decks.

Deck seams in internal floating roof tanks are a source of emissions to the extent that these seams may not be completely vapor tight if the deck is not welded. Generally, the same loss mechanisms for fittings apply to deck seams. The predominant mechanism depends on whether or not the deck is in contact with the stored liquid. The deck seam loss equation accounts for the effects of all contributing loss mechanisms.

7.1.3 Emission Estimation Procedures

The following section presents the emission estimation procedures for fixed roof, external floating roof, domed external floating roof, and internal floating roof tanks. These procedures are valid for all petroleum liquids, pure volatile organic liquids, and chemical mixtures with similar true vapor pressures. It is important to note that in all the emission estimation procedures the physical properties of the vapor do not include the noncondensibles (e. g., air) in the gas but only refer to the condensible components of the stored liquid. To aid in the emission estimation procedures, a list of variables with their corresponding definitions was developed and is presented in Table 7.1-1.

The factors presented in AP-42 are those that are currently available and have been reviewed and approved by the U. S. Environmental Protection Agency. As storage tank equipment vendors design new floating decks and equipment, new emission factors may be developed based on that equipment. If the new emission factors are reviewed and approved, the emission factors will be added to AP-42 during the next update.

The emission estimation procedures outlined in this chapter have been used as the basis for the development of a software program to estimate emissions from storage tanks. The software program entitled "TANKS" is available through the Technology Transfer Network (TTN) Bulletin Board System maintained by the U. S. Environmental Protection Agency.

7.1.3.1 Total Losses From Fixed Roof Tanks^{4,8-14} –

The following equations, provided to estimate standing storage and working loss emissions, apply to tanks with vertical cylindrical shells and fixed roofs. These tanks must be substantially liquid- and vapor-tight and must operate approximately at atmospheric pressure. The equations are not

intended to be used in estimating losses from unstable or boiling stocks or from mixtures of hydrocarbons or petrochemicals for which the vapor pressure is not known or cannot be readily predicted. Total losses from fixed roof tanks are equal to the sum of the standing storage loss and working loss:

$$L_T = L_S + L_W \quad (1-1)$$

where:

L_T = total losses, lb/yr

L_S = standing storage losses, lb/yr

L_W = working losses, lb/yr

Standing Storage Loss - Fixed roof tank breathing or standing storage losses can be estimated from:

$$L_S = 365 V_V W_V K_E K_S \quad (1-2)$$

where:

L_S = standing storage loss, lb/yr

V_V = vapor space volume, ft³

W_V = vapor density, lb/ft³

K_E = vapor space expansion factor, dimensionless

K_S = vented vapor saturation factor, dimensionless

365 = constant, d/yr

Tank Vapor Space Volume, V_V - The tank vapor space volume is calculated using the following equation:

$$V_V = \frac{\pi}{4} D^2 H_{VO} \quad (1-3)$$

where:

V_V = vapor space volume, ft³

D = tank diameter, ft, see Note 1 for horizontal tanks

H_{VO} = vapor space outage, ft

The vapor space outage, H_{VO} is the height of a cylinder of tank diameter, D , whose volume is equivalent to the vapor space volume of a fixed roof tank, including the volume under the cone or dome roof. The vapor space outage, H_{VO} , is estimated from:

$$H_{VO} = H_S - H_L + H_{RO} \quad (1-4)$$

where:

H_{VO} = vapor space outage, ft

H_S = tank shell height, ft

H_L = liquid height, ft

H_{RO} = roof outage, ft; see Note 2 for a cone roof or Note 3 for a dome roof

Notes:

1. The emission estimating equations presented above were developed for vertical fixed roof tanks. If a user needs to estimate emissions from a horizontal fixed roof tank, some of the tank parameters can be modified before using the vertical tank emission estimating equations. First, by assuming that the tank is one-half filled, the surface area of the liquid in the tank is approximately equal to the length of the tank times the diameter of the tank. Next, assume that this area represents a circle, i. e., that the liquid is an upright cylinder. Therefore, the effective diameter, D_E , is then equal to:

$$D_E = \sqrt{\frac{LD}{0.785}} \quad (1-5)$$

where:

D_E = effective tank diameter, ft

L = length of tank, ft

D = actual diameter of tank, ft

One-half of the actual diameter of the horizontal tank should be used as the vapor space outage, H_{VO} . This method yields only a very approximate value for emissions from horizontal storage tanks. For underground horizontal tanks, assume that no breathing or standing storage losses occur ($L_S = 0$) because the insulating nature of the earth limits the diurnal temperature change. No modifications to the working loss equation are necessary for either above-ground or underground horizontal tanks.

2. For a cone roof, the roof outage, H_{RO} , is calculated as follows:

$$H_{RO} = 1/3 H_R \quad (1-6)$$

where:

H_{RO} = roof outage (or shell height equivalent to the volume contained under the roof), ft

H_R = tank roof height, ft

The tank roof height, H_R , is equal to $S_R R_S$

where:

S_R = tank cone roof slope, if unknown, a standard value of 0.0625 ft/ft is used, ft/ft

R_S = tank shell radius, ft

3. For a dome roof, the roof outage, H_{RO} , is calculated as follows:

$$H_{RO} = H_R \left[1/2 + 1/6 \left[\frac{H_R}{R_S} \right]^2 \right] \quad (1-7)$$

where:

H_{RO} = roof outage, ft

H_R = tank roof height, ft

R_S = tank shell radius, ft

The tank roof height, H_R , is calculated:

$$H_R = R_R - (R_R^2 - R_S^2)^{0.5} \quad (1-8)$$

where:

H_R = tank roof height, ft

R_R = tank dome roof radius, ft

R_S = tank shell radius, ft

The value of R_R usually ranges from $0.8D - 1.2D$, where $D = 2 R_S$. If R_R is unknown, the tank diameter is used in its place. If the tank diameter is used as the value for R_R , Equations 1-7 and 1-8 reduce to $H_R = 0.268 R_S$ and $H_{RO} = 0.137 R_S$.

Vapor Density, W_V - The density of the vapor is calculated using the following equation:

$$W_V = \frac{M_V P_{VA}}{RT_{LA}} \quad (1-9)$$

where:

W_V = vapor density, lb/ft³

M_V = vapor molecular weight, lb/lb-mole; see Note 1

R = the ideal gas constant, 10.731 psia·ft³/lb-mole·°R

P_{VA} = vapor pressure at daily average liquid surface temperature, psia; see Notes 1 and 2

T_{LA} = daily average liquid surface temperature, °R; see Note 3

Notes:

1. The molecular weight of the vapor, M_V , can be determined from Table 7.1-2 and 7.1-3 for selected petroleum liquids and volatile organic liquids, respectively, or by analyzing vapor samples. Where mixtures of organic liquids are stored in a tank, M_V can be calculated from the liquid composition. The molecular weight of the vapor, M_V , is equal to the sum of the molecular weight, M_i , multiplied by the vapor mole fraction, y_i , for each component. The vapor mole fraction is equal to the partial pressure of component i divided by the total vapor pressure. The partial pressure of component i is equal to the true vapor pressure of component i (P) multiplied by the liquid mole fraction, (x_i). Therefore,

$$M_V = \sum M_i y_i = \sum M_i \left(\frac{P x_i}{P_{VA}} \right) \quad (1-10)$$

where:

P_{VA} , total vapor pressure of the stored liquid, by Raoult's Law, is:

$$P_{VA} = \sum P x_i \quad (1-11)$$

For more detailed information, please refer to Section 7.1.4.

2. True vapor pressure is the equilibrium partial pressure exerted by a volatile organic liquid, as defined by ASTM-D 2879 or as obtained from standard reference texts. Reid vapor pressure is the absolute vapor pressure of volatile crude oil and volatile nonviscous petroleum liquids, except liquified petroleum gases, as determined by ASTM-D-323. True vapor pressures for organic liquids can be determined from Table 7.1-3. True vapor pressure can be determined for crude oils using Figures 7.1-13a and 7.1-13b. For refined stocks (gasolines and naphthas), Table 7.1-2 or Figures 7.1-14a and 7.1-14b can be used. In order to use Figures 7.1-13a, 7.1-13b, 7.1-14a, or 7.1-14b, the stored liquid surface temperature, T_{LA} , must be determined in degrees Fahrenheit. See Note 3 to determine T_{LA} .

Alternatively, true vapor pressure for selected petroleum liquid stocks, at the stored liquid surface temperature, can be determined using the following equation:

$$P_{VA} = \exp [A - (B/T_{LA})] \quad (1-12a)$$

where:

exp = exponential function

A = constant in the vapor pressure equation, dimensionless

B = constant in the vapor pressure equation, °R

T_{LA} = daily average liquid surface temperature, °R

P_{VA} = true vapor pressure, psia

For selected petroleum liquid stocks, physical property data are presented in Table 7.1-2. For refined petroleum stocks, the constants A and B can be calculated from the equations presented in Figure 7.1-15 and the distillation slopes presented in Table 7.1-4. For crude oil stocks, the constants A and B can be calculated from the equations presented in Figure 7.1-16. Note that in Equation 1-12a, T_{LA} is determined in degrees Rankine instead of degrees Fahrenheit.

The true vapor pressure of organic liquids at the stored liquid temperature can be estimated by Antoine's equation:

$$\log P_{VA} = A - \frac{B}{T_{LA} + C} \quad (1-12b)$$

where:

A = constant in vapor pressure equation

B = constant in vapor pressure equation

C = constant in vapor pressure equation

T_{LA} = daily average liquid surface temperature, °C

P_{VA} = vapor pressure at average liquid surface temperature, mm Hg

For organic liquids, the values for the constants A, B, and C are listed in Table 7.1-5. Note that in Equation 1-12b, T_{LA} is determined in degrees Celsius instead of degrees Rankine. Also, in Equation 1-12b, P_{VA} is determined in mm of Hg rather than psia (760 mm Hg = 14.7 psia).

3. If the daily average liquid surface temperature, T_{LA} , is unknown, it is calculated using the following equation:

$$T_{LA} = 0.44T_{AA} + 0.56T_B + 0.0079 \alpha I \quad (1-13)$$

where:

T_{LA} = daily average liquid surface temperature, °R

T_{AA} = daily average ambient temperature, °R; see Note 4

T_B = liquid bulk temperature, °R; see Note 5

α = tank paint solar absorptance, dimensionless; see Table 7.1-6

I = daily total solar insolation factor, Btu/ft²·d; see Table 7.1-7

If T_{LA} is used to calculate P_{VA} from Figures 7.1-13a, 7.1-13b, 7.1-14a, or 7.1-14b, T_{LA} must be converted from degrees Rankine to degrees Fahrenheit (°F = °R - 460). If T_{LA} is used to calculate P_{VA} from Equation 1-12b, T_{LA} must be converted from degrees Rankine to degrees Celsius

(°C = [°R - 492]/1.8). Equation 1-13 should not be used to estimate liquid surface temperature from insulated tanks. In the case of insulated tanks, the average liquid surface temperature should be based on liquid surface temperature measurements from the tank.

4. The daily average ambient temperature, T_{AA} , is calculated using the following equation:

$$T_{AA} = (T_{AX} + T_{AN})/2 \quad (1-14)$$

where:

T_{AA} = daily average ambient temperature, °R

T_{AX} = daily maximum ambient temperature, °R

T_{AN} = daily minimum ambient temperature, °R

Table 7.1-7 gives values of T_{AX} and T_{AN} for selected U. S. cities.

5. The liquid bulk temperature, T_B , is calculated using the following equation:

$$T_B = T_{AA} + 6\alpha - 1 \quad (1-15)$$

where:

T_B = liquid bulk temperature, °R

T_{AA} = daily average ambient temperature, °R, as calculated in Note 4

α = tank paint solar absorptance, dimensionless; see Table 7.1-6.

Vapor Space Expansion Factor, K_E - The vapor space expansion factor, K_E , is calculated using the following equation:

$$K_E = \frac{\Delta T_V}{T_{LA}} + \frac{\Delta P_V - \Delta P_B}{P_A - P_{VA}} \quad (1-16)$$

where:

ΔT_V = daily vapor temperature range, °R; see Note 1

ΔP_V = daily vapor pressure range, psi; see Note 2

ΔP_B = breather vent pressure setting range, psi; see Note 3

P_A = atmospheric pressure, psia

P_{VA} = vapor pressure at daily average liquid surface temperature, psia; see Notes 1 and 2 for Equation 1-9

T_{LA} = daily average liquid surface temperature, °R; see Note 3 for Equation 1-9

Notes:

1. The daily vapor temperature range, ΔT_V , is calculated using the following equation:

$$\Delta T_V = 0.72 \Delta T_A + 0.028 \alpha I \quad (1-17)$$

where:

ΔT_V = daily vapor temperature range, °R

ΔT_A = daily ambient temperature range, °R; see Note 4

α = tank paint solar absorptance, dimensionless; see Table 7.1-6

I = daily total solar insolation factor, Btu/ft²-d; see Table 7.1-7

2. The daily vapor pressure range, ΔP_V , can be calculated using the following equation:

$$\Delta P_V = P_{VX} - P_{VN} \quad (1-18)$$

where:

ΔP_V = daily vapor pressure range, psia

P_{VX} = vapor pressure at the daily maximum liquid surface temperature, psia; see Note 5

P_{VN} = vapor pressure at the daily minimum liquid surface temperature, psia; see Note 5

The following method can be used as an alternate means of calculating ΔP_V for petroleum liquids:

$$\Delta P_V = \frac{0.50 B P_{VA} \Delta T_V}{T_{LA}^2} \quad (1-19)$$

where:

ΔP_V = daily vapor pressure range, psia

B = constant in the vapor pressure equation, °R; see Note 2 to Equation 1-9

P_{VA} = vapor pressure at the daily average liquid surface temperature, psia; see Notes 1 and 2 to Equation 1-9

T_{LA} = daily average liquid surface temperature, °R; see Note 3 to Equation 1-9

ΔT_V = daily vapor temperature range, °R; see Note 1

3. The breather vent pressure setting range, ΔP_B , is calculated using the following equation:

$$\Delta P_B = P_{BP} - P_{BV} \quad (1-20)$$

where:

ΔP_B = breather vent pressure setting range, psig

P_{BP} = breather vent pressure setting, psig

P_{BV} = breather vent vacuum setting, psig

If specific information on the breather vent pressure setting and vacuum setting is not available, assume 0.03 psig for P_{BP} and -0.03 psig for P_{BV} as typical values. If the fixed roof tank is of bolted or riveted construction in which the roof or shell plates are not vapor tight, assume that $\Delta P_B = 0$, even if a breather vent is used. The estimating equations for fixed roof tanks do not apply to either low or high pressure tanks. If the breather vent pressure or vacuum setting exceeds 1.0 psig, the standing storage losses could potentially be negative.

4. The daily ambient temperature range, ΔT_A , is calculated using the following equation:

$$\Delta T_A = T_{AX} - T_{AN} \quad (1-21)$$

where:

ΔT_A = daily ambient temperature range, °R

T_{AX} = daily maximum ambient temperature, °R

T_{AN} = daily minimum ambient temperature, °R

Table 7.1-7 gives values of T_{AX} and T_{AN} for selected cities in the United States.¹¹

5. The vapor pressures associated with daily maximum and minimum liquid surface temperature, P_{VX} and P_{VN} , respectively are calculated by substituting the corresponding temperatures, T_{LX} and T_{LN} , into the vapor pressure function discussed in Notes 1 and 2 to Equation 1-9. If T_{LX} and T_{LN} are unknown, Figure 7.1-17 can be used to calculate their values.

Vented Vapor Saturation Factor, K_S - The vented vapor saturation factor, K_S , is calculated using the following equation:

$$K_S = \frac{1}{1 + 0.053 P_{VA} H_{VO}} \quad (1-22)$$

where:

K_S = vented vapor saturation factor, dimensionless

P_{VA} = vapor pressure at daily average liquid surface temperature, psia; see Notes 1 and 2 to Equation 1-9

H_{VO} = vapor space outage, ft, as calculated in Equation 1-4

Working Loss - The working loss, L_W , can be estimated from:

$$L_W = 0.0010 M_V P_{VA} Q K_N K_P, \quad (1-23)$$

where:

L_W = working loss, lb/yr

M_V = vapor molecular weight, lb/lb-mole; see Note 1 to Equation 1-9

P_{VA} = vapor pressure at daily average liquid surface temperature, psia; see Notes 1 and 2 to Equation 1-9

Q = annual net throughput (tank capacity [bbl] times annual turnover rate), bbl/yr

K_N = turnover factor, dimensionless; see Figure 7.1-18
for turnovers > 36 , $K_N = (180 + N)/6N$
for turnovers ≤ 36 , $K_N = 1$

N = number of turnovers per year, dimensionless

$$N = \frac{5.614Q}{V_{LX}} \quad (1-24)$$

where:

N = number of turnovers per year, dimensionless

Q = annual net throughput, bbl/yr

V_{LX} = tank maximum liquid volume, ft^3

and

$$V_{LX} = \frac{\pi}{4} D^2 H_{LX} \quad (1-25)$$

where:

D = diameter, ft

H_{LX} = maximum liquid height, ft

K_P = working loss product factor, dimensionless, 0.75 for crude oils. For all other organic liquids, $K_P = 1$

7.1.3.2 Total Losses From Floating Roof Tanks^{3-5,13,15-17} _

Total floating roof tank emissions are the sum of rim seal, withdrawal, deck fitting, and deck seam losses. The equations presented in this subsection apply only to floating roof tanks. The equations are not intended to be used in the following applications:

1. To estimate losses from unstable or boiling stocks or from mixtures of hydrocarbons or petrochemicals for which the vapor pressure is not known or cannot readily be predicted;

2. To estimate losses from closed internal or closed domed external floating roof tanks (tanks vented only through a pressure/vacuum vent); or

3. To estimate losses from tanks in which the materials used in the rim seal and/or deck fittings are either deteriorated or significantly permeated by the stored liquid.

Total losses from floating roof tanks may be written as:

$$L_T = L_R + L_{WD} + L_F + L_D \quad (2-1)$$

where:

L_T = total loss, lb/yr

L_R = rim seal loss, lb/yr; see Equation 2-2

L_{WD} = withdrawal loss, lb/yr; see Equation 2-4

L_F = deck fitting loss, lb/yr; see Equation 2-5

L_D = deck seam loss (internal floating roof tanks only), lb/yr; see Equation 2-9

Rim Seal Loss - Rim seal loss from floating roof tanks can be estimated using the following equation:

$$L_R = (K_{Ra} + K_{Rb} v^n) DP^* M_V K_C \quad (2-2)$$

where:

L_R = rim seal loss, lb/yr

K_{Ra} = zero wind speed rim seal loss factor, lb-mole/ft·yr; see Table 7.1-8

K_{Rb} = wind speed dependent rim seal loss factor, lb-mole/(mph)ⁿft·yr; see Table 7.1-8

v = average ambient wind speed at tank site, mph; see Note 1

n = seal-related wind speed exponent, dimensionless; see Table 7.1-8

P^* = vapor pressure function, dimensionless; see Note 2

$$P^* = \frac{P_{VA}/P_A}{[1 + (1 - [P_{VA}/P_A])^{0.5}]^2} \quad (2-3)$$

where:

P_{VA} = vapor pressure at daily average liquid surface temperature, psia;
See Notes 1 and 2 to Equation 1-9 and Note 3 below

P_A = atmospheric pressure, psia

D = tank diameter, ft

M_V = average vapor molecular weight, lb/lb-mole; see Note 1 to Equation 1-9,

K_C = product factor; $K_C = 0.4$ for crude oils; $K_C = 1$ for all other organic liquids.

Notes:

1. If the ambient wind speed at the tank site is not available, use wind speed data from the nearest local weather station or values from Table 7.1-9. If the tank is an internal or domed external floating roof tank, the value of v is zero.

2. P^* can be calculated or read directly from Figure 7.1-19.

3. The API recommends using the stock liquid temperature to calculate P_{VA} for use in Equation 2-3 in lieu of the liquid surface temperature. If the stock liquid temperature is unknown, API recommends the following equations to estimate the stock temperature:

Tank Color	Average Annual Stock Temperature, T_s (°F)
White	$T_{AA} + 0^a$
Aluminum	$T_{AA} + 2.5$
Gray	$T_{AA} + 3.5$
Black	$T_{AA} + 5.0$

$^aT_{AA}$ is the average annual ambient temperature in degrees Fahrenheit.

Withdrawal Loss - The withdrawal loss from floating roof storage tanks can be estimated using Equation 2-4.

$$L_{WD} = \frac{(0.943)QCW_L}{D} \left[1 + \frac{N_C F_C}{D} \right] \quad (2-4)$$

where:

L_{WD} = withdrawal loss, lb/yr

Q = annual throughput (tank capacity [bbl] times annual turnover rate), bbl/yr

C = shell clingage factor, bbl/1,000 ft²; see Table 7.1-10

W_L = average organic liquid density, lb/gal; see Note 1

D = tank diameter, ft

0.943 = constant, 1,000 ft³·gal/bbl²

N_C = number of fixed roof support columns, dimensionless; see Note 2

F_C = effective column diameter, ft (column perimeter [ft]/ π); see Note 3

Notes:

1. A listing of the average organic liquid density for select petrochemicals is provided in Tables 7.1-2 and 7.1-3. If W_L is not known for gasoline, an average value of 6.1 lb/gal can be assumed.

2. For a self-supporting fixed roof or an external floating roof tank:

$$N_C = 0.$$

For a column-supported fixed roof:

$$N_C = \text{use tank-specific information or see Table 7.1-11.}$$

3. Use tank-specific effective column diameter or

$$F_C = \begin{array}{l} 1.1 \text{ for 9-inch by 7-inch built-up columns, } 0.7 \text{ for 8-inch-diameter pipe} \\ \text{columns, and } 1.0 \text{ if column construction details are not known} \end{array}$$

Deck Fitting Loss - Deck fitting losses from floating roof tanks can be estimated by the following equation:

$$L_F = F_F P^* M_V K_C \quad (2-5)$$

where:

L_F = the deck fitting loss, lb/yr

F_F = total deck fitting loss factor, lb-mole/yr

$$F_F = [(N_{F_1} K_{F_1}) + (N_{F_2} K_{F_2}) + \dots + (N_{F_{n_f}} K_{F_{n_f}})] \quad (2-6)$$

where:

N_{F_i} = number of deck fittings of a particular type ($i = 0, 1, 2, \dots, n_f$), dimensionless

K_{F_i} = deck fitting loss factor for a particular type fitting
($i = 0, 1, 2, \dots, n_f$), lb-mole/yr; see Equation 2-7

n_f = total number of different types of fittings, dimensionless

P^* , M_V , K_C are as defined for Equation 2-2.

The value of F_F may be calculated by using actual tank-specific data for the number of each fitting type (N_F) and then multiplying by the fitting loss factor for each fitting (K_F).

The deck fitting loss factor, K_{F_i} for a particular type of fitting, can be estimated by the following equation:

$$K_{F_i} = K_{Fa_i} + K_{Fb_i} (K_v v)^{m_i} \quad (2-7)$$

where:

K_{F_i} = loss factor for a particular type of deck fitting, lb-mole/yr

K_{Fa_i} = zero wind speed loss factor for a particular type of fitting, lb-mole/yr

K_{Fb_i} = wind speed dependent loss factor for a particular type of fitting, lb-mole/(mph)^m·yr

m_i = loss factor for a particular type of deck fitting, dimensionless

$i = 1, 2, \dots, n$, dimensionless

K_v = fitting wind speed correction factor, dimensionless; see below

v = average ambient wind speed, mph

For external floating roof tanks, the fitting wind speed correction factor, K_v , is equal to 0.7. For internal and domed external floating roof tanks, the value of v in Equation 2-7 is zero and the equation becomes:

$$K_{F_i} = K_{Fa_i} \quad (2-8)$$

Loss factors K_{Fa} , K_{Fb} , and m are provided in Table 7.1-12 for the most common deck fittings used on floating roof tanks. These factors apply only to typical deck fitting conditions and when the average ambient wind speed is below 15 miles per hour. Typical numbers of deck fittings for floating roof tanks are presented in Tables 7.1-11, 7.1-12, 7.1-13, 7.1-14, and 7.1-15.

Deck Seam Loss - Neither welded deck internal floating roof tanks nor external floating roof tanks have deck seam losses. Internal floating roof tanks with bolted decks may have deck seam losses. Deck seam loss can be estimated by the following equation:

$$L_D = K_D S_D D^2 P^* M_V K_C \quad (2-9)$$

where:

K_D = deck seam loss per unit seam length factor, lb-mole/ft-yr

= 0.0 for welded deck

= 0.14 for bolted deck; see Note

S_D = deck seam length factor, ft/ft²

= $\frac{L_{seam}}{A_{deck}}$

where:

L_{seam} = total length of deck seams, ft

A_{deck} = area of deck, $\text{ft}^2 = \pi D^2/4$

D , P^* , M_V , and K_C are as defined for Equation 2-2

If the total length of the deck seam is not known, Table 7.1-16 can be used to determine S_D . For a deck constructed from continuous metal sheets with a 7-ft spacing between the seams, a value of 0.14 ft/ft^2 can be used. A value of 0.33 ft/ft^2 can be used for S_D when a deck is constructed from rectangular panels 5 ft by 7.5 ft. Where tank-specific data concerning width of deck sheets or size of deck panels are unavailable, a default value for S_D can be assigned. A value of 0.20 ft/ft^2 can be assumed to represent the most common bolted decks currently in use.

Note: Recently vendors of bolted decks have been using various techniques, such as gasketing the deck seams, in an effort to reduce deck seam losses. However, emission factors are not currently available in AP-42 that represent the emission reduction, if any, achieved by these techniques. Some vendors have developed specific factors for their deck designs; however, use of these factors is not recommended until approval has been obtained from the governing regulatory agency or permitting authority.

7.1.3.3 Variable Vapor Space Tanks¹⁸ –

Variable vapor space filling losses result when vapor is displaced by liquid during filling operations. Since the variable vapor space tank has an expandable vapor storage capacity, this loss is not as large as the filling loss associated with fixed roof tanks. Loss of vapor occurs only when the tank's vapor storage capacity is exceeded. Equation 3-1 assumes that one-fourth of the expansion capacity is available at the beginning of each transfer.

Variable vapor space system filling losses can be estimated from:

$$L_V = (2.40 \times 10^{-2}) (M_V P_{VA} / V_1) [(V_1) - (0.25 V_2 N_2)] \quad (3-1)$$

where:

L_V = variable vapor space filling loss, lb/1,000 gal throughput

M_V = molecular weight of vapor in storage tank, lb/lb-mole; see Note 1 to Equation 1-9

P_{VA} = true vapor pressure at the daily average liquid surface temperature, psia; see Notes 1 and 2 to Equation 1-9

V_1 = volume of liquid pumped into system, throughput, bbl/yr

V_2 = volume expansion capacity of system, bbl; see Note 1

N_2 = number of transfers into system, dimensionless; see Note 2

Notes:

1. V_2 is the volume expansion capacity of the variable vapor space achieved by roof lifting or diaphragm flexing.
2. N_2 is the number of transfers into the system during the time period that corresponds to a throughput of V_1 .

The accuracy of Equation 3-1 is not documented. Special tank operating conditions may result in actual losses significantly different from the estimates provided by Equation 3-1. For example, if one or more tanks with interconnected vapor spaces are filled while others are emptied simultaneously, all or part of the expelled vapors will be transferred to the tank, or tanks, being emptied. This is called balanced pumping. Equation 3-1 does not account for balanced pumping, and will overestimate losses under this condition. It should also be noted that, although not developed for use with heavier petroleum liquids such as kerosenes and fuel oils, the equation is recommended for use with heavier petroleum liquids in the absence of better data.

7.1.3.4 Pressure Tanks –

Losses occur during withdrawal and filling operations in low-pressure (2.5 to 15 psig) tanks when atmospheric venting occurs. High-pressure tanks are considered closed systems, with virtually no emissions. Vapor recovery systems are often found on low-pressure tanks. Fugitive losses are also associated with pressure tanks and their equipment, but with proper system maintenance, these losses are considered insignificant. No appropriate correlations are available to estimate vapor losses from pressure tanks.

7.1.3.5 Variations Of Emission Estimation Procedures –

All of the emission estimation procedures presented in Section 7.1.3 can be used to estimate emissions for shorter time periods by manipulating the inputs to the equations for the time period in question. For all of the emission estimation procedures, the daily average liquid surface temperature should be based on the appropriate temperature and solar insolation data for the time period over which the estimate is to be evaluated. The subsequent calculation of the vapor pressure should be based on the corrected daily liquid surface temperature. For example, emission calculations for the month of June would be based only on the meteorological data for June. It is important to note that a 1-month time frame is recommended as the shortest time period for which emissions should be estimated.

In addition to the temperature and vapor pressure corrections, the constant in the standing storage loss equation for fixed roof tanks would need to be revised based on the actual time frame used. The constant, 365, is based on the number of days in a year. To change the equation for a different time period, the constant should be changed to the appropriate number of days in the time period for which emissions are being estimated. The only change that would need to be made to the working loss equation for fixed roof tanks would be to change the throughput per year to the throughput during the time period for which emissions are being estimated.

Other than changing the meteorological data and the vapor pressure data, the only changes needed for the floating roof rim seal, deck fitting, and deck seam losses would be to modify the time frame by dividing the individual losses by the appropriate number of days or months. The only change to the withdrawal losses would be to change the throughput to the throughput for the time period for which emissions are being estimated.

Another variation that is frequently made to the emission estimation procedures is an adjustment in the working or withdrawal loss equations if the tank is operated as a surge tank or constant level tank. For constant level tanks or surge tanks where the throughput and turnovers are high but the liquid level in the tank remains relatively constant, the actual throughput or turnovers should not be used in the working loss or withdrawal loss equations. For these tanks, the turnovers should be estimated by determining the average change in the liquid height. The average change in height should then be divided by the total shell height. This adjusted turnover value should then be multiplied by the actual throughput to obtain the net throughput for use in the loss equations. Alternatively, a default turnover rate of four could be used based on data from these type tanks.

7.1.4 Hazardous Air Pollutants (HAP) Speciation Methodology

In some cases it may be important to know the annual emission rate for a component (e. g., HAP) of a stored liquid mixture. There are two basic approaches that can be used to estimate emissions for a single component of a stored liquid mixture. One approach involves calculating the total losses based upon the known physical properties of the mixture (i. e., gasoline) and then determining the individual component losses by multiplying the total loss by the weight fraction of the desired component. The second approach is similar to the first approach except that the mixture properties are unknown; therefore, the mixture properties are first determined based on the composition of the liquid mixture.

Case 1 — If the physical properties of the mixture are known (P_{VA} , M_V , M_L and W_L), the total losses from the tank should be estimated using the procedures described previously for the particular tank type. The component losses are then determined from either Equation 4-1 or 4-2. For fixed roof tanks, the emission rate for each individual component can be estimated by:

$$L_{T_i} = (Z_{V_i})(L_T) \quad (4-1)$$

where:

L_{T_i} = emission rate of component i, lb/yr

Z_{V_i} = weight fraction of component i in the vapor, lb/lb

L_T = total losses, lb/yr

For floating roof tanks, the emission rate for each individual component can be estimated by:

$$L_{T_i} = (Z_{V_i})(L_R + L_F + L_D) + (Z_{L_i})(L_{WD}) \quad (4-2)$$

where:

L_{T_i} = emission rate of component i, lb/yr

Z_{V_i} = weight fraction of component i in the vapor, lb/lb

L_R = rim seal losses, lb/yr

L_F = deck fitting losses, lb/yr

L_D = deck seam losses, lb/yr

Z_{L_i} = weight fraction of component i in the liquid, lb/lb

L_{WD} = withdrawal losses, lb/yr

If Equation 4-1 is used in place of Equation 4-2 for floating roof tanks, the value obtained will be approximately the same value as that achieved with Equation 4-2 because withdrawal losses are typically minimal for floating roof tanks.

In order to use Equations 4-1 and 4-2, the weight fraction of the desired component in the liquid and vapor phase is needed. The liquid weight fraction of the desired component is typically known or can be readily calculated for most mixtures. In order to calculate the weight fraction in the vapor phase, Raoult's Law must first be used to determine the partial pressure of the component. The partial pressure of the component can then be divided by the total vapor pressure of the mixture to determine the mole fraction of the component in the vapor phase. Raoult's Law states that the mole fraction of the component in the liquid (x_i) multiplied by the vapor pressure of the pure component (at the daily average liquid surface temperature) (P) is equal to the partial pressure (P_i) of that component:

$$P_i = (P)(x_i) \quad (4-3)$$

where:

P_i = partial pressure of component i, psia

P = vapor pressure of pure component i at the daily average liquid surface temperature, psia

x_i = liquid mole fraction, lb-mole/lb-mole

The vapor pressure of each component can be calculated from Antoine's equation or found in standard references, as shown in Section 7.1.3.1. In order to use Equation 4-3, the liquid mole fraction must be determined from the liquid weight fraction by:

$$x_i = (Z_{L_i})(M_L) / (M_i) \quad (4-4)$$

where:

x_i = liquid mole fraction of component i, lb-mole/lb-mole

Z_{L_i} = weight fraction of component i in the liquid, lb/lb

M_L = molecular weight of liquid stock, lb/lb-mole

M_i = molecular weight of component i, lb/lb-mole

If the molecular weight of the liquid is not known, the liquid mole fraction can be determined by assuming a total weight of the liquid mixture (see Example 1 in Section 7.1.5).

The liquid mole fraction and the vapor pressure of the component at the daily average liquid surface temperature can then be substituted into Equation 4-3 to obtain the partial pressure of the component. The vapor mole fraction of the component can be determined from the following equation:

$$y_i = \frac{P_i}{P_{VA}} \quad (4-5)$$

where:

y_i = vapor mole fraction of component i, lb-mole/lb-mole

P_i = partial pressure of component i, psia

P_{VA} = total vapor pressure of liquid mixture, psia

The weight fractions in the vapor phase are calculated from the mole fractions in the vapor phase.

$$Z_{Vi} = \frac{y_i M_i}{M_V} \quad (4-6)$$

where:

Z_{Vi} = vapor weight fraction of component i, lb/lb

y_i = vapor mole fraction of component i, lb-mole/lb-mole

M_i = molecular weight of component i, lb/lb-mole

M_V = molecular weight of vapor stock, lb/lb-mole

The liquid and vapor weight fractions of each desired component and the total losses can be substituted into either Equations 4-1 or 4-2 to estimate the individual component losses.

Case 2 — For cases where the mixture properties are unknown but the composition of the liquid is known (i. e., nonpetroleum organic mixtures), the equations presented above can be used to obtain a reasonable estimate of the physical properties of the mixture. For nonaqueous organic mixtures, Equation 4-3 can be used to determine the partial pressure of each component. If Equation 4-4 is used to determine the liquid mole fractions, the molecular weight of the liquid stock must be known. If the molecular weight of the liquid stock is unknown, then the liquid mole fractions can be determined by assuming a weight basis and calculating the number of moles (see Example 1 in Section 7.1.5). The partial pressure of each component can then be determined from Equation 4-3.

For special cases, such as wastewater, where the liquid mixture is a dilute aqueous solution, Henry's Law should be used instead of Raoult's Law in calculating total losses. Henry's Law states that the mole fraction of the component in the liquid phase multiplied by the Henry's Law constant for the component in the mixture is equal to the partial pressure (P_i) for that component. For wastewater, Henry's Law constants are typically provided in the form of atm·m³/g-mole.

Therefore, the appropriate form of Henry's Law equation is:

$$P_i = (H_A) (C_i) \quad (4-7)$$

where:

P_i = partial pressure of component i, atm

H_A = Henry's Law constant for component i, atm·m³/g-mole

C_i = concentration of component i in the wastewater, g-mole/m³; see Note

Section 4.3 of AP-42 presents Henry's Law constants for selected organic liquids. The partial pressure calculated from Equation 4-7 will need to be converted from atmospheres to psia (1 atm = 14.7 psia).

Note: Typically wastewater concentrations are given in mg/liter, which is equivalent to g/m³. To convert the concentrations to g-mole/m³ divide the concentration by the molecular weight of the component.

The total vapor pressure of the mixture can be calculated from the sum of the partial pressures:

$$P_{VA} = \sum P_i \quad (4-8)$$

where:

P_{VA} = vapor pressure at daily average liquid surface temperature, psia

P_i = partial pressure of component i, psia

This procedure can be used to determine the vapor pressure at any temperature. After computing the total vapor pressure, the mole fractions in the vapor phase are calculated using Equation 4-5. The vapor mole fractions are used to calculate the molecular weight of the vapor, M_V . The molecular weight of the vapor can be calculated by:

$$M_V = \sum M_i y_i \quad (4-9)$$

where:

M_V = molecular weight of the vapor, lb/lb-mole

M_i = molecular weight of component i, lb/lb-mole

y_i = vapor mole fraction of component i, lb-mole/lb-mole

Another variable that may need to be calculated before estimating the total losses, if it is not available in a standard reference, is the density of the liquid, W_L . If the density of the liquid is unknown, it can be estimated based on the liquid weight fractions of each component (see Section 7.1.5, Example 3).

All of the mixture properties are now known (P_{VA} , M_V , and W_L). These values can now be used with the emission estimation procedures outlined in Section 7.1.3 to estimate total losses. After calculating the total losses, the component losses can be calculated by using either Equations 4-1 or 4-2. Prior to calculating component losses, Equation 4-6 must be used to determine the vapor weight fractions of each component.

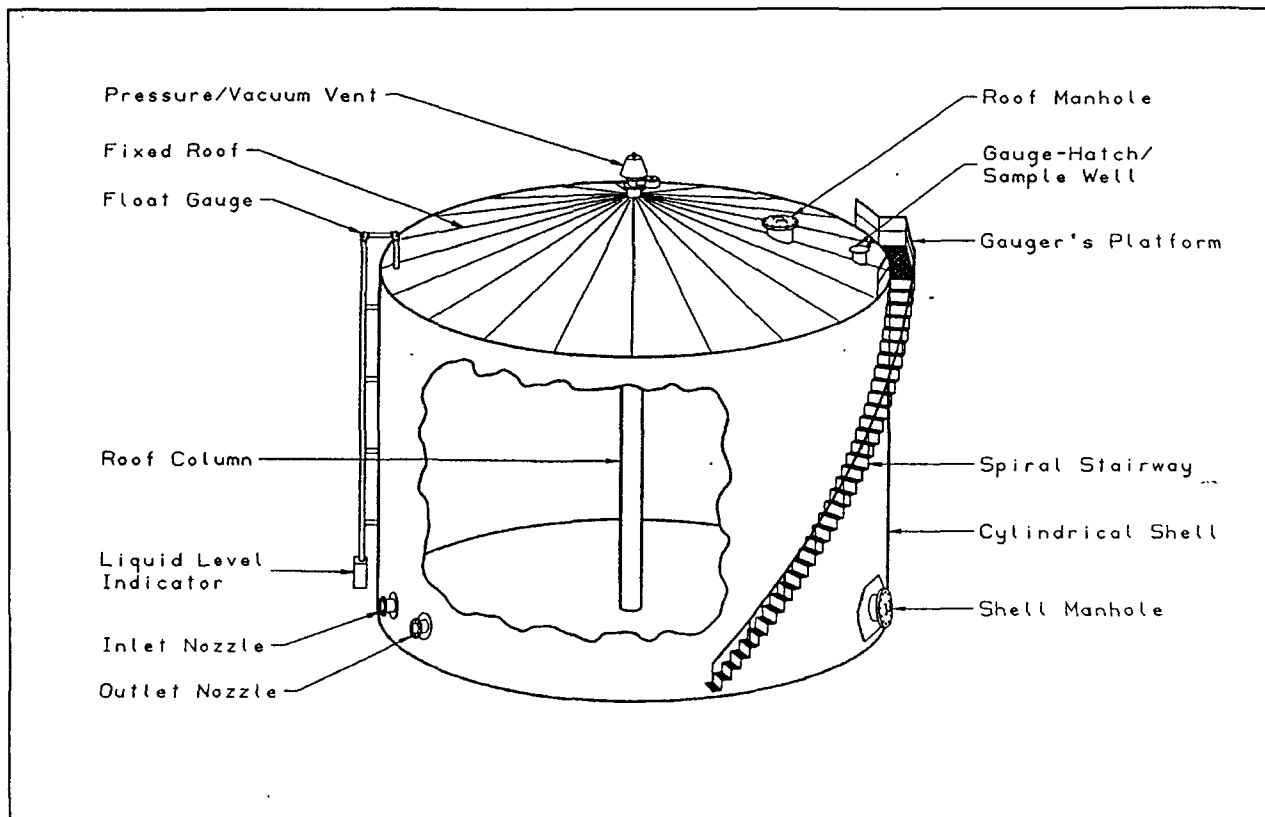


Figure 7.1-1. Typical fixed-roof tank.¹

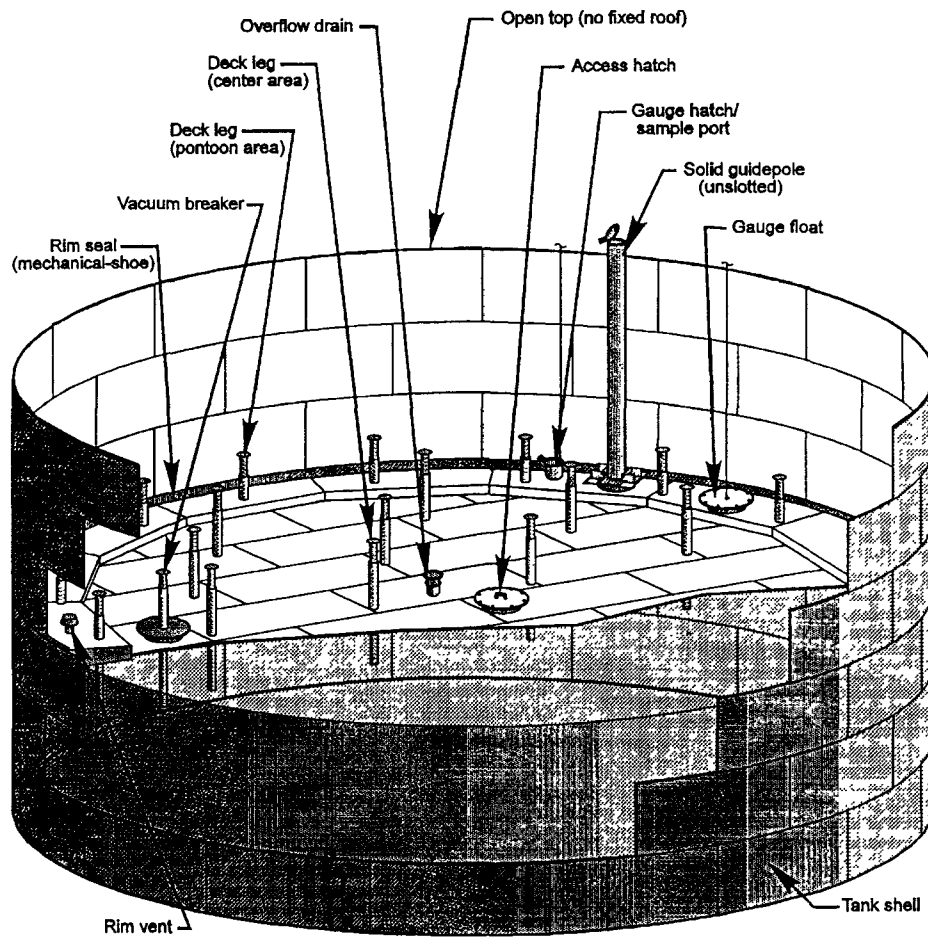


Figure 7.1-2. External floating roof tank (pontoon type).²⁰

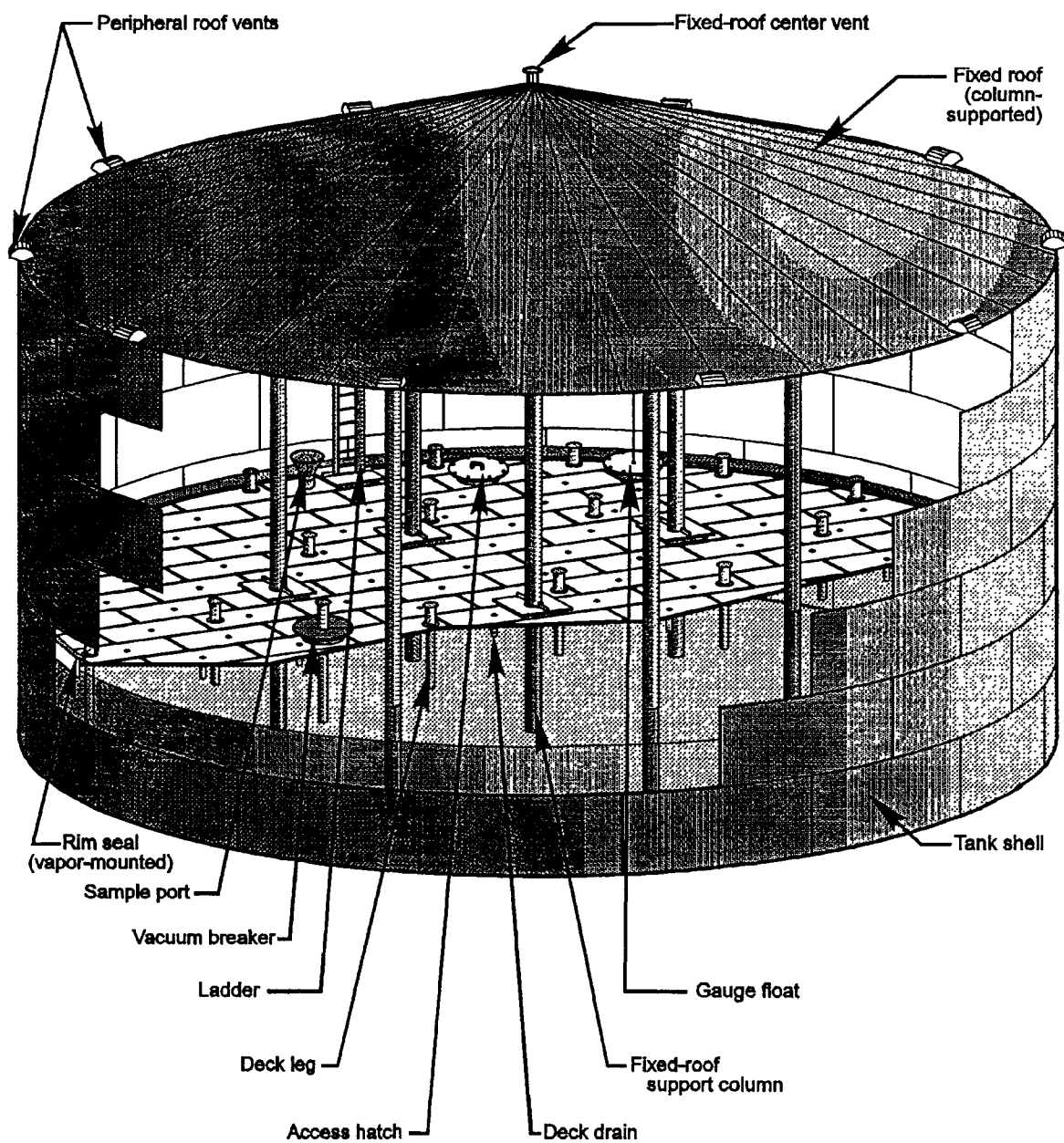


Figure 7.1-4. Internal floating roof tank.²⁰

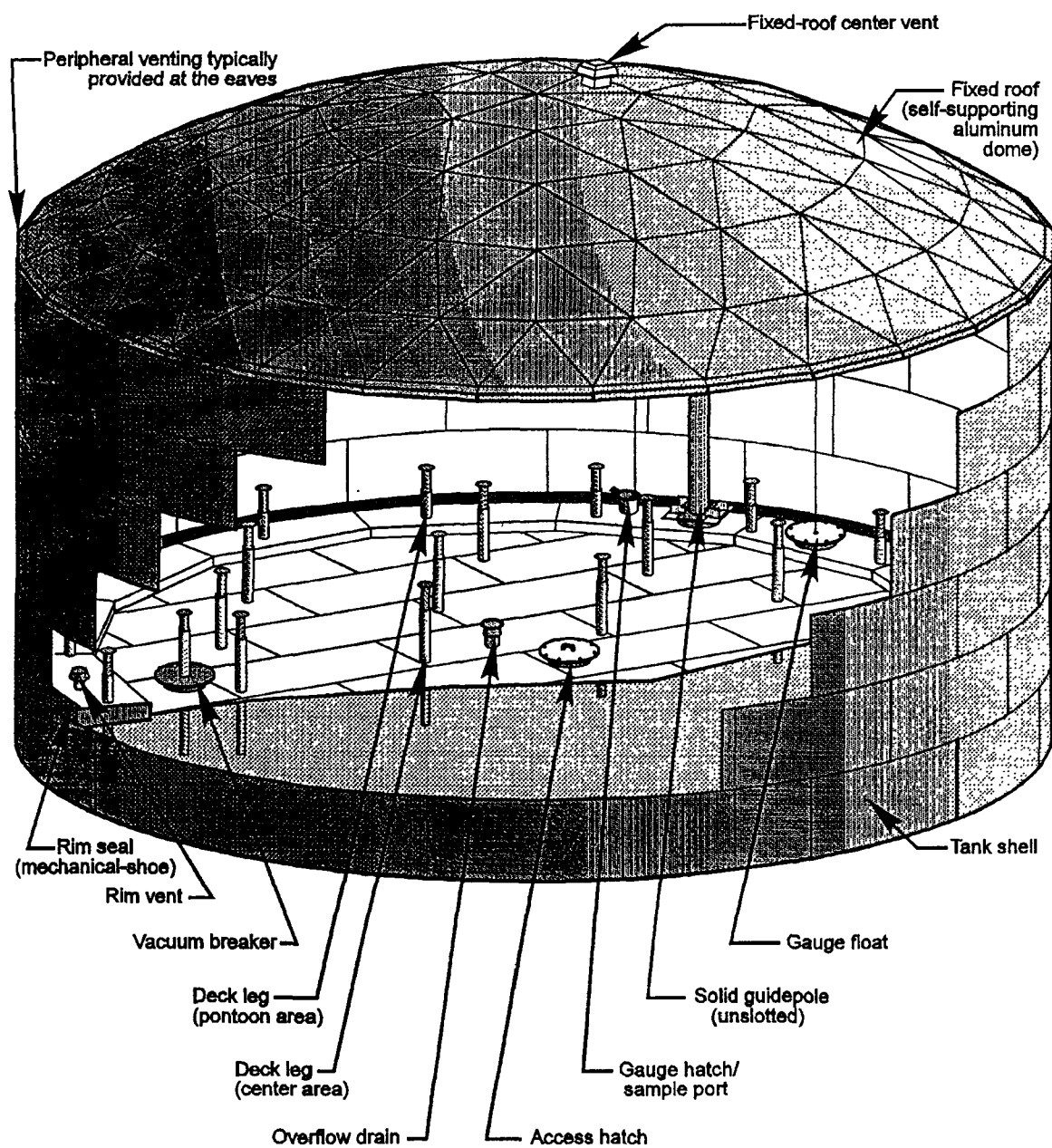


Figure 7.1-5. Domed external floating roof tank.²⁰

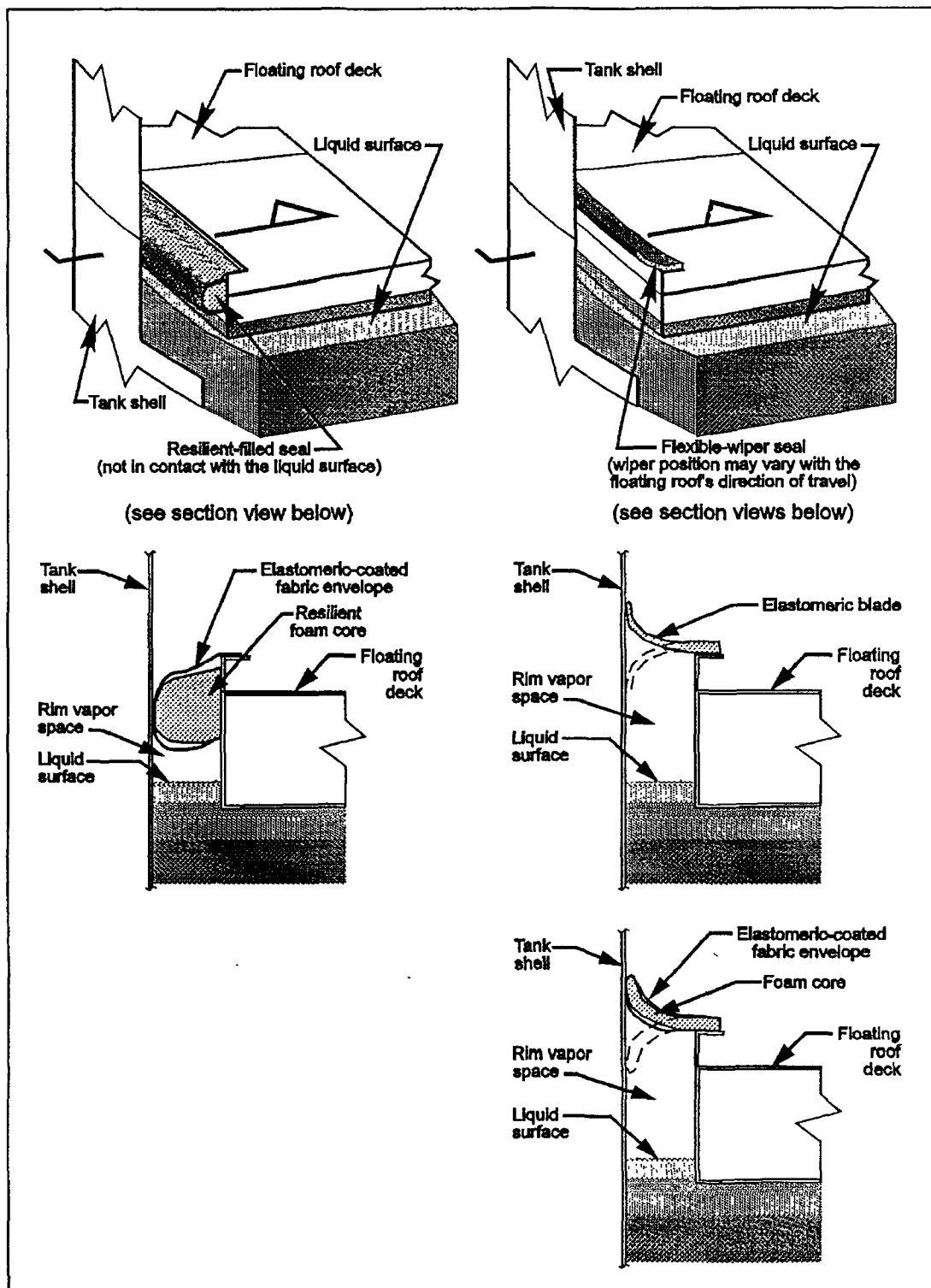


Figure 7.1-6. Vapor-mounted primary seals.²⁰

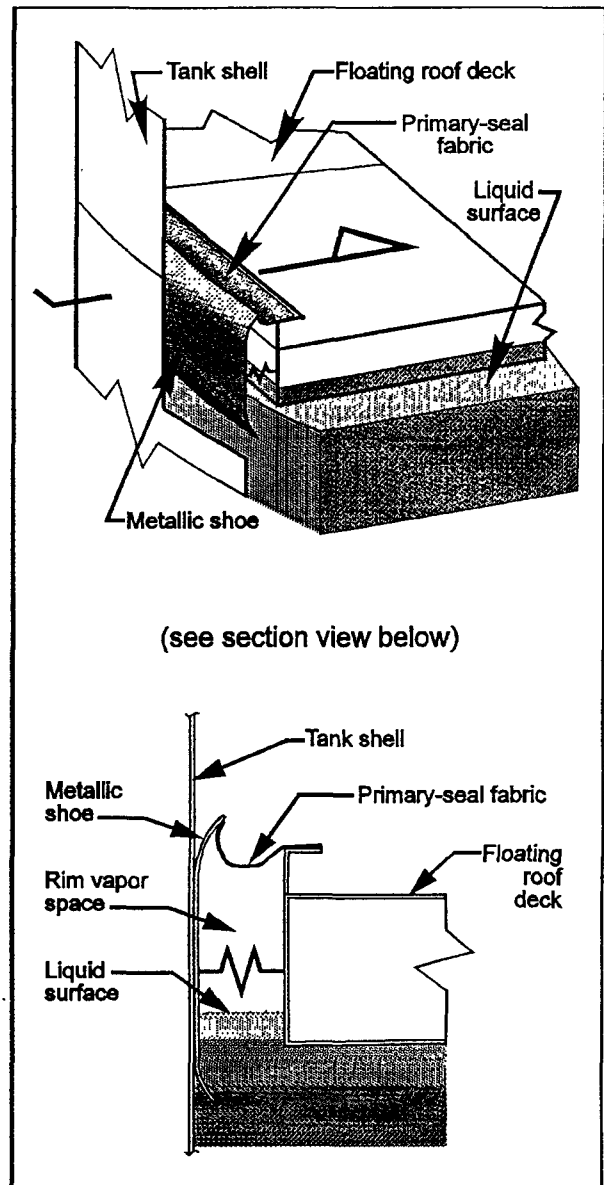
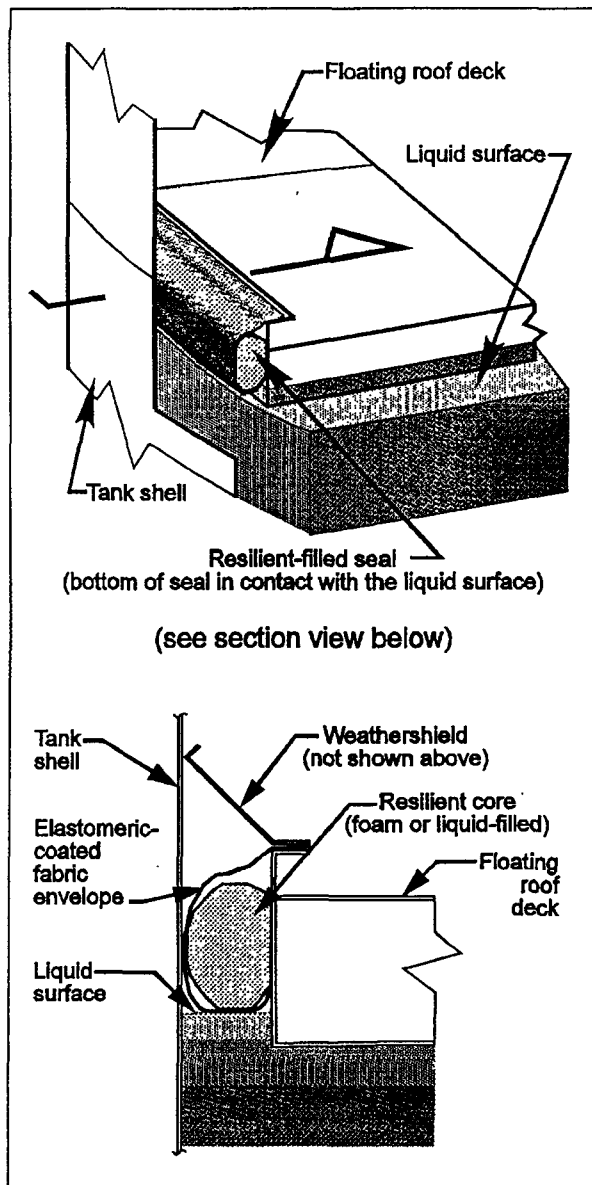


Figure 7.1-7. Liquid-mounted and mechanical shoe primary seals.²⁰

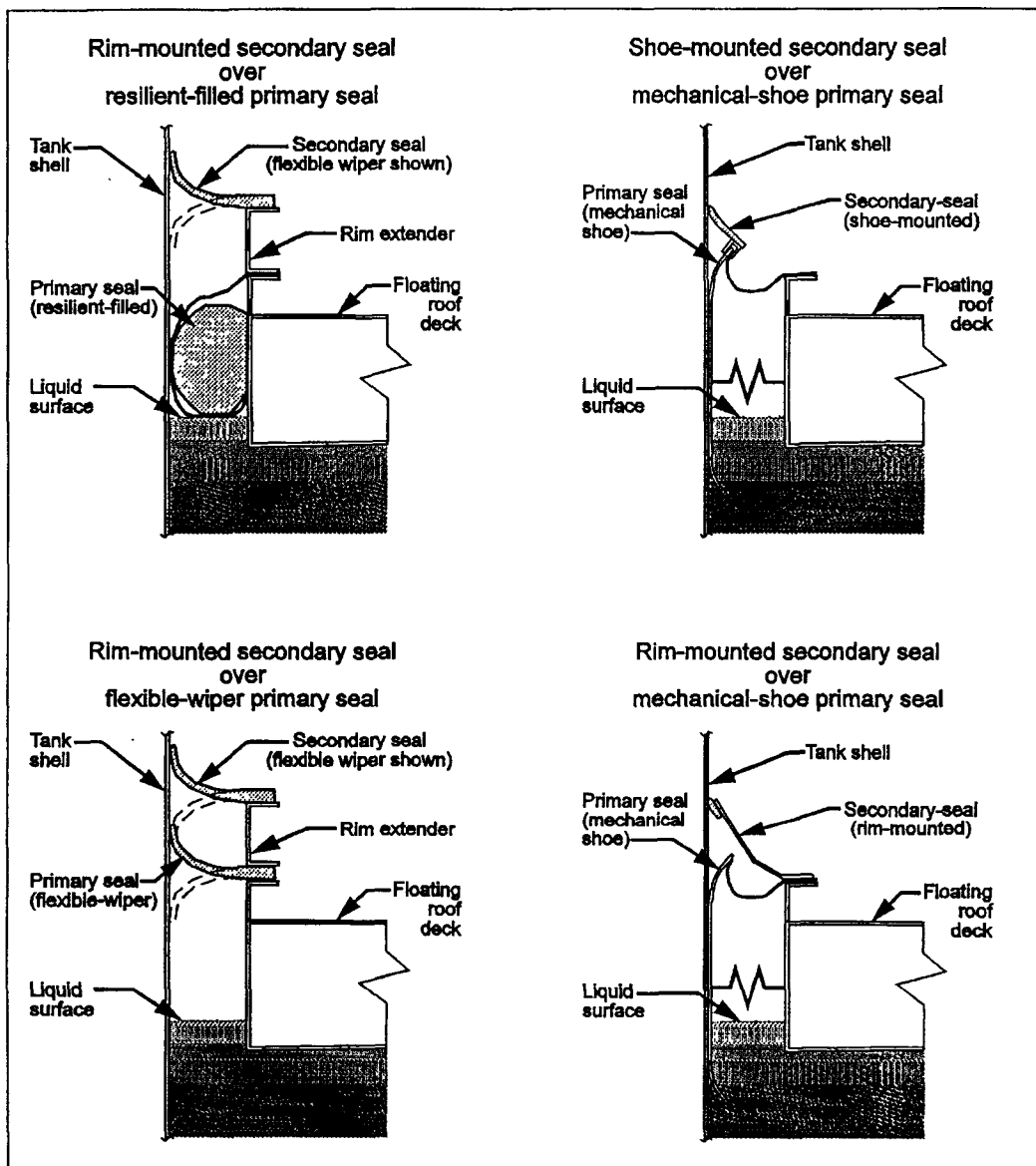
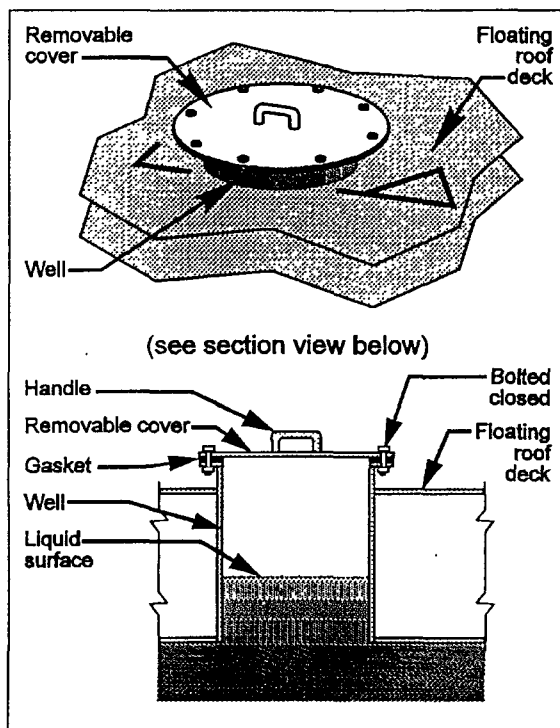
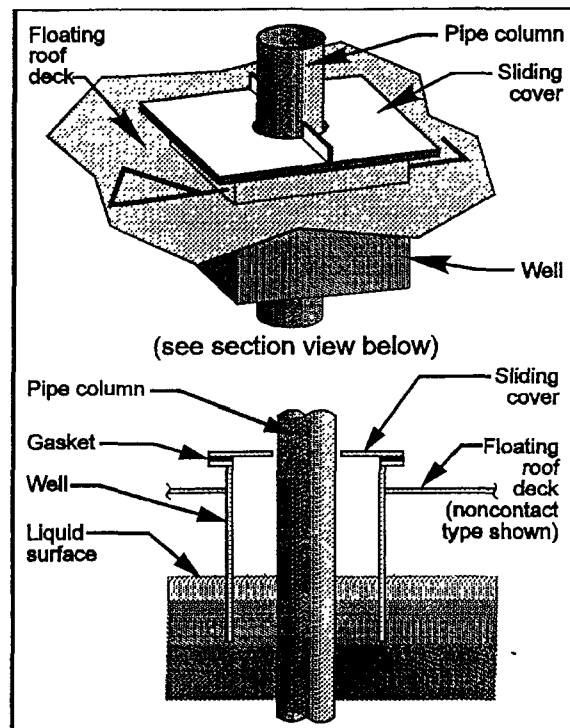


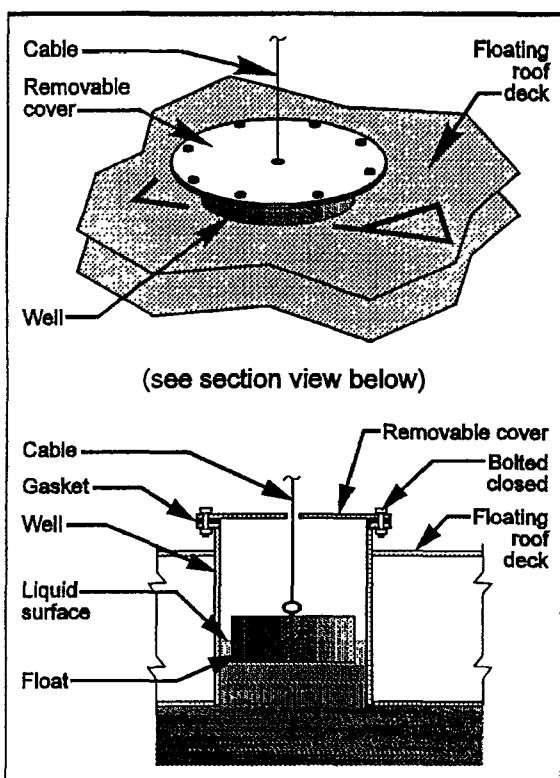
Figure 7.1-8. Secondary rim seals.²⁰



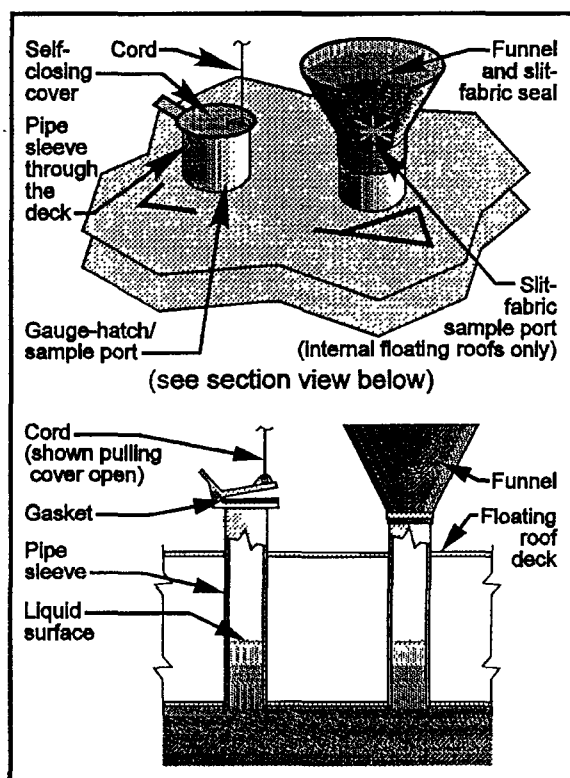
Access Hatch



Fixed-Roof Support Column

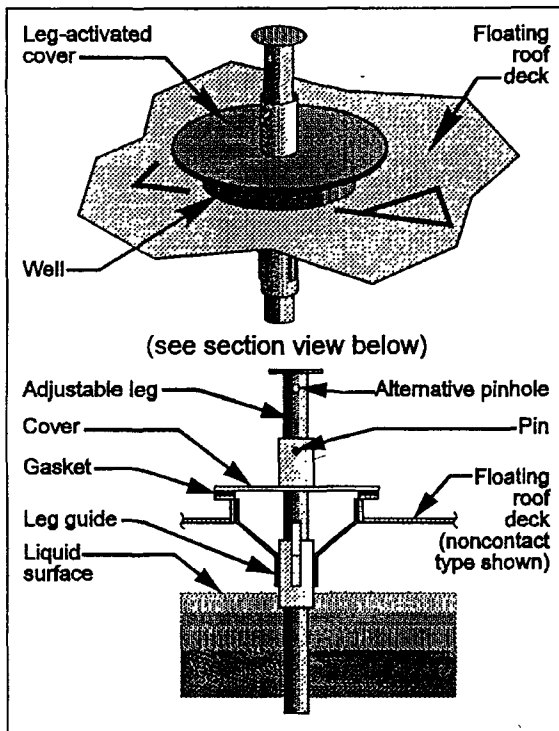


Gauge float

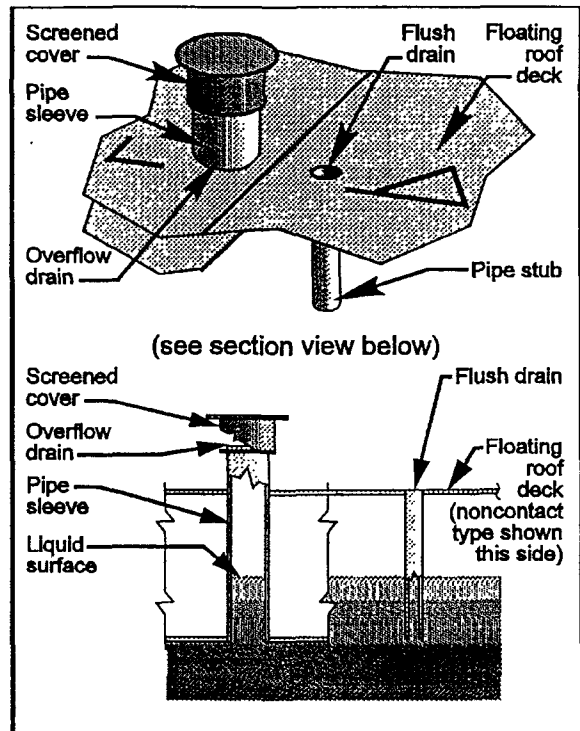


Sample Ports

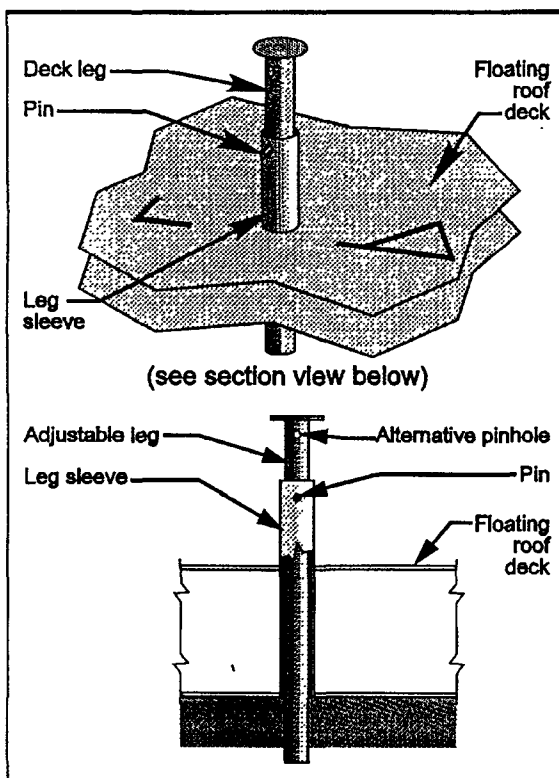
Figure 7.1-9. Deck fittings for floating roof tanks.²⁰



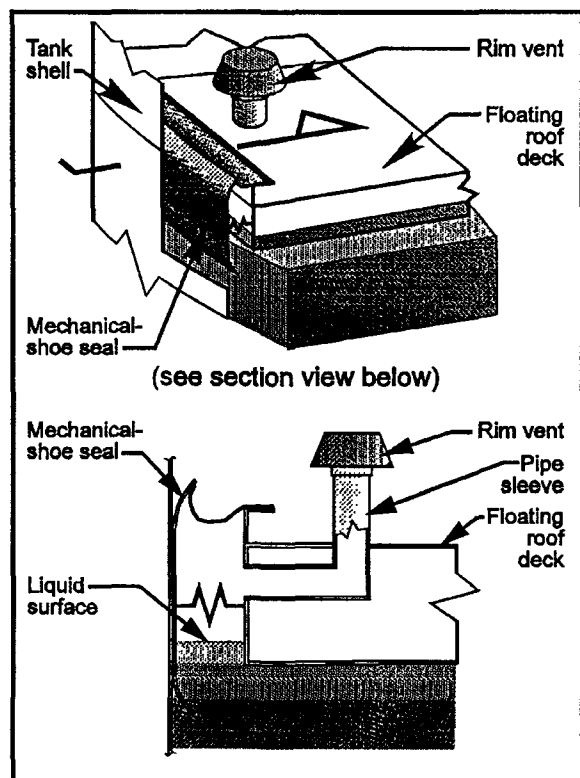
Vacuum Breaker



Deck Drains

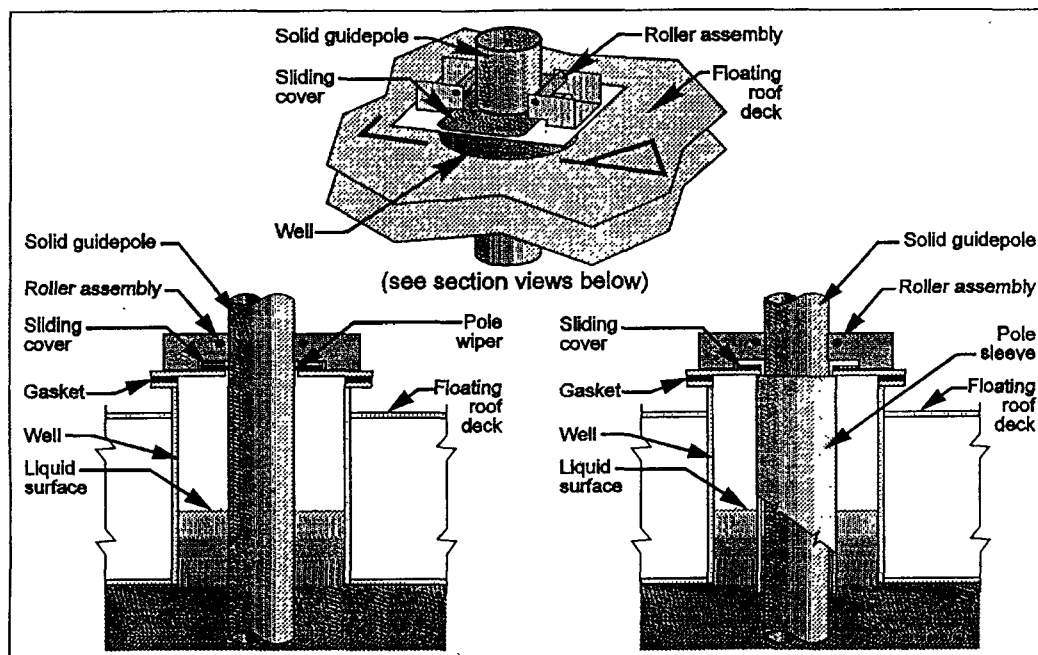


Deck Leg

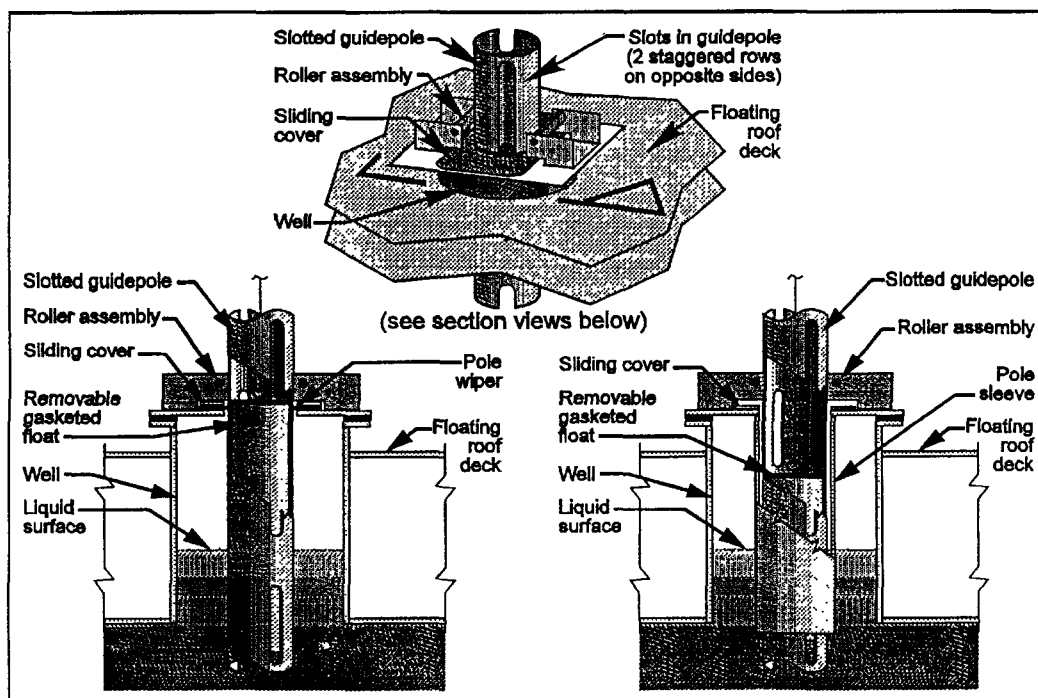


Rim Vent

Figure 7.1-10. Deck fittings for floating roof tanks.²⁰



Unslotted (solid) Guidepole



Slotted (perforated) Guidepole

Figure 7.1-11. Slotted and unslotted guidepoles.²⁰

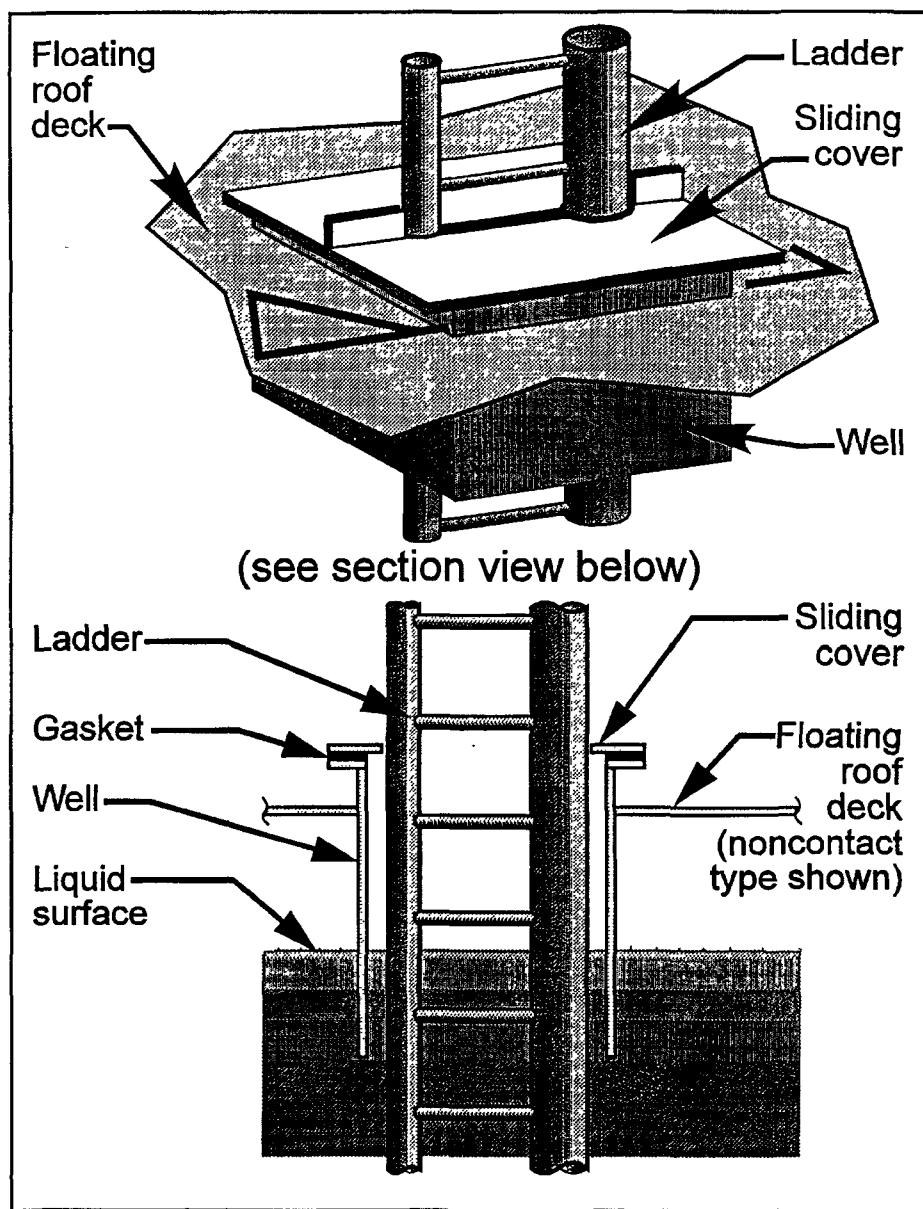


Figure 7.1-12. Ladder well.²⁰

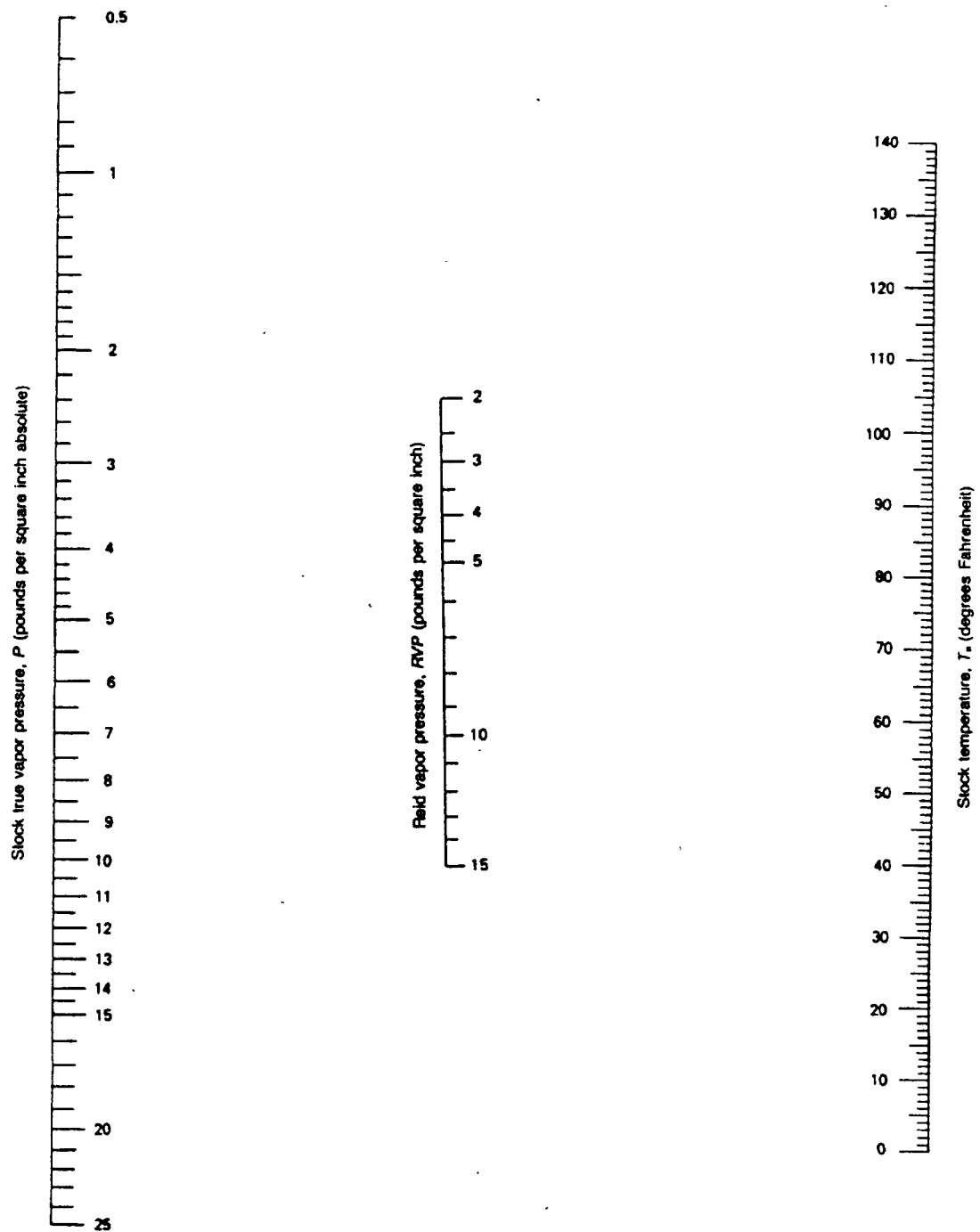


Figure 7.1-13a. True vapor pressure of crude oils with a Reid vapor pressure of 2 to 15 pounds per square inch.⁴

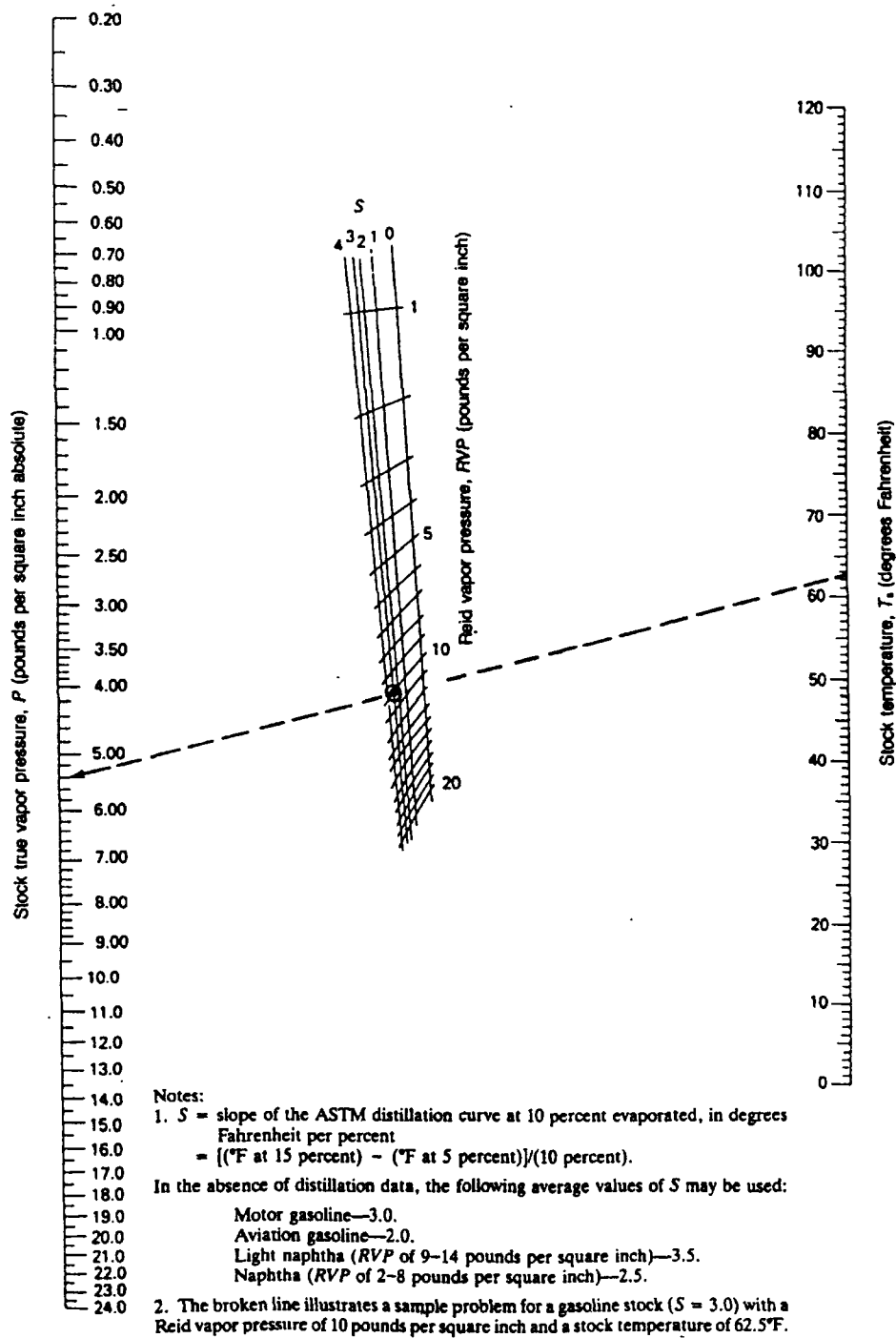


Figure 7.1-14a. True vapor pressure of refined petroleum stocks with a Reid vapor pressure of 1 to 20 pounds per square inch.⁴

$$P = \exp \left\{ \left[\left(\frac{2,799}{T + 459.6} \right) - 2.227 \right] \log_{10} (\text{RVP}) - \left(\frac{7,261}{T + 459.6} \right) + 12.82 \right\}$$

Where:

P = stock true vapor pressure, in pounds per square inch absolute.

T = stock temperature, in degrees Fahrenheit.

RVP = Reid vapor pressure, in pounds per square inch.

Note: This equation was derived from a regression analysis of points read off Figure 7.1-13a over the full range of Reid vapor pressures, slopes of the ASTM distillation curve at 10 percent evaporated, and stock temperatures. In general, the equation yields P values that are within +0.05 pound per square inch absolute of the values obtained directly from the nomograph.

Figure 7.1-13b. Equation for true vapor pressure of crude oils with a Reid vapor pressure of 2 to 15 pounds per square inch.⁴

$$P = \exp \left\{ \left[0.7553 - \left(\frac{413.0}{T + 459.6} \right) \right] S^{0.5} \log_{10} (\text{RVP}) - \left[1.854 - \left(\frac{1,042}{T + 459.6} \right) \right] S^{0.5} + \left[\left(\frac{2,416}{T + 459.6} \right) - 2.013 \right] \log_{10} (\text{RVP}) - \left(\frac{8,742}{T + 459.6} \right) + 15.64 \right\}$$

Where:

P = stock true vapor pressure, in pounds per square inch absolute.

T = stock temperature, in degrees Fahrenheit.

RVP = Reid vapor pressure, in pounds per square inch.

S = slope of the ASTM distillation curve at 10 percent evaporated, in degrees Fahrenheit per percent.

Note: This equation was derived from a regression analysis of points read off Figure 7.1-14a over the full range of Reid vapor pressures, slopes of the ASTM distillation curve at 10 percent evaporated, and stock temperatures. In general, the equation yields P values that are within +0.05 pound per square inch absolute of the values obtained directly from the nomograph.

Figure 7.1-14b. Equation for true vapor pressure of refined petroleum stocks with a Reid vapor pressure of 1 to 20 pounds per square inch.⁴

$$A = 15.64 - 1.854 S^{0.5} - (0.8742 - 0.3280 S^{0.5}) \ln(\text{RVP})$$

$$B = 8,742 - 1,042 S^{0.5} - (1,049 - 179.4 S^{0.5}) \ln(\text{RVP})$$

where:

RVP = stock Reid vapor pressure, in pounds per square inch

\ln = natural logarithm function

S = stock ASTM-D86 distillation slope at 10 volume percent evaporation ($^{\circ}\text{F}/\text{vol } \%$)

Figure 7.1-15. Equations to determine vapor pressure constants A and B for refined petroleum stocks.⁸

$$A = 12.82 - 0.9672 \ln (\text{RVP})$$

$$B = 7,261 - 1,216 \ln (\text{RVP})$$

where:

RVP = Reid vapor pressure, psi

ln = natural logarithm function

Figure 7.1-16. Equations to determine vapor pressure Constants A and B for crude oil stocks.⁸

Daily Maximum and Minimum Liquid Surface Temperature, (°R)

$$T_{LX} = T_{LA} + 0.25 \Delta T_V$$

$$T_{LN} = T_{LA} - 0.25 \Delta T_V$$

where:

T_{LX} = daily maximum liquid surface temperature, °R

T_{LA} is as defined in Note 3 to Equation 1-9

ΔT_V is as defined in Note 1 to Equation 1-16

T_{LN} = daily minimum liquid surface temperature, °R

Figure 7.1-17. Equations for the daily maximum and minimum liquid surface temperatures.⁸

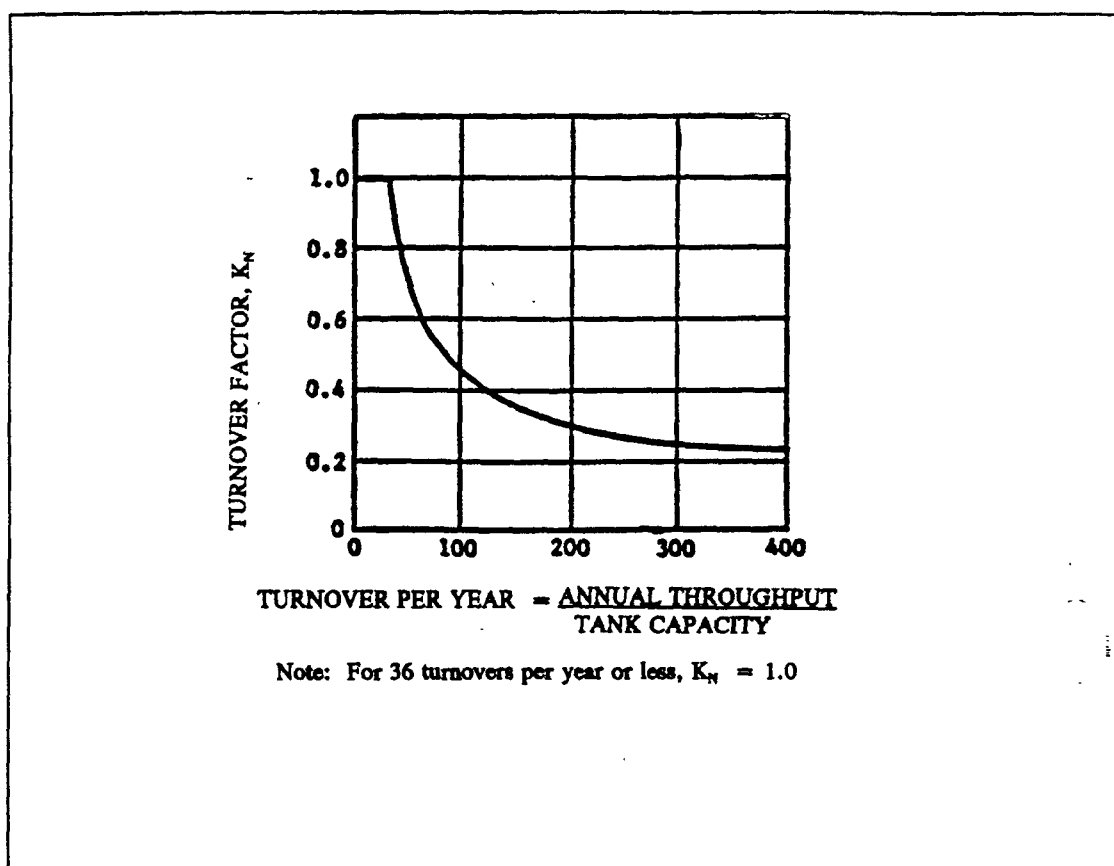
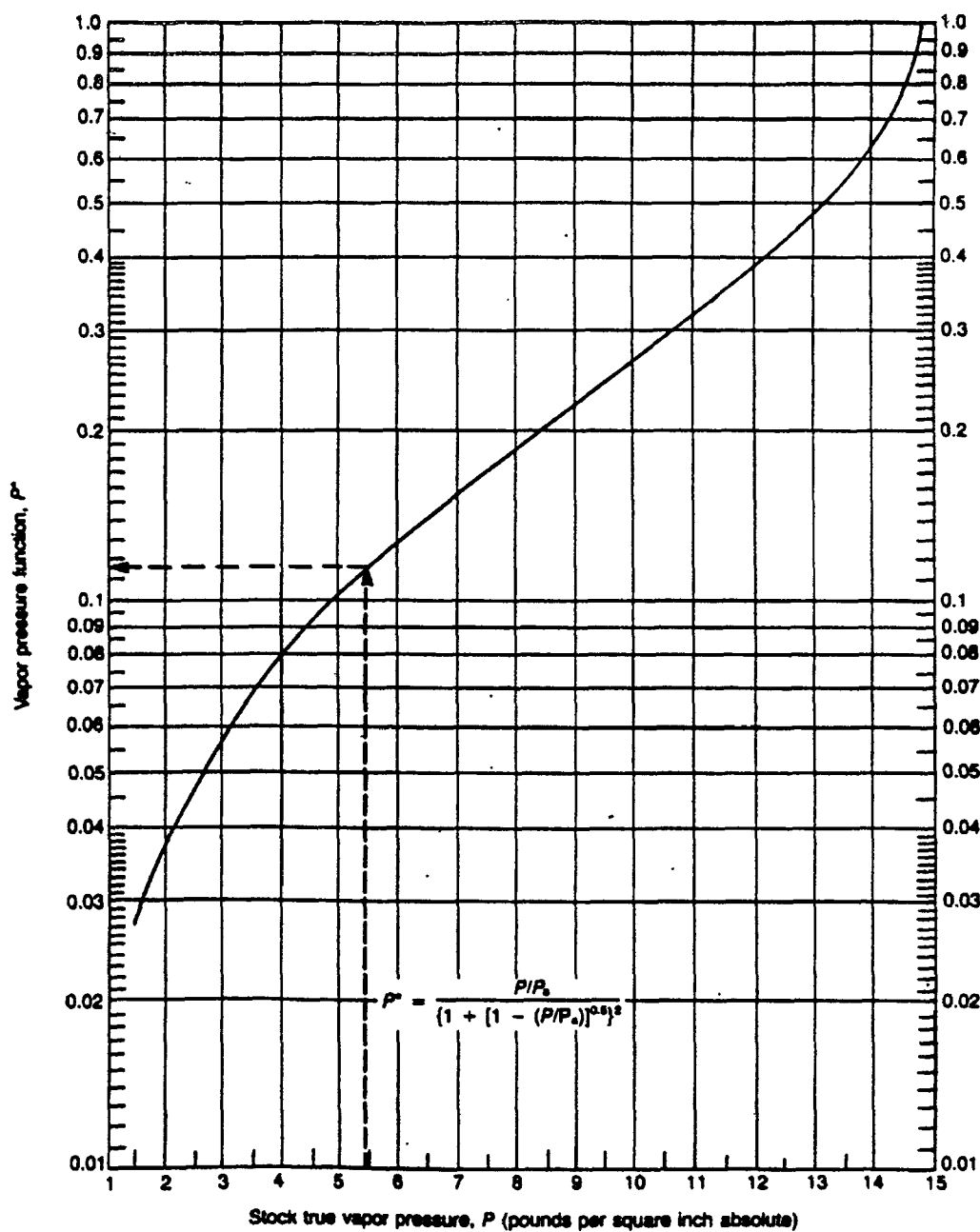


Figure 7.1-18. Turnover factor (K_N) for fixed roof tanks.⁸



Notes:

1. Broken line illustrates sample problem for $P = 5.4$ pounds per square inch absolute.
2. Curve is for atmospheric pressure, P_a , equal to 14.7 pounds per square inch absolute.

Figure 7.1-19. Vapor pressure function.⁴

Table 7.1-1. LIST OF ABBREVIATIONS USED IN THE TANK EQUATIONS

Variable	Description	Variable	Description	Variable	Description
L_T	total losses, lb/yr	P	true vapor pressure of component i, psia	P_{BP}	breather vent pressure setting, psig
L_S	standing storage losses, lb/yr	A	constant in vapor pressure equation, dimensionless	P_{BV}	breather vent vacuum setting, psig
L_W	working losses, lb/yr	B	constant in vapor pressure equation, °R	Q	annual net throughput, bbl/yr
V_V	vapor space volume, ft ³	T_{AA}	daily average ambient temperature, °R	K_N	turnover factor, dimensionless
W_V	vapor space expansion factor, dimensionless	T_B	liquid bulk temperature, °R	N	number of turnovers per year, dimensionless
K_E	vented vapor saturation factor, dimensionless	α	tank paint solar absorptance, dimensionless	π	constant, (3.14159)
D	tank diameter, ft	I	daily total solar insolation factor, Btu/ft ² -d	V_{LX}	tank maximum liquid volume, ft ³
H_{VO}	vapor space outage, ft	T_{AX}	daily maximum ambient temperature, °R	H_{LX}	maximum liquid height, ft
H_S	tank shell height, ft	T_{AN}	daily minimum ambient temperature, °R	K_P	working loss product factor for fixed roof tanks, dimensionless
H_L	liquid height, ft	D_E	effective tank diameter, ft	L_R	rim seal loss, lb/yr
H_{RO}	roof outage, ft	L	length of tank, ft	L_{WD}	withdrawal loss, lb/yr
H_R	tank roof height, ft	ΔT_V	daily vapor temperature range, °R	L_F	deck fitting loss, lb/yr
S_R	tank cone roof slope, ft/ft	ΔP_V	daily vapor pressure range, psi	K_{Ra}	zero wind speed rim seal loss factor, lb-mole/ft-yr
R_S	tank shell radius, ft	ΔP_B	breather vent pressure setting range, psig	K_{Rb}	wind speed dependent rim seal loss factor, lb-mole/(mph) ⁿ ft-yr
R_R	tank dome roof radius, ft	P_A	atmospheric pressure, psi	v	average wind speed, mph
M_V	vapor molecular weight, lb/lb-mole	ΔT_A	daily ambient temperature range, °R	n	seal-related wind speed exponent, dimensionless
R	ideal gas constant, (10.731 psia-ft ³ /lb-mole-°R)	P_{VX}	vapor pressure at the daily maximum liquid surface temperature, psia	P^*	vapor pressure function, dimensionless
P_{VA}	vapor pressure at daily average liquid surface temperature, psia	P_{VN}	vapor pressure at the daily minimum liquid surface temperature, psia	F_R	rim deck loss factor, lb-mole/ft-yr
T_{LA}	daily average liquid surface temperature, °R			K_C	product factor for floating roof tanks, dimensionless
M_i	molecular weight of component i, lb/lb-mole			C	shell clingage factor, bbl/1,000 ft ²
y_i	vapor mole fraction of component i, lb-mole/lb-mole			W_L	average organic liquid density, lb/gal
x_i	liquid mole fraction of component i, lb-mole/lb-mole			F_F	total deck fitting loss factor, lb-mole/yr

Table 7.1-1 (cont.).

Variable	Description	Variable	Description
N_{F_i}	number of deck fittings of a particular type, dimensionless	Z_{V_i}	vapor weight fraction of component i , lb/lb
N_c	number of columns	N_{TOTAL}	total number of moles in mixture, lb-mole
N_{vb}	number of vacuum breakers	W_i	liquid density of component i , lb/ft ³
N_d	number of drains	L_{T_i}	emission rate of component i , lb/yr
N_l	number of deck legs	L_v	variable vapor space filling loss, lb/1,000 gal throughput
n_f	total number of different types of fittings, dimensionless	V_1	volume of liquid pumped into system, bbl/yr
K_{F_i}	loss factor for a particular type of deck fitting, lb-mole/yr	V_2	volume expansion capacity, bbl
N_{Fa_i}	zero wind speed loss factor for a particular type of deck fitting, lb-mole/yr	N_2	number of transfers into system, dimensionless
N_{Fb_i}	wind speed dependent loss factor for a particular type of fitting, lb-mole/ mph ^m -yr		
K_v	fitting wind speed correction factor, dimensionless		
m_i	loss factor for a particular type of deck fitting, dimensionless		
i	1,2,...,n, dimensionless		
L_p	deck seam loss, lb/yr		
N_C	number of columns, dimensionless		
F_C	effective column diameter, ft		
K_D	deck seam loss per unit seam length factor, lb-mole/ft-yr		
S_D	deck seam length factor, ft/ft ²		
L_{seam}	total length of deck seam, ft		
A_{deck}	area of deck, ft ²		
P_i	partial pressure of component i , psia		
Z_{L_i}	liquid weight fraction of component i , lb/lb		
M_L	molecular weight of liquid mixture, lb/lb-mole		

Table 7.1-2. PROPERTIES (M_v , W_{VC} , P_{VA} , W_L) OF SELECTED PETROLEUM LIQUIDS^a

Petroleum Liquid	Vapor Molecular Weight at 60°F, M_v (lb/lb-mole)	Condensed Vapor Density At 60°F, W_{VC} (lb/gal)	Liquid Density At 60°F, W_L (lb/gal)	True Vapor Pressure, P_{VA} (psi)					
				40°F	50°F	60°F	70°F	80°F	100°F
Gasoline RVP 13	62	4.9	5.6	4.7	5.7	6.9	8.3	9.9	11.7
Gasoline RVP 10	66	5.1	5.6	3.4	4.2	5.2	6.2	7.4	8.8
Gasoline RVP 7	68	5.2	5.6	2.3	2.9	3.5	4.3	5.2	6.2
Crude oil RVP 5	50	4.5	7.1	1.8	2.3	2.8	3.4	4.0	4.8
Jet naphtha (JP-4)	80	5.4	6.4	0.8	1.0	1.3	1.6	1.9	2.4
Jet kerosene	130	6.1	7.0	0.0041	0.0060	0.0085	0.011	0.015	0.021
Distillate fuel oil No. 2	130	6.1	7.1	0.0031	0.0045	0.0074	0.0090	0.012	0.016
Residual oil No. 6	190	6.4	7.9	0.00002	0.00003	0.00004	0.00006	0.00009	0.00013

^a References 10 and 11.

Table 7.1-3. PHYSICAL PROPERTIES OF SELECTED PETROCHEMICALS^a

Name	Formula	Molecular Weight	Boiling Point At 1 Atmosphere (°F)	Liquid Density At 60°F (lb/gal)	Vapor Pressure (psia) At						
					40°F	50°F	60°F	70°F	80°F	90°F	100°F
Acetone	CH ₃ COCH ₃	58.08	133.0	6.628	1.682	2.185	2.862	3.713	4.699	5.917	7.251
Acetonitrile	CH ₃ CN	41.05	178.9	6.558	0.638	0.831	1.083	1.412	1.876	2.456	3.133
Acrylonitrile	CH ₂ :CHCN	53.06	173.5	6.758	0.812	0.967	1.373	1.779	2.378	3.133	4.022
Allyl alcohol	CH ₂ :CHCH ₂ OH	58.08	206.6	7.125	0.135	0.193	0.261	0.387	0.522	0.716	1.006
Allyl chloride	CH ₂ :CHCH ₂ Cl	76.53	113.2	7.864	2.998	3.772	4.797	6.015	7.447	9.110	11.025
Ammonium hydroxide (28.8% solution)	NH ₄ OH--H ₂ O	35.05	83.0	7.481	5.130	6.630	8.480	10.760	13.520	16.760	20.680
Benzene	C ₆ H ₆	78.11	176.2	7.365	0.638	0.870	1.160	1.508	1.972	2.610	3.287
iso-Butyl alcohol	(CH ₃) ₂ CHCH ₂ OH	74.12	227.1	6.712	0.058	0.097	0.135	0.193	0.271	0.387	0.541
tert-Butyl alcohol	(CH ₃) ₃ COH	74.12	180.5	6.595	0.174	0.290	0.425	0.638	0.909	1.238	1.702
n-Butyl chloride	CH ₃ CH ₂ CH ₂ CH ₂ Cl	92.57	172.0	7.430	0.715	1.006	1.320	1.740	2.185	2.684	3.481
Carbon disulfide	CS ₂	76.13	115.3	10.588	3.036	3.867	4.834	6.014	7.387	9.185	11.215
Carbon tetrachloride	CCl ₄	153.84	170.2	13.366	0.793	1.064	1.412	1.798	2.301	2.997	3.771
Chloroform	CHCl ₃	119.39	142.7	12.488	1.528	1.934	2.475	3.191	4.061	5.163	6.342
Chloroprene	CH ₂ :CCl:CH:CH ₂	88.54	138.9	8.046	1.760	2.320	2.901	3.655	4.563	5.685	6.981
Cyclohexane	C ₆ H ₁₂	84.16	177.3	6.522	0.677	0.928	1.218	1.605	2.069	2.610	3.249
Cyclopentane	C ₅ H ₁₀	70.13	120.7	6.248	2.514	3.287	4.177	5.240	6.517	8.063	9.668
1,1-Dichloroethane	CH ₃ CHCl ₂	98.97	135.1	9.861	1.682	2.243	2.901	3.771	4.738	5.840	7.193
1,2-Dichloroethane	CH ₂ ClCH ₂ Cl	98.97	182.5	10.500	0.561	0.773	1.025	1.431	1.740	2.243	2.804
cis-1,2- Dichloro-ethylene	CHCl:CHCl	96.95	140.2	10.763	1.450	2.011	2.668	3.461	4.409	5.646	6.807
trans-1,2-Dichloro-ethylene	CHCl:CHCl	96.95	119.1	10.524	2.552	3.384	4.351	5.530	6.807	8.315	10.016
Diethylamine	(C ₂ H ₅) ₂ NH	73.14	131.9	5.906	1.644	1.992	2.862	3.867	4.892	6.130	7.541
Diethyl ether	C ₂ H ₅ OC ₂ H ₅	74.12	94.3	5.988	4.215	5.666	7.019	8.702	10.442	13.342	Boils
Di-iso-propyl ether	(CH ₃) ₂ CHOCH(CH ₃) ₂	102.17	153.5	6.075	1.199	1.586	2.127	2.746	3.481	4.254	5.298
1,4-Dioxane	O-CH ₂ CH ₂ OCH ₂ CH ₂	88.10	214.7	8.659	0.232	0.329	0.425	0.619	0.831	1.141	1.508
Dipropyl ether	CH ₃ CH ₂ CH ₂ OCH ₂ CH ₂ CH ₃	102.17	195.8	6.260	0.425	0.619	0.831	1.102	1.431	1.876	2.320
Ethyl acetate	C ₂ H ₅ OOCCCH ₃	88.10	170.9	7.551	0.580	0.831	1.102	1.489	1.934	2.514	3.191
Ethyl acrylate	C ₂ H ₅ OOCCCH:CH ₂	100.11	211.8	7.750	0.213	0.290	0.425	0.599	0.831	1.122	1.470
Ethyl alcohol	C ₂ H ₅ OH	46.07	173.1	6.610	0.193	0.406	0.619	0.870	1.218	1.682	2.320

Table 7.1-3 (cont.).

Name	Formula	Molecular Weight	Boiling Point At 1 Atmosphere (°F)	Liquid Density At 60°F (Pounds Per Gallon)	Vapor Pressure (Pounds Per Square Inch Absolute) At						
					40°F	50°F	60°F	70°F	80°F	90°F	100°F
Freon 11	CCl ₃ F	137.38	75.4	12.480	7.032	8.804	10.900	13.40	16.31	19.69	23.60
<i>n</i> -Heptane	CH ₃ (CH ₂) ₅ CH ₃	100.20	209.2	5.727	0.290	0.406	0.541	0.735	0.967	1.238	1.586
<i>n</i> -Hexane	CH ₃ (CH ₂) ₄ CH ₃	86.17	155.7	5.527	1.102	1.450	1.876	2.436	3.055	3.906	4.892
Hydrogen cyanide	HCN	27.03	78.3	5.772	6.284	7.831	9.514	11.853	15.392	18.563	22.237
Isooctane	(CH ₃) ₃ CCH ₂ CH(CH ₃) ₂	114.22	210.6	5.794	0.213	0.387	0.580	0.812	1.093	1.392	1.740
Isopentane	(CH ₃) ₂ CHCH ₂ CH ₃	72.15	82.1	5.199	5.878	7.889	10.005	12.530	15.334	18.370	21.657
Isoprene	(CH ₂):C(CH ₃)CH:CH ₂	68.11	93.5	5.707	4.757	6.130	7.677	9.668	11.699	14.503	17.113
Isopropyl alcohol	(CH ₃) ₂ -CHOH	60.09	180.1	6.573	0.213	0.329	0.483	0.677	0.928	1.296	1.779
Methacrylonitrile	CH ₂ :CH(CH ₃)CN	67.09	194.5	6.738	0.483	0.657	0.870	1.160	1.470	1.934	2.456
Methyl acetate	CH ₃ OOCCH ₃	74.08	134.8	7.831	1.489	2.011	2.746	3.693	4.699	5.762	6.961
Methyl acrylate	CH ₃ OOCCH:CH ₂	86.09	176.9	7.996	0.599	0.773	1.025	1.354	1.798	2.398	3.055
Methyl alcohol	CH ₃ OH	32.04	148.4	6.630	0.735	1.006	1.412	1.953	2.610	3.461	4.525
Methylcyclohexane	CH ₃ -C ₆ H ₁₁	98.18	213.7	6.441	0.309	0.425	0.541	0.735	0.986	1.315	1.721
Methylcyclopentane	CH ₃ C ₅ H ₉	84.16	161.3	6.274	0.909	1.160	1.644	2.224	2.862	3.616	4.544
Methylene chloride	CH ₂ Cl ₂	84.94	104.2	11.122	3.094	4.254	5.434	6.787	8.702	10.329	13.342
Methyl ethyl ketone	CH ₃ COC ₂ H ₅	72.10	175.3	6.747	0.715	0.928	1.199	1.489	2.069	2.668	3.345
Methyl methacrylate	CH ₃ OOC(CH ₃):CH ₂	100.11	212.0	7.909	0.116	0.213	0.348	0.541	0.773	1.064	1.373
Methyl propyl ether	CH ₃ OC ₃ H ₇	74.12	102.1	6.166	3.674	4.738	6.091	7.058	9.417	11.602	13.729
Nitromethane	CH ₃ NO ₂	61.04	214.2	9.538	0.213	0.251	0.348	0.503	0.715	1.006	1.334
<i>n</i> -Pentane	CH ₃ (CH ₂) ₃ CH ₃	72.15	96.9	5.253	4.293	5.454	6.828	8.433	10.445	12.959	15.474
<i>n</i> -Propylamine	C ₃ H ₇ NH ₂	59.11	119.7	6.030	2.456	3.191	4.157	5.250	6.536	8.044	9.572
1,1,1-Trichloroethane	CH ₃ CCl ₃	133.42	165.2	11.216	0.909	1.218	1.586	2.030	2.610	3.307	4.199
Trichloroethylene	CHCl:CCl ₂	131.40	188.6	12.272	0.503	0.677	0.889	1.180	1.508	2.030	2.610
Toluene	CH ₃ -C ₆ H ₅	92.13	231.1	7.261	0.174	0.213	0.309	0.425	0.580	0.773	1.006
Vinyl acetate	CH ₂ :CHOOCCH ₃	86.09	162.5	7.817	0.735	0.986	1.296	1.721	2.262	3.113	4.022
Vinylidene chloride	CH ₂ :CCl ₂	96.5	89.1	10.383	4.990	6.344	7.930	9.806	11.799	15.280	23.210

a Reference 11.

Table 7.1-4. ASTM DISTILLATION SLOPE FOR SELECTED REFINED PETROLEUM STOCKS^a

Refined Petroleum Stock	Reid Vapor Pressure, RVP (psi)	ASTM-D86 Distillation Slope At 10 Volume Percent Evaporated, (°F/vol%)
Aviation gasoline	ND	2.0
Naphtha	2-8	2.5
Motor gasoline	ND	3.0
Light naphtha	9-14	3.5

^a Reference 8. ND = no data.

Table 7.1-5. VAPOR PRESSURE EQUATION CONSTANTS
FOR ORGANIC LIQUIDS^a

Name	Vapor Pressure Equation Constants		
	A	B	C
	(Dimensionless)	(°C)	(°C)
Acetaldehyde	8.005	1600.017	291.809
Acetic acid	7.387	1533.313	222.309
Acetic anhydride	7.149	1444.718	199.817
Acetone	7.117	1210.595	229.664
Acetonitrile	7.119	1314.4	230
Acrylamide	11.2932	3939.877	273.16
Acrylic acid	5.652	648.629	154.683
Acrylonitrile	7.038	1232.53	222.47
Aniline	7.32	1731.515	206.049
Benzene	6.905	1211.033	220.79
Butanol (iso)	7.4743	1314.19	186.55
Butanol-(1)	7.4768	1362.39	178.77
Carbon disulfide	6.942	1169.11	241.59
Carbon tetrachloride	6.934	1242.43	230
Chlorobenzene	6.978	1431.05	217.55
Chloroform	6.493	929.44	196.03
Chloroprene	6.161	783.45	179.7
Cresol(-M)	7.508	1856.36	199.07
Cresol(-O)	6.911	1435.5	165.16
Cresol(-P)	7.035	1511.08	161.85
Cumene (isopropylbenzene)	6.963	1460.793	207.78
Cyclohexane	6.841	1201.53	222.65
Cyclohexanol	6.255	912.87	109.13
Cyclohexanone	7.8492	2137.192	273.16
Dichloroethane(1,2)	7.025	1272.3	222.9
Dichloroethylene(1,2)	6.965	1141.9	231.9
Diethyl (N,N) anilin	7.466	1993.57	218.5
Dimethyl formamide	6.928	1400.87	196.43
Dimethyl hydrazine (1,1)	7.408	1305.91	225.53
Dimethyl phthalate	4.522	700.31	51.42
Dinitrobenzene	4.337	229.2	-137
Dioxane(1,4)	7.431	1554.68	240.34
Epichlorohydrin	8.2294	2086.816	273.16
Ethanol	8.321	1718.21	237.52
Ethanolamine(mono-)	7.456	1577.67	173.37
Ethyl acetate	7.101	1244.95	217.88
Ethyl acrylate	7.9645	1897.011	273.16
Ethyl benzene	6.975	1424.255	213.21
Ethyl chloride	6.986	1030.01	238.61
Ethyl ether	6.92	1064.07	228.8
Formic acid	7.581	1699.2	260.7
Furan	6.975	1060.87	227.74
Furfural	6.575	1198.7	162.8
Heptane(iso)	6.8994	1331.53	212.41
Hexane(-N)	6.876	1171.17	224.41

Table 7.1-5 (cont.).

Name	Vapor Pressure Equation Constants		
	A	B	C
	(Dimensionless)	(°C)	(°C)
Hexanol(-1)	7.86	1761.26	196.66
Hydrocyanic acid	7.528	1329.5	260.4
Methanol	7.897	1474.08	229.13
Methyl acetate	7.065	1157.63	219.73
Methyl ethyl ketone	6.9742	1209.6	216
Methyl isobutyl ketone	6.672	1168.4	191.9
Methyl methacrylate	8.409	2050.5	274.4
Methyl styrene (alpha)	6.923	1486.88	202.4
Methylene chloride	7.409	1325.9	252.6
Morpholine	7.7181	1745.8	235
Naphthalene	7.01	1733.71	201.86
Nitrobenzene	7.115	1746.6	201.8
Pentachloroethane	6.74	1378	197
Phenol	7.133	1516.79	174.95
Picoline(-2)	7.032	1415.73	211.63
Propanol (iso)	8.117	1580.92	219.61
Propylene glycol	8.2082	2085.9	203.540
Propylene oxide	8.2768	1656.884	273.16
Pyridine	7.041	1373.8	214.98
Resorcinol	6.9243	1884.547	186.060
Styrene	7.14	1574.51	224.09
Tetrachloroethane(1,1,1,2)	6.898	1365.88	209.74
Tetrachloroethane(1,1,2,2)	6.631	1228.1	179.9
Tetrachloroethylene	6.98	1386.92	217.53
Tetrahydrofuran	6.995	1202.29	226.25
Toluene	6.954	1344.8	219.48
Trichloro(1,1,2)trifluoroethane	6.88	1099.9	227.5
Trichloroethane(1,1,1)	8.643	2136.6	302.8
Trichloroethane(1,1,2)	6.951	1314.41	209.2
Trichloroethylene	6.518	1018.6	192.7
Trichlorofluoromethane	6.884	1043.004	236.88
Trichloropropane(1,2,3)	6.903	788.2	243.23
Vinyl acetate	7.21	1296.13	226.66
Vinylidene chloride	6.972	1099.4	237.2
Xylene(-M)	7.009	1426.266	215.11
Xylene(-O)	6.998	1474.679	213.69

^aReference 12.

Table 7.1-6. PAINT SOLAR ABSORPTANCE FOR FIXED ROOF TANKS^a

Paint Color	Paint Shade Or Type	Paint Factors (α)	
		Paint Condition	
		Good	Poor
Aluminum	Specular	0.39	0.49
Aluminum	Diffuse	0.60	0.68
Gray	Light	0.54	0.63
Gray	Medium	0.68	0.74
Red	Primer	0.89	0.91
White	NA	0.17	0.34

^a Reference 8. If specific information is not available, a white shell and roof, with the paint in good condition, can be assumed to represent the most common or typical tank paint in use. If the tank roof and shell are painted a different color, α is determined from $\alpha = (\alpha_R + \alpha_S)/2$; where α_R is the tank roof paint solar absorptance and α_S is the tank shell paint solar absorptance. NA = not applicable.

Table 7.1-7. METEOROLOGICAL DATA (T_{AX}, T_{AN}, I) FOR SELECTED U.S. LOCATIONS^a

Location	Property		Monthly Averages												Annual Average
	Symbol	Units	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Birmingham, AL	T _{AX}	°F	52.7	57.3	65.2	75.2	81.6	87.9	90.3	89.7	84.6	74.8	63.7	55.9	73.2
	T _{AN}	°F	33.0	35.2	42.1	50.4	58.3	65.9	69.8	69.1	63.6	50.4	40.5	35.2	51.1
	I	Btu/ft ² -d	707	967	1296	1674	1857	1919	1810	1724	1455	1211	858	661	1345
Montgomery, AL	T _{AX}	°F	57.0	60.9	68.1	77.0	83.6	88.8	91.5	91.2	86.9	77.5	67.0	59.8	75.9
	T _{AN}	°F	36.4	38.8	45.5	53.3	61.1	68.4	71.8	71.1	66.4	53.1	43.0	37.9	53.9
	I	Btu/ft ² -d	752	1013	1341	1729	1897	1972	1841	1746	1468	1262	915	719	1388
Homer, AK	T _{AX}	°F	27.0	31.2	34.4	42.1	49.8	56.3	60.5	60.3	54.8	44.0	34.9	27.7	43.6
	T _{AN}	°F	14.4	17.4	19.3	28.1	34.6	41.2	45.1	45.2	39.7	30.6	22.8	15.8	29.5
	I	Btu/ft ² -d	122	334	759	1248	1583	1751	1598	1189	791	437	175	64	838
Phoenix, AZ	T _{AX}	°F	65.2	69.7	74.5	83.1	92.4	102.3	105.0	102.3	98.2	87.7	74.3	66.4	85.1
	T _{AN}	°F	39.4	42.5	46.7	53.0	61.5	70.6	79.5	77.5	70.9	59.1	46.9	40.2	57.3
	I	Btu/ft ² -d	1021	1374	1814	2355	2677	2739	2487	2293	2015	1577	1151	932	1869
Tucson, AZ	T _{AX}	°F	64.1	67.4	71.8	80.1	88.8	98.5	98.5	95.9	93.5	84.1	72.2	65.0	81.7
	T _{AN}	°F	38.1	40.0	43.8	49.7	57.5	67.4	73.8	72.0	67.3	56.7	45.2	39.0	54.2
	I	Btu/ft ² -d	1099	1432	1864	2363	2671	2730	2341	2183	1979	1602	1208	996	1872
Fort Smith, AR	T _{AX}	°F	48.4	53.8	62.5	73.7	81.0	88.5	93.6	92.9	85.7	75.9	61.9	52.1	72.5
	T _{AN}	°F	26.6	30.9	38.5	49.1	58.2	66.3	70.5	68.9	62.1	49.0	37.7	30.2	49.0
	I	Btu/ft ² -d	744	999	1312	1616	1912	2089	2065	1877	1502	1201	851	682	1404
Little Rock, AR	T _{AX}	°F	49.8	54.5	63.2	73.8	81.7	89.5	92.7	92.3	85.6	75.8	62.4	53.2	72.9
	T _{AN}	°F	29.9	33.6	41.2	50.9	59.2	67.5	71.4	69.6	63.0	50.4	40.0	33.2	50.8
	I	Btu/ft ² -d	731	1003	1313	1611	1929	2107	2032	1861	1518	1228	847	674	1404
Bakersfield, CA	T _{AX}	°F	57.4	63.7	68.6	75.1	83.9	92.2	98.8	96.4	90.8	81.0	67.4	57.6	77.7
	T _{AN}	°F	38.9	42.6	45.5	50.1	57.2	64.3	70.1	68.5	63.8	54.9	44.9	38.7	53.3
	I	Btu/ft ² -d	766	1102	1595	2095	2509	2749	2684	2421	1992	1458	942	677	1749
Long Beach, CA	T _{AX}	°F	66.0	67.3	68.0	70.9	73.4	77.4	83.0	83.8	82.5	78.4	72.7	67.4	74.2
	T _{AN}	°F	44.3	45.9	47.7	50.8	55.2	58.9	62.6	64.0	61.6	56.6	49.6	44.7	53.5
	I	Btu/ft ² -d	928	1215	1610	1938	2065	2140	2300	2100	1701	1326	1004	847	1598
Los Angeles AP, CA	T _{AX}	°F	64.6	65.5	65.1	66.7	69.1	72.0	75.3	76.5	76.4	74.0	70.3	66.1	70.1
	T _{AN}	°F	47.3	48.6	49.7	52.2	55.7	59.1	62.6	64.0	62.5	58.5	52.1	47.8	55.0
	I	Btu/ft ² -d	926	1214	1619	1951	2060	2119	2308	2080	1681	1317	1004	849	1594
Sacramento, CA	T _{AX}	°F	52.6	59.4	64.1	71.0	79.7	87.4	93.3	91.7	87.6	77.7	63.2	53.2	73.4
	T _{AN}	°F	37.9	41.2	42.4	45.3	50.1	55.1	57.9	57.6	55.8	50.0	42.8	37.9	47.8
	I	Btu/ft ² -d	597	939	1458	2004	2435	2684	2688	2368	1907	1315	782	538	1643
San Francisco AP, CA	T _{AX}	°F	55.5	59.0	60.6	63.0	66.3	69.6	71.0	71.8	73.4	70.0	62.7	56.3	64.9
	T _{AN}	°F	41.5	44.1	44.9	46.6	49.3	52.0	53.3	54.2	54.3	51.2	46.3	42.2	48.3
	I	Btu/ft ² -d	708	1009	1455	1920	2226	2377	2392	2117	1742	1226	821	642	1608

Table 7.1-7 (cont.).

Location	Property		Monthly Averages												Annual Average
	Symbol	Units	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Santa Maria, CA	T _{AX}	°F	62.8	64.2	63.9	65.6	67.3	69.9	72.1	72.8	74.2	73.3	68.9	64.6	68.3
	T _{AN}	°F	38.8	40.3	40.9	42.7	46.2	49.6	52.4	53.2	51.8	47.6	42.1	38.3	45.3
	I	Btu/ft ² -d	854	1141	1582	1921	2141	2349	2341	2106	1730	1353	974	804	1608
Denver, CO	T _{AX}	°F	43.1	46.9	51.2	61.0	70.7	81.6	88.0	85.8	77.5	66.8	52.4	46.1	64.3
	T _{AN}	°F	15.9	20.2	24.7	33.7	43.6	52.4	58.7	57.0	47.7	36.9	25.1	18.9	36.2
	I	Btu/ft ² -d	840	1127	1530	1879	2135	2351	2273	2044	1727	1301	884	732	1568
Grand Junction, CO	T _{AX}	°F	35.7	44.5	54.1	65.2	76.2	87.9	94.0	90.3	81.9	68.7	51.0	38.7	65.7
	T _{AN}	°F	15.2	22.4	29.7	38.2	48.0	56.6	63.8	61.5	52.2	41.1	28.2	17.9	39.6
	I	Btu/ft ² -d	791	1119	1554	1986	2380	2599	2465	2182	1834	1345	918	731	1659
Wilmington, DE	T _{AX}	°F	39.2	41.8	50.9	63.0	72.7	81.2	85.6	84.1	77.8	66.7	54.8	43.6	63.5
	T _{AN}	°F	23.2	24.6	32.6	41.8	51.7	61.2	66.3	65.4	58.0	45.9	36.4	27.3	44.5
	I	Btu/ft ² -d	571	827	1149	1480	1710	1883	1823	1615	1318	984	645	489	1208
Atlanta, GA	T _{AX}	°F	51.2	55.3	63.2	73.2	79.8	85.6	87.9	87.6	82.3	72.9	62.6	54.1	71.3
	T _{AN}	°F	32.6	34.5	41.7	50.4	58.7	65.9	69.2	68.7	63.6	51.4	41.3	34.8	51.1
	I	Btu/ft ² -d	718	969	1304	1686	1854	1914	1812	1709	1422	1200	883	674	1345
Savannah, GA	T _{AX}	°F	60.3	63.1	69.9	77.8	84.2	88.6	90.8	90.1	85.6	77.8	69.5	62.5	76.7
	T _{AN}	°F	37.9	40.0	46.8	54.1	62.3	68.5	71.5	71.4	67.6	55.9	45.5	39.4	55.1
	I	Btu/ft ² -d	795	1044	1399	1761	1852	1844	1784	1621	1364	1217	941	754	1365
Honolulu, HI	T _{AX}	°F	79.9	80.4	81.4	82.7	84.8	86.2	87.1	88.3	88.2	86.7	83.9	81.4	84.2
	T _{AN}	°F	65.3	65.3	67.3	68.7	70.2	71.9	73.1	73.6	72.9	72.2	69.2	66.5	69.7
	I	Btu/ft ² -d	1180	1396	1622	1796	1949	2004	2002	1967	1810	1540	1266	1133	1639
Chicago, IL	T _{AX}	°F	29.2	33.9	44.3	58.8	70.0	79.4	83.3	82.1	75.5	64.1	48.2	35.0	58.7
	T _{AN}	°F	13.6	18.1	27.6	38.8	48.1	57.7	62.7	61.7	53.9	42.9	31.4	20.3	39.7
	I	Btu/ft ² -d	507	760	1107	1459	1789	2007	1944	1719	1354	969	566	402	1215
Springfield, IL	T _{AX}	°F	32.8	38.0	48.9	64.0	74.6	84.1	87.1	84.7	79.3	67.5	51.2	38.4	62.6
	T _{AN}	°F	16.3	20.9	30.3	42.6	52.5	62.0	65.9	63.7	55.8	44.4	32.9	23.0	42.5
	I	Btu/ft ² -d	585	861	1143	1515	1866	2097	2058	1806	1454	1068	677	490	1302
Indianapolis, IN	T _{AX}	°F	34.2	38.5	49.3	63.1	73.4	82.3	85.2	83.7	77.9	66.1	50.8	39.2	62.0
	T _{AN}	°F	17.8	21.1	30.7	41.7	51.5	60.9	64.9	62.7	55.3	43.4	32.8	23.7	42.2
	I	Btu/ft ² -d	496	747	1037	1398	1638	1868	1806	1644	1324	977	579	417	1165
Wichita, KS	T _{AX}	°F	39.8	46.1	55.8	68.1	77.1	87.4	92.9	91.5	82.0	71.2	55.1	44.6	67.6
	T _{AN}	°F	19.4	24.1	32.4	44.5	54.6	64.7	69.8	67.9	59.2	46.9	33.5	24.2	45.1
	I	Btu/ft ² -d	784	1058	1406	1783	2036	2264	2239	2032	1616	1250	871	690	1502

Table 7.1-7 (cont.).

Location	Property		Monthly Averages												Annual Average
	Symbol	Units	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Louisville, KY	T _{AX}	°F	40.8	45.0	54.9	67.5	76.2	84.0	87.6	86.7	80.6	69.2	55.5	45.4	66.1
	T _{AN}	°F	24.1	26.8	35.2	45.6	54.6	63.3	67.5	66.1	59.1	46.2	36.6	28.9	46.2
	I	Btu/ft ² -d	546	789	1102	1467	1720	1904	1838	1680	1361	1042	653	488	1216
Baton Rouge, LA	T _{AX}	°F	61.1	64.5	71.6	79.2	85.2	90.6	91.4	90.8	87.4	80.1	70.1	63.8	78.0
	T _{AN}	°F	40.5	42.7	49.4	57.5	64.3	70.0	72.8	72.0	68.3	56.3	47.2	42.3	57.0
	I	Btu/ft ² -d	785	1054	1379	1681	1871	1926	1746	1677	1464	1301	920	737	1379
Lake Charles, LA	T _{AX}	°F	60.8	64.0	70.5	77.8	84.1	89.4	91.0	90.8	87.5	80.8	70.5	64.0	77.6
	T _{AN}	°F	42.2	44.5	50.8	58.9	65.6	71.4	73.5	72.8	68.9	57.7	48.9	43.8	58.3
	I	Btu/ft ² -d	728	1010	1313	1570	1849	1970	1788	1657	1485	1381	917	706	1365
New Orleans, LA	T _{AX}	°F	61.8	64.6	71.2	78.6	84.5	89.5	90.7	90.2	86.8	79.4	70.1	64.4	77.7
	T _{AN}	°F	43.0	44.8	51.6	58.8	65.3	70.9	73.5	73.1	70.1	59.0	49.9	44.8	58.7
	I	Btu/ft ² -d	835	1112	1415	1780	1968	2004	1814	1717	1514	1335	973	779	1437
Detroit, MI	T _{AX}	°F	30.6	33.5	43.4	57.7	69.4	79.0	83.1	81.5	74.4	62.5	47.6	35.4	58.2
	T _{AN}	°F	16.1	18.0	26.5	36.9	46.7	56.3	60.7	59.4	52.2	41.2	31.4	21.6	38.9
	I	Btu/ft ² -d	417	680	1000	1399	1716	1866	1835	1576	1253	876	478	344	1120
Grand Rapids, MI	T _{AX}	°F	29.0	31.7	41.6	56.9	69.4	78.9	83.0	81.1	73.4	61.4	46.0	33.8	57.2
	T _{AN}	°F	14.9	15.6	24.5	35.6	45.5	55.3	59.8	58.1	50.8	40.4	30.9	20.7	37.7
	I	Btu/ft ² -d	370	648	1014	1412	1755	1957	1914	1676	1262	858	446	311	1135
Minneapolis-St. Paul, MN	T _{AX}	°F	19.9	26.4	37.5	56.0	69.4	78.5	83.4	80.9	71.0	59.7	41.1	26.7	54.2
	T _{AN}	°F	2.4	8.5	20.8	36.0	47.6	57.7	62.7	60.3	50.2	39.4	25.3	11.7	35.2
	I	Btu/ft ² -d	464	764	1104	1442	1737	1928	1970	1687	1255	860	480	353	1170
Jackson, MS	T _{AX}	°F	56.5	60.9	68.4	77.3	84.1	90.5	92.5	92.1	87.6	78.6	67.5	60.0	76.3
	T _{AN}	°F	34.9	37.2	44.2	52.9	60.8	67.9	71.3	70.2	65.1	51.4	42.3	37.1	52.9
	I	Btu/ft ² -d	754	1026	1369	1708	1941	2024	1909	1781	1509	1271	902	709	1409
Billings, MT	T _{AX}	°F	29.9	37.9	44.0	55.9	66.4	76.3	86.6	84.3	72.3	61.0	44.4	36.0	57.9
	T _{AN}	°F	11.8	18.8	23.6	33.2	43.3	51.6	58.0	56.2	46.5	37.5	25.5	18.2	35.4
	I	Btu/ft ² -d	486	763	1190	1526	1913	2174	2384	2022	1470	987	561	421	1325
Las Vegas, NV	T _{AX}	°F	56.0	62.4	68.3	77.2	87.4	98.6	104.5	101.9	94.7	81.5	66.0	57.1	79.6
	T _{AN}	°F	33.0	37.7	42.3	49.8	59.0	68.6	75.9	73.9	65.6	53.5	41.2	33.6	52.8
	I	Btu/ft ² -d	978	1340	1824	2319	2646	2778	2588	2355	2037	1540	1086	881	1864
Newark, NJ	T _{AX}	°F	38.2	40.3	49.1	61.3	71.6	80.6	85.6	84.0	76.9	66.0	54.0	42.3	62.5
	T _{AN}	°F	24.2	25.3	33.3	42.9	53.0	62.4	67.9	67.0	59.4	48.3	39.0	28.6	45.9
	I	Btu/ft ² -d	552	793	1109	1449	1687	1795	1760	1565	1273	951	596	454	1165

Table 7.1-7 (cont.).

Location	Property		Monthly Averages												Annual Average
	Symbol	Units	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Roswell, NM	T _{AX}	°F	55.4	60.4	67.7	76.9	85.0	93.1	93.7	91.3	84.9	75.8	63.1	56.7	75.3
	T _{AN}	°F	27.4	31.4	37.9	46.8	55.6	64.8	69.0	67.0	59.6	47.5	35.0	28.2	47.5
	I	Btu/ft ² -d	1047	1373	1807	2218	2459	2610	2441	2242	1913	1527	1131	952	1810
Buffalo, NY	T _{AX}	°F	30.0	31.4	40.4	54.4	65.9	75.6	80.2	78.2	71.4	60.2	47.0	35.0	55.8
	T _{AN}	°F	17.0	17.5	25.6	36.3	46.3	56.4	61.2	59.6	52.7	42.7	33.6	22.5	39.3
	I	Btu/ft ² -d	349	546	889	1315	1597	1804	1776	1513	1152	784	403	283	1034
New York, NY (LaGuardia Airport)	T _{AX}	°F	37.4	39.2	47.3	59.6	69.7	78.7	83.9	82.3	75.2	64.5	52.9	41.5	61.0
	T _{AN}	°F	26.1	27.3	34.6	44.2	53.7	63.2	68.9	68.2	61.2	50.5	41.2	30.8	47.5
	I	Btu/ft ² -d	548	795	1118	1457	1690	1802	1784	1583	1280	951	593	457	1171
Cleveland, OH	T _{AX}	°F	32.5	34.8	44.8	57.9	68.5	78.0	81.7	80.3	74.2	62.7	49.3	37.5	58.5
	T _{AN}	°F	18.5	19.9	28.4	38.3	47.9	57.2	61.4	60.5	54.0	43.6	34.3	24.6	40.7
	I	Btu/ft ² -d	388	601	922	1350	1681	1843	1828	1583	1240	867	466	318	1091
Columbus, OH	T _{AX}	°F	34.7	38.1	49.3	62.3	72.6	81.3	84.4	83.0	76.9	65.0	50.7	39.4	61.5
	T _{AN}	°F	19.4	21.5	30.6	40.5	50.2	59.0	63.2	61.7	54.6	42.8	33.5	24.7	41.8
	I	Btu/ft ² -d	459	677	980	1353	1647	1813	1755	1641	1282	945	538	387	1123
Toledo, OH	T _{AX}	°F	30.7	34.0	44.6	59.1	70.5	79.9	83.4	81.8	75.1	63.3	47.9	35.5	58.8
	T _{AN}	°F	15.5	17.5	26.1	36.5	46.6	56.0	60.2	58.4	51.2	40.1	30.6	20.6	38.3
	I	Btu/ft ² -d	435	680	997	1384	1717	1878	1849	1616	1276	911	498	355	1133
Oklahoma City, OK	T _{AX}	°F	46.6	52.2	61.0	71.7	79.0	87.6	93.5	92.8	84.7	74.3	59.9	50.7	71.2
	T _{AN}	°F	25.2	29.4	37.1	48.6	57.7	66.3	70.6	69.4	61.9	50.2	37.6	29.1	48.6
	I	Btu/ft ² -d	801	1055	1400	1725	1918	2144	2128	1950	1554	1233	901	725	1461
Tulsa, OK	T _{AX}	°F	45.6	51.9	60.8	72.4	79.7	87.9	93.9	93.0	85.0	74.9	60.2	50.3	71.3
	T _{AN}	°F	24.8	29.5	37.7	49.5	58.5	67.5	72.4	70.3	62.5	50.3	38.1	29.3	49.2
	I	Btu/ft ² -d	732	978	1306	1603	1822	2021	2031	1865	1473	1164	827	659	1373
Astoria, OR	T _{AX}	°F	46.8	50.6	51.9	55.5	60.2	63.9	67.9	68.6	67.8	61.4	53.5	48.8	58.1
	T _{AN}	°F	35.4	37.1	36.9	39.7	44.1	49.2	52.2	52.6	49.2	44.3	39.7	37.3	43.1
	I	Btu/ft ² -d	315	545	866	1253	1608	1626	1746	1499	1183	713	387	261	1000
Portland, OR	T _{AX}	°F	44.3	50.4	54.5	60.2	66.9	72.7	79.5	78.6	74.2	63.9	52.3	46.4	62.0
	T _{AN}	°F	33.5	36.0	37.4	40.6	46.4	52.2	55.8	55.8	51.1	44.6	38.6	35.4	44.0
	I	Btu/ft ² -d	310	554	895	1308	1663	1773	2037	1674	1217	724	388	260	1067
Philadelphia, PA	T _{AX}	°F	38.6	41.1	50.5	63.2	73.0	81.7	86.1	84.6	77.8	66.5	54.5	43.0	63.4
	T _{AN}	°F	23.8	25.0	33.1	42.6	52.5	61.5	66.8	66.0	58.6	46.5	37.1	28.0	45.1
	I	Btu/ft ² -d	555	795	1108	1434	1660	1811	1758	1575	1281	959	619	470	1169

Table 7.1-7 (cont.).

Location	Property		Monthly Averages												Annual Average
	Symbol	Units	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Pittsburgh, PA	T _{AX} T _{AN} I	°F °F Btu/ft ² -d	34.1 19.2 424	36.8 20.7 625	47.6 29.4 943	60.7 39.4 1317	70.8 48.5 1602	79.1 57.1 1762	82.7 61.3 1689	81.1 60.1 1510	74.8 53.3 1209	62.9 42.1 895	49.8 33.3 505	38.4 24.3 347	59.9 40.7 1069
Providence, RI	T _{AX} T _{AN} I	°F °F Btu/ft ² -d	36.4 20.0 506	37.7 20.9 739	45.5 29.2 1032	57.5 38.3 1374	67.6 47.6 1655	76.6 57.0 1776	81.7 63.3 1695	80.3 61.9 1499	73.1 53.8 1209	63.2 43.1 907	51.9 34.8 538	40.5 24.1 419	59.3 41.2 1112
Columbia, SC	T _{AX} T _{AN} I	°F °F Btu/ft ² -d	56.2 33.2 762	59.5 34.6 1021	67.1 41.9 1355	77.0 50.5 1747	83.8 59.1 1895	89.2 66.1 1947	91.9 70.1 1842	91.0 69.4 1703	85.5 63.9 1439	76.5 50.3 1211	67.1 40.6 921	58.8 34.7 722	75.3 51.2 1380
Sioux Falls, SD	T _{AX} T _{AN} I	°F °F Btu/ft ² -d	22.9 1.9 533	29.3 8.9 802	40.1 20.6 1152	58.1 34.6 1543	70.5 45.7 1894	80.3 56.3 2100	86.2 61.8 2150	83.9 59.7 1845	73.5 48.5 1410	62.1 36.7 1005	43.7 22.3 608	29.3 10.1 441	56.7 33.9 1290
Memphis, TN	T _{AX} T _{AN} I	°F °F Btu/ft ² -d	48.3 30.9 683	53.0 34.1 945	61.4 41.9 1278	72.9 52.2 1639	81.0 60.9 1885	88.4 68.9 2045	91.5 72.6 1972	90.3 70.8 1824	84.3 64.1 1471	74.5 51.3 1205	61.4 41.1 817	52.3 34.3 629	71.6 51.9 1366
Amarillo, TX	T _{AX} T _{AN} I	°F °F Btu/ft ² -d	49.1 21.7 960	53.1 26.1 1244	60.8 32.0 1631	71.0 42.0 2019	79.1 51.9 2212	88.2 61.5 2393	91.4 66.2 2281	89.6 64.5 2103	82.4 56.9 1761	72.7 45.5 1404	58.7 32.1 1033	51.8 24.8 872	70.7 43.8 1659
Corpus Christi, TX	T _{AX} T _{AN} I	°F °F Btu/ft ² -d	66.5 46.1 898	69.9 48.7 1147	76.1 55.7 1430	82.1 63.9 1642	86.7 69.5 1866	91.2 74.1 2094	94.2 75.6 2186	94.1 75.8 1991	90.1 72.8 1687	83.9 64.1 1416	75.1 54.9 1043	69.3 48.8 845	81.6 62.5 1521
Dallas, TX	T _{AX} T _{AN} I	°F °F Btu/ft ² -d	54.0 33.9 822	59.1 37.8 1071	67.2 44.9 1422	76.8 55.0 1627	84.4 62.9 1889	93.2 70.8 2135	97.8 74.7 2122	97.3 73.7 1950	89.7 67.5 1587	79.5 56.3 1276	66.2 44.9 936	58.1 37.4 780	76.9 55.0 1468
Houston, TX	T _{AX} T _{AN} I	°F °F Btu/ft ² -d	61.9 40.8 772	65.7 43.2 1034	72.1 49.8 1297	79.0 58.3 1522	85.1 64.7 1775	90.9 70.2 1898	93.6 72.5 1828	93.1 72.1 1686	88.7 68.1 1471	81.9 57.5 1276	71.6 48.6 924	65.2 42.7 730	79.1 57.4 1351
Midland-Odessa, TX	T _{AX} T _{AN} I	°F °F Btu/ft ² -d	57.6 29.7 1081	62.1 33.3 1383	69.8 40.2 1839	78.8 49.4 2192	86.0 58.2 2430	93.0 66.6 2562	94.2 69.2 2389	93.1 68.0 2210	86.4 61.9 1844	77.7 51.1 1522	65.5 39.0 1176	59.7 32.2 1000	77.0 49.9 1802
Salt Lake City, UT	T _{AX} T _{AN} I	°F °F Btu/ft ² -d	37.4 19.7 639	43.7 24.4 989	51.5 29.9 1454	61.1 37.2 1894	72.4 45.2 2362	83.3 53.3 2561	93.2 61.8 2590	90.0 59.7 2254	80.0 50.0 1843	66.7 39.3 1293	50.2 29.2 788	38.9 21.6 570	64.0 39.3 1603

Table 7.1-7 (cont.).

Location	Property		Monthly Averages												Annual Average
	Symbol	Units	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Richmond, VA	T _{AX}	°F	46.7	49.6	58.5	70.6	77.9	84.8	88.4	87.1	81.0	70.5	60.5	50.2	68.8
	T _{AN}	°F	26.5	28.1	35.8	45.1	54.2	62.2	67.2	66.4	59.3	46.7	37.3	29.6	46.5
	I	Btu/ft ² day	632	877	1210	1566	1762	1872	1774	1601	1348	1033	733	567	1248
Seattle, WA (Sea-Tac Airport)	T _{AX}	°F	43.9	48.8	51.1	56.8	64.0	69.2	75.2	73.9	68.7	59.5	50.3	45.6	58.9
	T _{AN}	°F	34.3	36.8	37.2	40.5	46.0	51.1	54.3	54.3	51.2	45.3	39.3	36.3	43.9
	I	Btu/ft ² day	262	495	849	1294	1714	1802	2248	1616	1148	656	337	211	1053
Charleston, WV	T _{AX}	°F	41.8	45.4	55.4	67.3	76.0	82.5	85.2	84.2	78.7	67.7	55.6	45.9	65.5
	T _{AN}	°F	23.9	25.8	34.1	43.3	51.8	59.4	63.8	63.1	56.4	44.0	35.0	27.8	44.0
	I	Btu/ft ² day	498	707	1010	1356	1639	1776	1683	1514	1272	972	613	440	1123
Huntington, WV	T _{AX}	°F	41.1	45.0	55.2	67.2	75.7	82.6	85.6	84.4	78.7	67.6	55.2	45.2	65.3
	T _{AN}	°F	24.5	26.6	35.0	44.4	52.8	60.7	65.1	64.0	57.2	44.9	35.9	28.5	45.0
	I	Btu/ft ² day	526	757	1067	1448	1710	1844	1769	1580	1306	1004	638	467	1176
Cheyenne, WY	T _{AX}	°F	37.3	40.7	43.6	54.0	64.6	75.4	83.1	80.8	72.1	61.0	46.5	40.4	58.3
	T _{AN}	°F	14.8	17.9	20.6	29.6	39.7	48.5	54.6	52.8	43.7	34.0	23.1	18.2	33.1
	I	Btu/ft ² day	766	1068	1433	1771	1995	2258	2230	1966	1667	1242	823	671	1491

^a References 13 and 14, T_{AX} = daily maximum ambient temperature, T_{AN} = daily minimum ambient temperature, I = daily total solar insolation factor.

Table 7.1-8. RIM-SEAL LOSS FACTORS, K_{Ra} , K_{Rb} , and n ,
FOR FLOATING ROOF TANKS^a

Tank Construction And Rim-Seal System	Average-Fitting Seals		
	K_{Ra} (lb-mole/ft-yr)	K_{Rb} [lb-mole/(mph) ⁿ -ft-yr]	n (dimensionless)
Welded Tanks			
Mechanical-shoe seal			
Primary only ^b	5.8	0.3	2.1
Shoe-mounted secondary	1.6	0.3	1.6
Rim-mounted secondary	0.6	0.4	1.0
Liquid-mounted seal			
Primary only	1.6	0.3	1.5
Weather shield	0.7	0.3	1.2
Rim-mounted secondary	0.3	0.6	0.3
Vapor-mounted seal			
Primary only	6.7 ^c	0.2	3.0
Weather shield	3.3	0.1	3.0
Rim-mounted secondary	2.2	0.003	4.3
Riveted Tanks			
Mechanical-shoe seal			
Primary only	10.8	0.4	2.0
Shoe-mounted secondary	9.2	0.2	1.9
Rim-mounted secondary	1.1	0.3	1.5

Note: The rim-seal loss factors K_{Ra} , K_{Rb} , and n may only be used for wind speeds below 15 miles per hour.

^a Reference 15.

^b If no specific information is available, a welded tank with an average-fitting mechanical-shoe primary seal can be used to represent the most common or typical construction and rim-seal system in use for external and domed external floating roof tanks.

^c If no specific information is available, this value can be assumed to represent the most common or typical rim-seal system currently in use for internal floating roof tanks.

Table 7.1-9. AVERAGE ANNUAL WIND SPEED (v) FOR SELECTED U. S. LOCATIONS^a

Location	Wind Speed (mph)	Location	Wind Speed (mph)	Location	Wind Speed (mph)
Alabama		Arizona (continued)		Delaware	
Birmingham	7.2	Winslow	8.9	Wilmington	9.1
Huntsville	8.2	Yuma	7.8	District of Columbia	
Mobile	9.0			Dulles Airport	7.4
Montgomery	6.6	Arkansas		National Airport	9.4
		Fort Smith	7.6		
Alaska		Little Rock	7.8	Florida	
Anchorage	6.9			Apalachicola	7.8
Annette	10.6	California		Daytona Beach	8.7
Barrow	11.8	Bakersfield	6.4	Fort Meyers	8.1
Barter Island	13.2	Blue Canyon	6.8	Jacksonville	8.0
Bethel	12.8	Eureka	6.8	Key West	11.2
Bettles	6.7	Fresno	6.3	Miami	9.3
Big Delta	8.2	Long Beach	6.4	Orlando	8.5
Cold Bay	17.0	Los Angeles (City)	6.2	Pensacola	8.4
Fairbanks	5.4	Los Angeles Int'l. Airport	7.5	Tallahassee	6.3
Gulkana	6.8	Mount Shasta	5.1	Tampa	8.4
Homer	7.6	Sacramento	7.9	West Palm Beach	9.6
Juneau	8.3	San Diego	6.9		
King Salmon	10.8	San Francisco (City)	8.7	Georgia	
Kodiak	10.8	San Francisco Airport	10.6	Athens	7.4
Kotzebue	13.0	Santa Maria	7.0	Atlanta	9.1
McGrath	5.1	Stockton	7.5	Augusta	6.5
Nome	10.7			Columbus	6.7
St. Paul Island	17.7	Colorado		Macon	7.6
Talkeetna	4.8	Colorado Springs	10.1	Savannah	7.9
Valdez	6.0	Denver	8.7		
Yakutat	7.4	Grand Junction	8.1	Hawaii	
		Pueblo	8.7	Hilo	7.2
Arizona				Honolulu	11.4
Flagstaff	6.8	Connecticut		Kahului	12.8
Phoenix	6.3	Bridgeport	12.0	Lihue	12.2
Tucson	8.3	Hartford	8.5		

Table 7.1-9 (cont.).

Location	Wind Speed (mph)	Location	Wind Speed (mph)	Location	Wind Speed (mph)
Idaho		Louisiana		Mississippi	
Boise	8.8	Baton Rouge	7.6	Jackson	7.4
Pocatello	10.2	Lake Charles	8.7	Meridian	6.1
		New Orleans	8.2		
Illinois		Shreveport	8.4	Missouri	
Cairo	8.5			Columbia	9.9
Chicago	10.3	Maine		Kansas City	10.8
Moline	10.0	Caribou	11.2	Saint Louis	9.7
Peoria	10.0	Portland	8.8	Springfield	10.7
Rockford	10.0				
Springfield	11.2	Maryland		Montana	
		Baltimore	9.2	Billings	11.2
Indiana				Glasgow	10.8
Evansville	8.1	Massachusetts		Great Falls	12.8
Fort Wayne	10.0	Blue Hill Observatory	15.4	Helena	7.8
Indianapolis	9.6	Boston	12.5	Kalispell	6.6
South Bend	10.3	Worcester	10.1	Missoula	6.2
Iowa		Michigan		Nebraska	
Des Moines	10.9	Alpena	8.1	Grand Island	11.9
Sioux City	11.0	Detroit	10.4	Lincoln	10.4
Waterloo	10.7	Flint	10.2	Norfolk	11.7
		Grand Rapids	9.8	North Platte	10.2
Kansas		Houghton Lake	8.9	Omaha	10.6
Concordia	12.3	Lansing	10.0	Scottsbluff	10.6
Dodge City	14.0	Muskegon	10.7	Valentine	9.7
Goodland	12.6	Sault Sainte Marie	9.3		
Topeka	10.0			Nevada	
Wichita	12.3	Minnesota		Elko	6.0
		Duluth	11.1	Ely	10.3
Kentucky		International Falls	8.9	Las Vegas	9.3
Cincinnati Airport	9.1	Minneapolis-Saint Paul	10.6	Reno	6.6
Jackson	7.2	Rochester	13.1	Winnemucca	8.0
Lexington	9.3	Saint Cloud	8.0		
Louisville	8.4				

Table 7.1-9 (cont.).

Location	Wind Speed (mph)	Location	Wind Speed (mph)	Location	Wind Speed (mph)
New Hampshire		Ohio		Rhode Island	
Concord	6.7	Akron	9.8	Providence	10.6
Mount Washington	35.3	Cleveland	10.6		
		Columbus	8.5	South Carolina	
New Jersey		Dayton	9.9	Charleston	8.6
Atlantic City	10.1	Mansfield	11.0	Columbia	6.9
Newark	10.2	Toledo	9.4	Greenville-Spartanburg	6.9
		Youngstown	9.9		
New Mexico				South Dakota	
Albuquerque	9.1	Oklahoma		Aberdeen	11.2
Roswell	8.6	Oklahoma City	12.4	Huron	11.5
		Tulsa	10.3	Rapid City	11.3
New York				Sioux Falls	11.1
Albany	8.9	Oregon			
Birmingham	10.3	Astoria	8.6	Tennessee	
Buffalo	12.0	Eugene	7.6	Bristol-Johnson City	5.5
				Chattanooga	6.1
New York (Central Park)	9.4	Medford	4.8	Knoxville	7.0
New York (JFK Airport)	12.0	Pendleton	8.7		
New York (La Guardia Airport)	12.2	Portland	7.9	Memphis	8.9
Rochester	9.7	Salem	7.1	Nashville	8.0
Syracuse	9.5	Sexton Summit	11.8	Oak Ridge	4.4
North Carolina		Pennsylvania		Texas	
Asheville	7.6	Allentown	9.2	Abilene	12.0
Cape Hatteras	11.1	Avoca	8.3	Amarillo	13.6
Charlotte	7.5	Erie	11.3	Austin	9.2
Greensboro-High Point	7.5	Harrisburg	7.6	Brownsville	11.5
Raleigh	7.8	Philadelphia	9.5	Corpus Christi	12.0
Wilmington	8.8	Pittsburgh Int'l Airport	9.1	Dallas-Fort Worth	10.8
		Williamsport	7.8	Del Rio	9.9
North Dakota				El Paso	8.9
Bismark	10.2	Puerto Rico		Galveston	11.0
Fargo	12.3	San Juan	8.4	Houston	7.9
Williston	10.1			Lubbock	12.4

Table 7.1-9 (cont.).

Location	Wind Speed (mph)	Location	Wind Speed (mph)
Texas (continued)		Wisconsin	
Midland-Odessa	11.1	Green Bay	10.0
Port Arthur	9.8	La Crosse	8.8
San Angelo	10.4	Madison	9.9
San Antonio	9.3	Milwaukee	11.6
Victoria	10.1		
Waco	11.3	Wyoming	
Wichita Falls	11.7	Casper	12.9
		Cheyenne	13.0
Utah		Lander	6.8
Salt Lake City	8.9	Sheridan	8.0
Vermont			
Burlington	8.9		
Virginia			
Lynchburg	7.7		
Norfolk	10.7		
Richmond	7.7		
Roanoke	8.1		
Washington			
Olympia	6.7		
Quillayute	6.1		
Seattle Int'l. Airport	9.0		
Spokane	8.9		
Walla Walla	5.3		
Yakima	7.1		
West Virginia			
Belkley	9.1		
Charleston	6.3		
Elkins	6.2		
Huntington	6.6		

^a Reference 13.

Table 7.1-10. AVERAGE CLINGAGE FACTORS, C^a
(bbl/10³ ft²)

Product Stored	Shell Condition		
	Light Rust	Dense Rust	Guniting Lining
Gasoline	0.0015	0.0075	0.15
Single-component stocks	0.0015	0.0075	0.15
Crude oil	0.0060	0.030	0.60

^a Reference 3. If no specific information is available, the values in this table can be assumed to represent the most common or typical condition of tanks currently in use.

Table 7.1-11. TYPICAL NUMBER OF COLUMNS AS A FUNCTION OF TANK DIAMETER FOR INTERNAL FLOATING ROOF TANKS WITH COLUMN-SUPPORTED FIXED ROOFS^a

Tank Diameter Range D, (ft)	Typical Number Of Columns, N_C
0 < D ≤ 85	1
85 < D ≤ 100	6
100 < D ≤ 120	7
120 < D ≤ 135	8
135 < D ≤ 150	9
150 < D ≤ 170	16
170 < D ≤ 190	19
190 < D ≤ 220	22
220 < D ≤ 235	31
235 < D ≤ 270	37
270 < D ≤ 275	43
275 < D ≤ 290	49
290 < D ≤ 330	61
330 < D ≤ 360	71
360 < D ≤ 400	81

^a Reference 4. This table was derived from a survey of users and manufacturers. The actual number of columns in a particular tank may vary greatly with age, fixed roof style, loading specifications, and manufacturing prerogatives. Data in this table should not be used when actual tank data are available.

Table 7.1-12. DECK-FITTING LOSS FACTORS, K_{Fa} , K_{Fb} ,
AND m , AND TYPICAL NUMBER OF DECK FITTINGS, N_F ^a

Fitting Type And Construction Details	Loss Factors			Typical Number Of Fittings, N_F
	K_{Fa} (lb-mole/yr)	K_{Fb} (lb-mole/(mph) ^m -yr)	m (dimensionless)	
Access hatch (24-inch diameter well)				1
Bolted cover, gasketed ^b	1.6	0	0	
Unbolted cover, ungasketed	36 ^c	5.9	1.2	
Unbolted cover, gasketed	31	5.2	1.3	
Fixed roof support column well ^d				N_C (Table 7.1-11)
Round pipe, ungasketed sliding cover	31			
Round pipe, gasketed sliding cover	25			
Round pipe, flexible fabric sleeve seal	10			
Built-up column, ungasketed sliding cover ^c	47			
Built-up column, gasketed sliding cover	33			
Unslotted guide-pole and well (8-inch diameter unslotted pole, 21-inch diameter well)				1
Ungasketed sliding cover ^b	31	150	1.4	
Ungasketed sliding cover w/pole sleeve	25	2.2	2.1	
Gasketed sliding cover	25	13	2.2	
Gasketed sliding cover w/pole wiper	14	3.7	0.78	
Gasketed sliding cover w/pole sleeve	8.6	12	0.81	
Slotted guide-pole/sample well (8-inch diameter slotted pole, 21-inch diameter well) ^e				f
Ungasketed or gasketed sliding cover	43	270	1.4	
Ungasketed or gasketed sliding cover, with float ^g	31	36	2.0	
Gasketed sliding cover, with pole wiper	41	48	1.4	
Gasketed sliding cover, with pole sleeve	11	46	1.4	
Gasketed sliding cover, with pole sleeve and pole wiper	8.3	4.4	1.6	
Gasketed sliding cover, with float and pole wiper ^g	21	7.9	1.8	
Gasketed sliding cover, with float, pole sleeve, and pole wiper ^h	11	9.9	0.89	
Gauge-float well (automatic gauge)				1
Unbolted cover, ungasketed ^b	14 ^c	5.4	1.1	
Unbolted cover, gasketed	4.3	17	0.38	
Bolted cover, gasketed	2.8	0	0	
Gauge-hatch/sample port				1
Weighted mechanical actuation, gasketed ^b	0.47	0.02	0.97	
Weighted mechanical actuation, ungasketed	2.3	0	0	
Slit fabric seal, 10% open area ^c	12			
Vacuum breaker				N_{vb} (Table 7.1-13) ^j
Weighted mechanical actuation, ungasketed	7.8	0.01	4.0	
Weighted mechanical actuation, gasketed ^b	6.2 ^c	1.2	0.94	

Table 7.1-12 (cont.).

Fitting Type And Construction Details	Loss Factors			Typical Number Of Fittings, N_F
	K_{Fa} (lb-mole/yr)	K_{Fb} (lb-mole/(mph) ^m -yr)	m (dimensionless)	
Deck drain (3-inch diameter)				N_d (Table 7.1-13)
Open ^b	1.5	0.21	1.7	
90% closed	1.8	0.14	1.1	
Stub drain (1-inch diameter) ^k	1.2			N_d (Table 7.1-15)
Deck leg (3-inch diameter)				N_l (Table 7.1-15), (Table 7.1-14)
Adjustable, internal floating deck ^c	7.9			
Adjustable, pontoon area - ungasketed ^b	2.0	0.37	0.91	
Adjustable, pontoon area - gasketed	1.3	0.08	0.65	
Adjustable, pontoon area - sock	1.2	0.14	0.65	
Adjustable, center area - ungasketed ^b	0.82	0.53	0.14	
Adjustable, center area - gasketed ^m	0.53	0.11	0.13	
Adjustable, center area - sock ^m	0.49	0.16	0.14	
Adjustable, double-deck roofs	0.82	0.53	0.14	
Fixed	0	0	0	
Rim vent ⁿ				1
Weighted mechanical actuation, ungasketed	0.68	1.8	1.0	
Weighted mechanical actuation, gasketed ^b	0.71	0.10	1.0	
Ladder well				1 ^d
Sliding cover, ungasketed ^c	76			
Sliding cover, gasketed	56			

Note: The deck-fitting loss factors, K_{Fa} , K_{Fb} , and m, may only be used for wind speeds below 15 miles per hour.

^a Reference 5, unless otherwise indicated.

^b If no specific information is available, this value can be assumed to represent the most common or typical deck fitting currently in use for external and domed external floating roof tanks.

^c If no specific information is available, this value can be assumed to represent the most common or typical deck fitting currently in use for internal floating roof tanks.

^d Column wells and ladder wells are not typically used with self supported fixed roofs.

^e References 16,19.

^f A slotted guide-pole/sample well is an optional fitting and is not typically used.

^g Tests were conducted with floats positioned with the float wiper at and 1 inch above the sliding cover. The user is cautioned against applying these factors to floats that are positioned with the wiper or top of the float below the sliding cover ("short floats"). The emission factor for such a float is expected to be between the factors for a guidepole without a float and with a float, depending upon the position of the float top and/or wiper within the guidepole.

^h Tests were conducted with floats positioned with the float wiper at varying heights with respect to the sliding cover. This fitting configuration also includes a pole sleeve which restricts the airflow from the well vapor space into the slotted guidepole. Consequently, the float position within the guidepole (at, above, or below the sliding cover) is not expected to significantly affect emission levels for this fitting configuration, since the function of the pole sleeve is to restrict the flow of vapor from the vapor space below the deck into the guidepole.

^j $N_{vb} = 1$ for internal floating roof tanks.

^k Stub drains are not used on welded contact internal floating decks.

^m These loss factors were derived using the results from pontoon-area deck legs with gaskets and socks.

ⁿ Rim vents are used only with mechanical-shoe primary seals.

Table 7.1-13. EXTERNAL FLOATING ROOF TANKS: TYPICAL NUMBER OF VACUUM BREAKERS, N_{vb} , AND DECK DRAINS, N_d ^a

Tank Diameter D (feet) ^b	Number Of Vacuum Breakers, N_{vb}		Number Of Deck drains, N_d
	Pontoon Roof	Double-Deck Roof	
50	1	1	1
100	1	1	1
150	2	2	2
200	3	2	3
250	4	3	5
300	5	3	7
350	6	4	ND
400	7	4	ND

^a Reference 3. This table was derived from a survey of users and manufacturers. The actual number of vacuum breakers may vary greatly depending on throughput and manufacturing prerogatives. The actual number of deck drains may also vary greatly depending on the design rainfall and manufacturing prerogatives. For tanks more than 350 feet in diameter, actual tank data or the manufacturer's recommendations may be needed for the number of deck drains. This table should not be used when actual tank data are available. ND = no data.

^b If the actual diameter is between the diameters listed, the closest diameter listed should be used. If the actual diameter is midway between the diameters listed, the next larger diameter should be used.

Table 7.1-14. EXTERNAL FLOATING ROOF TANKS: TYPICAL NUMBER OF ROOF LEGS, N_l^a

Tank Diameter, D (feet) ^b	Pontoon Roof		Number Of Legs On Double-Deck Roof
	Number Of Pontoon Legs	Number Of Center Legs	
30	4	2	6
40	4	4	7
50	6	6	8
60	9	7	10
70	13	9	13
80	15	10	16
90	16	12	20
100	17	16	25
110	18	20	29
120	19	24	34
130	20	28	40
140	21	33	46
150	23	38	52
160	26	42	58
170	27	49	66
180	28	56	74
190	29	62	82
200	30	69	90
210	31	77	98
220	32	83	107
230	33	92	115
240	34	101	127
250	35	109	138
260	36	118	149
270	36	128	162
280	37	138	173
290	38	148	186
300	38	156	200
310	39	168	213
320	39	179	226
330	40	190	240
340	41	202	255
350	42	213	270
360	44	226	285
370	45	238	300
380	46	252	315
390	47	266	330
400	48	281	345

^a Reference 3. This table was derived from a survey of users and manufacturers. The actual number of roof legs may vary greatly depending on age, style of floating roof, loading specifications, and manufacturing prerogatives. This table should not be used when actual tank data are available.

^b If the actual diameter is between the diameters listed, the closest diameter listed should be used. If the actual diameter is midway between the diameters listed, the next larger diameter should be used.

Table 7.1-15. INTERNAL FLOATING ROOF TANKS: TYPICAL NUMBER OF DECK LEGS, N_1 , AND STUB DRAINS, N_d^a

Deck fitting type	Typical Number Of Fittings, N_F
Deck leg or hanger well ^b	$(5 + \frac{D}{10} + \frac{D^2}{600})$
Stub drain (1-inch diameter) ^{b,c}	$(\frac{D^2}{125})$

^a Reference 4

^b D = tank diameter, ft

^c Not used on welded contact internal floating decks.

Table 7.1-16. DECK SEAM LENGTH FACTORS (S_D) FOR TYPICAL DECK CONSTRUCTIONS FOR INTERNAL FLOATING ROOF TANKS^a

Deck Construction	Typical Deck Seam Length Factor, S_D (ft/ft ²)
Continuous sheet construction ^b	
5 ft wide	0.20 ^c
6 ft wide	0.17
7 ft wide	0.14
Panel construction ^d	
5 x 7.5 ft rectangular	0.33
5 x 12 ft rectangular	0.28

^a Reference 4. Deck seam loss applies to bolted decks only.

^b $S_D = 1/W$, where W = sheet width (ft).

^c If no specific information is available, this value can be assumed to represent the most common bolted decks currently in use.

^d $S_D = (L+W)/LW$, where W = panel width (ft) and L = panel length (ft).

7.1.5 Sample Calculations

Example 1 - Chemical Mixture in a Fixed Roof Tank

Determine the yearly emission rate of the total product mixture and each component for a chemical mixture stored in a vertical cone roof tank in Denver, Colorado. The chemical mixture contains (for every 3,171 lb of mixture) 2,812 lb of benzene, 258 lb of toluene, and 101 lb of cyclohexane. The tank is 6 ft in diameter, 12 ft high, usually holds about 8 ft of product, and is painted white. The tank working volume is 1,690 gallons. The number of turnovers per year for the tank is five (i. e., the throughput of the tank is 8,450 gal/yr).

Solution

1. Determine tank type. The tank is a fixed-cone roof, vertical tank.
2. Determine estimating methodology. The product is made up of three organic liquids, all of which are miscible in each other, which makes a homogenous mixture if the material is well mixed. The tank emission rate will be based upon the properties of the mixture. Raoult's Law (as discussed in the HAP Speciation Section) is assumed to apply to the mixture and will be used to determine the properties of the mixture.
3. Select equations to be used. For a vertical, fixed roof storage tank, the following equations apply:

$$L_T = L_S + L_W \quad (1-1)$$

$$L_S = 365 W_V V_V K_E K_S \quad (1-2)$$

$$L_W = 0.0010 M_V P_{VA} Q K_N K_P \quad (1-23)$$

where:

L_T = total loss, lb/yr

L_S = standing storage loss, lb/yr

L_W = working loss, lb/yr

V_V = tank vapor space volume, ft³

$$V_V = \pi/4 D^2 H_{VO} \quad (1-3)$$

W_V = vapor density, lb/ft³

$$W_V = \frac{M_V P_{VA}}{RT_{LA}} \quad (1-9)$$

K_E = vapor space expansion factor, dimensionless

$$K_E = \frac{\Delta T_V}{T_{LA}} + \frac{\Delta P_V - \Delta P_B}{P_A - P_{VA}} \quad (1-16)$$

K_S = vented vapor space saturation factor, dimensionless

$$K_S = \frac{1}{1 + 0.053 P_{VA} H_{VO}} \quad (1-22)$$

D = diameter, ft

H_{VO} = vapor space outage, ft

M_V = molecular weight of vapor, lb/lb-mole

P_{VA} = vapor pressure at the daily average liquid surface temperature, psia

$$R = \text{ideal gas constant} = \frac{10.731 \text{ psia} \cdot \text{ft}^3}{\text{lb-mole} \cdot ^\circ\text{R}}$$

T_{LA} = daily average liquid surface temperature, °R

ΔT_V = daily vapor temperature range, °R

ΔP_V = daily vapor pressure range, psia

ΔP_B = breather vent pressure setting range, psi

P_A = atmospheric pressure, psia

Q = annual net throughput, bbl/yr

K_N = working loss turnover factor, dimensionless

K_P = working loss product factor, dimensionless

4. Calculate each component of the standing storage loss and working loss functions.

a. Tank vapor space volume, V_V :

$$V_V = \pi/4 D^2 H_{VO} \quad (1-3)$$

D = 6 ft (given)

For a cone roof, the vapor space outage, H_{VO} is calculated by:

$$H_{VO} = H_S - H_L + H_{RO} \quad (1-4)$$

H_S = tank shell height, 12 ft (given)

H_L = stock liquid height, 8 ft (given)

$$H_{RO} = \text{roof outage, } 1/3 H_R = 1/3(S_R)(R_S) \quad (1-6)$$

S_R = tank cone roof slope, 0.0625 ft/ft (given) (see Note 1 to Equation 1-4)

R_S = tank shell radius = $1/2 D = 1/2 (6) = 3$

Substituting values in Equation 1-6 yields,

$$H_{RO} = \frac{1}{3} (0.0625)(3) = 0.0625 \text{ ft}$$

Then use Equation 1-4 to calculate H_{VO} ,

$$H_{VO} = 12 - 8 + 0.0625 = 4.0625 \text{ ft}$$

Therefore,

$$V_V = \frac{\pi}{4} (6)^2 (4.0625) = 114.86 \text{ ft}^3$$

b. Vapor density, W_V :

$$W_V = \frac{M_V P_{VA}}{R T_{LA}} \quad (1-9)$$

R = ideal gas constant = $10.731 \frac{\text{psia} \cdot \text{ft}^3}{\text{lb-mole} \cdot ^\circ\text{R}}$

M_V = stock vapor molecular weight, lb/lb-mole

P_{VA} = stock vapor pressure at the daily average liquid surface temperature, psia

T_{LA} = daily average liquid surface temperature, $^\circ\text{R}$

First, calculate T_{LA} using Equation 1-13.

$$T_{LA} = 0.44 T_{AA} + 0.56 T_B + 0.0079 \alpha I \quad (1-13)$$

where:

T_{AA} = daily average ambient temperature, °R

T_B = liquid bulk temperature, °R

I = daily total solar insolation, Btu/ft²·d = 1,568 (see Table 7.1-7)

α = tank paint solar absorptance = 0.17 (see Table 7.1-6)

T_{AA} and T_B must be calculated from Equations 1-14 and 1-15.

$$T_{AA} = \frac{T_{AX} + T_{AN}}{2} \quad (1-14)$$

from Table 7.1-7, for Denver, Colorado:

T_{AX} = daily maximum ambient temperature = 64.3°F

T_{AN} = daily minimum ambient temperature = 36.2°F

Converting to °R:

$T_{AX} = 64.3 + 460 = 524.3^\circ\text{R}$

$T_{AN} = 36.2 + 460 = 496.2^\circ\text{R}$

Therefore,

$T_{AA} = (524.3 + 496.2)/2 = 510.25^\circ\text{R}$

$T_B = \text{liquid bulk temperature} = T_{AA} + 6\alpha - 1 \quad (1-15)$

$T_{AA} = 510.25^\circ\text{R}$ from previous calculation

α = paint solar absorptance = 0.17 (see Table 7.1-6)

I = daily total solar insolation on a horizontal surface = 1,568 Btu/ft²·d (see Table 7.1-7)

Substituting values in Equation 1-15

$T_B = 510.25 + 6(0.17) - 1 = 510.27^\circ\text{R}$

Using Equation 1-13,

$T_{LA} = (0.44)(510.25^\circ\text{R}) + 0.56(510.27^\circ\text{R}) + 0.0079(0.17)(1,568) = 512.36^\circ\text{R}$

Second, calculate P_{VA} using Raoult's Law.

According to Raoult's Law, the partial pressure of a component is the product of its pure vapor pressure and its liquid mole fraction. The sum of the partial pressures is equal to the total vapor pressure of the component mixture stock.

The pure vapor pressures for benzene, toluene, and cyclohexane can be calculated from Antoine's equation. Table 7.1-5 provides the Antoine's coefficients for benzene, which are $A = 6.905$, $B = 1,211.033$, and $C = 220.79$. For toluene, $A = 6.954$, $B = 1,344.8$, and $C = 219.48$. For cyclohexane, $A = 6.841$, $B = 1,201.53$, and $C = 222.65$. Therefore:

$$\log P = A - \frac{B}{T + C}$$

$$T_{LA}, \text{ average liquid surface temperature } (^{\circ}\text{C}) = (512.36 - 492)/1.8 = 11$$

For benzene,

$$\log P = 6.905 - \frac{1,211.033}{(11^{\circ}\text{C} + 220.79)}$$

$$P = 47.90 \text{ mmHg} = 0.926 \text{ psia}$$

Similarly for toluene and cyclohexane,

$$P = 0.255 \text{ psia for toluene}$$

$$P = 0.966 \text{ psia for cyclohexane}$$

In order to calculate the mixture vapor pressure, the partial pressures need to be calculated for each component. The partial pressure is the product of the pure vapor pressures of each component (calculated above) and the mole fractions of each component in the liquid.

The mole fractions of each component are calculated as follows:

Component	Amount, lb	$\div M_i$	Moles	x_i
Benzene	2,812	78.1	36.0	0.90
Toluene	258	92.1	2.80	0.07
Cyclohexane	101	84.2	1.20	0.03
Total			40.0	1.00

where:

M_i = molecular weight of component

x_i = liquid mole fraction

The partial pressures of the components can then be calculated by multiplying the pure vapor pressure by the liquid mole fraction as follows:

Component	P at 52°F	x_i	P_{partial}
Benzene	0.926	0.90	0.833
Toluene	0.255	0.07	0.018
Cyclohexane	0.966	0.03	0.029
Total		1.0	0.880

The vapor pressure of the mixture is then 0.880 psia.

Third, calculate the molecular weight of the vapor, M_V . Molecular weight of the vapor depends upon the mole fractions of the components in the vapor.

$$M_V = \sum M_i y_i$$

where:

M_i = molecular weight of the component

y_i = vapor mole fraction

The vapor mole fractions, y_i , are equal to the partial pressure of the component divided by the total vapor pressure of the mixture.

Therefore,

$$y_{\text{benzene}} = P_{\text{partial}}/P_{\text{total}} = 0.833/0.880 = 0.947$$

Similarly, for toluene and cyclohexane,

$$y_{\text{toluene}} = P_{\text{partial}}/P_{\text{total}} = 0.020$$

$$y_{\text{cyclohexane}} = P_{\text{partial}}/P_{\text{total}} = 0.033$$

The mole fractions of the vapor components sum to 1.0.

The molecular weight of the vapor can be calculated as follows:

Component	M_i	y_i	M_V
Benzene	78.1	0.947	74.0
Toluene	92.1	0.020	1.84
Cyclohexane	84.2	0.033	2.78
Total		1.0	78.6

Since all variables have now been solved, the stock density, W_V , can be calculated:

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

$$\frac{(78.6) (0.880)}{(10.731) (512.36)} = 1.26 \times 10^{-2} \frac{\text{lb}}{\text{ft}^3}$$

c. Vapor space expansion factor, K_E :

$$K_E = \frac{\Delta T_V}{T_{LA}} + \frac{\Delta P_V - \Delta P_B}{P_A - P_{VA}} \quad (1-16)$$

where:

ΔT_V = daily vapor temperature range, °R

ΔP_V = daily vapor pressure range, °R

ΔP_B = breather vent pressure setting range, psia

P_A = atmospheric pressure, 14.7 psia (given)

P_{VA} = vapor pressure at daily average liquid surface temperature, psia = 0.880 psia (from Step 4b)

T_{LA} = daily average liquid surface temperature, °R = 512.36°R (from Step 4b)

First, calculate the daily vapor temperature range from Equation 1-17:

$$\Delta T_V = 0.72 \Delta T_A + 0.028 \alpha I \quad (1-17)$$

where:

ΔT_V = daily vapor temperature range, °R

ΔT_A = daily ambient temperature range = $T_{AX} - T_{AN}$

α = tank paint solar absorptance, 0.17 (given)

I = daily total solar insolation, 1,568 Btu/ft²·d (given)

from Table 7.1-7, for Denver, Colorado:

$T_{AX} = 64.3^\circ\text{F}$

$T_{AN} = 36.2^\circ\text{F}$

Converting to °R,

$$T_{AX} = 64.3 + 460 = 524.3^{\circ}\text{R}$$

$$T_{AN} = 36.2 + 460 = 496.2^{\circ}\text{R}$$

From equation 1-17 and $\Delta T_{AX} = T_{AX} - T_{AN}$

$$\Delta T_A = 524.3 - 496.2 = 28.1^{\circ}\text{R}$$

Therefore,

$$\Delta T_V = 0.72 (28.1) + (0.028)(0.17)(1568) = 27.7^{\circ}\text{R}$$

Second, calculate the daily vapor pressure range using Equation 1-18:

$$\Delta P_V = P_{VX} - P_{VN} \quad (1-18)$$

P_{VX}, P_{VN} = vapor pressures at the daily maximum, minimum liquid temperatures can be calculated in a manner similar to the P_{VA} calculation shown earlier.

$$T_{LX} = \text{maximum liquid temperature, } T_{LA} + 0.25 \Delta T_V \text{ (from Figure 7.1-17)}$$

$$T_{LN} = \text{minimum liquid temperature, } T_{LA} - 0.25 \Delta T_V \text{ (from Figure 7.1-17)}$$

$$T_{LA} = 512.36 \text{ (from Step 4b)}$$

$$\Delta T_V = 27.7^{\circ}\text{R}$$

$$T_{LX} = 512.36 + (0.25) (27.7) = 519.3^{\circ}\text{R or } 59^{\circ}\text{F}$$

$$T_{LN} = 512.36 - (0.25) (27.7) = 505.4^{\circ}\text{R or } 45^{\circ}\text{F}$$

Using Antoine's equation, the pure vapor pressures of each component at the minimum liquid surface temperature are:

$$P_{\text{benzene}} = 0.758 \text{ psia}$$

$$P_{\text{toluene}} = 0.203 \text{ psia}$$

$$P_{\text{cyclohexane}} = 0.794 \text{ psia}$$

The partial pressures for each component at T_{LN} can then be calculated as follows:

Component	P at 45°F	x_i	P_{partial}
Benzene	0.758	0.90	0.68
Toluene	0.203	0.07	0.01
Cyclohexane	0.794	0.03	0.02
Total		1.0	0.71

Using Antoine's equation, the pure vapor pressures of each component at the maximum liquid surface temperature are:

$$P_{\text{benzene}} = 1.14 \text{ psia}$$

$$P_{\text{toluene}} = 0.32 \text{ psia}$$

$$P_{\text{cyclohexane}} = 1.18 \text{ psia}$$

The partial pressures for each component at T_{LX} can then be calculated as follows:

Component	P	x_i	P_{partial}
Benzene	1.14	0.90	1.03
Toluene	0.32	0.07	0.02
Cyclohexane	1.18	0.03	0.04
Total		1.0	1.09

Therefore, the vapor pressure range, $\Delta P_V = P_{LX} - P_{LN} = 1.09 - 0.710 = 0.38 \text{ psia}$.

Next, calculate the breather vent pressure, ΔP_B , from Equation 1-20:

$$\Delta P_B = P_{BP} - P_{BV} \quad (1-20)$$

where:

$$P_{BP} = \text{breather vent pressure setting} = 0.03 \text{ psia (given) (see Note 3 to Equation 1-16)}$$

$$P_{BV} = \text{breather vent vacuum setting} = -0.03 \text{ psig (given) (see Note 3 to Equation 1-16)}$$

$$\Delta P_B = 0.03 - (-0.03) = 0.06 \text{ psig}$$

Finally, K_E , can be calculated by substituting values into Equation 1-16.

$$K_E = \frac{(27.7)}{(512.36)} + \frac{0.38 - 0.06 \text{ psia}}{14.7 \text{ psia} - 0.880 \text{ psia}} = 0.077$$

d. Vented vapor space saturation factor, K_S :

$$K_S = \frac{1}{1 + 0.053 P_{VA} H_{VO}} \quad (1-22)$$

where:

$$P_{VA} = 0.880 \text{ psia (from Step 4b)}$$

$$H_{VO} = 4.0625 \text{ ft (from Step 4a)}$$

$$K_S = \frac{1}{1 + 0.053(0.880)(4.0625)} = 0.841$$

5. Calculate standing storage losses.

$$L_S = 365 W_V V_V K_E K_S$$

Using the values calculated above:

$$W_V = 1.26 \times 10^{-2} \frac{\text{lb}}{\text{ft}^3} \text{ (from Step 4b)}$$

$$V_V = 114.86 \text{ ft}^3 \text{ (from Step 4a)}$$

$$K_E = 0.077 \text{ (from Step 4c)}$$

$$K_S = 0.841 \text{ (from Step 4d)}$$

$$L_S = 365 (1.26 \times 10^{-2})(114.86)(0.077)(0.841) = 34.2 \text{ lb/yr}$$

6. Calculate working losses.

The amount of VOCs emitted as a result of filling operations can be calculated from the following equation:

$$L_W = (0.0010) (M_V)(P_{VA})(Q)(K_N)(K_P) \quad (1-23)$$

From Step 4:

$$M_V = 78.6 \text{ (from Step 4b)}$$

$$P_{VA} = 0.880 \text{ psia (from Step 4b)}$$

$$Q = 8,450 \text{ gal/yr} \times 2.381 \text{ bbl/100 gal} = 201 \text{ bbl/yr (given)}$$

$$K_P = \text{product factor, dimensionless} = 1 \text{ for volatile organic liquids, } 0.75 \text{ for crude oils}$$

$$K_N = 1 \text{ for turnovers} \leq 36 \text{ (given)}$$

$$N = \text{turnovers per year} = 5 \text{ (given)}$$

$$L_W = (0.0010)(78.6)(0.880)(201)(1)(1) = 13.9 \text{ lb/yr}$$

7. Calculate total losses, L_T .

$$L_T = L_S + L_W$$

where:

$$L_S = 34.2 \text{ lb/yr}$$

$$L_W = 13.9 \text{ lb/yr}$$

$$L_T = 34.7 + 13.9 = 48.1 \text{ lb/yr}$$

8. Calculate the amount of each component emitted from the tank.

The amount of each component emitted is equal to the weight fraction of the component in the vapor times the amount of total VOC emitted. Assuming 100 moles of vapor are present, the number of moles of each component will be equal to the mole fraction multiplied by 100. This assumption is valid regardless of the actual number of moles present. The vapor mole fractions were determined in Step 4b. The weight of a component present in a mixture is equal to the product of the number of moles and molecular weight, M_i , of the component. The weight fraction of each component is calculated as follows:

$$\text{Weight fraction} = \frac{\text{pounds}_i}{\text{total pounds}}$$

Therefore,

Component	No. of moles \times	M_i	= Pounds _i	Weight fraction
Benzene	$(0.947 \times 100) = 94.7$	78.1	7,396	0.94
Toluene	$(0.02 \times 100) = 2.0$	92.1	184	0.02
Cyclohexane	$(0.033 \times 100) = 3.3$	84.3	278	0.04
Total	100		7,858	1.0

The amount of each component emitted is then calculated as:

$$\text{Emissions of component}_i = (\text{weight fraction}_i)(L_T)$$

Component	Weight fraction \times	Total VOC emitted, lb/yr	= Emissions, lb/yr
Benzene	0.94	48.1	45.2
Toluene	0.02	48.1	0.96
Cyclohexane	0.04	48.1	1.92
Total			48.1

Example 2 - Chemical Mixture in a Horizontal Tank - Assuming that the tank mentioned in Example 1 is now horizontal, calculate emissions. (Tank diameter is 6 ft and length is 12 ft.)

Solution:

Emissions from horizontal tanks can be calculated by adjusting parameters in the fixed roof equations. Specifically, an effective diameter, D_E , is used in place of the tank diameter, D . The vapor space height, H_{VO} , is assumed to be half the actual tank diameter.

1. Horizontal tank adjustments. Make adjustments to horizontal tank values so that fixed roof tank equations can be used. The effective diameter, D_E , is calculated as follows:

$$D_E = \sqrt{\frac{DL}{0.785}}$$
$$D_E = \sqrt{\frac{(6)(12)}{0.785}} = 9.577 \text{ ft}$$

The vapor space height, H_{VO} is calculated as follows:

$$H_{VO} = 1/2 D = 1/2 (6) = 3 \text{ ft}$$

2. Given the above adjustments the standing storage loss, L_S , can be calculated.

Calculate values for each effected variable in the standing loss equation.

$$L_S = 365 V_V W_V K_E K_S$$

V_V and K_S depend on the effective tank diameter, D_E , and vapor space height, H_{VO} .

These variables can be calculated using the values derived in Step 1:

$$V_V = \frac{\pi}{4} (D_E)^2 H_{VO}$$

$$V_V = \frac{\pi}{4} (9.577)^2 (3) = 216.10 \text{ ft}^3$$

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

$$K_S = \frac{1}{1 + (0.053) (0.880) (3)} = 0.877$$

3. Calculate standing storage loss using the values calculated in Step 2.

$$L_S = 365 V_V W_V K_E K_S$$

$$V_V = 216.10 \text{ ft}^3 \text{ (from Step 2)}$$

$$W_V = 1.26 \times 10^{-2} \text{ lb/ft}^3 \text{ (from Step 4b, example 1)}$$

$$K_E = 0.077 \text{ (from Step 4c, example 1)}$$

$$K_S = 0.877 \text{ (from Step 2)}$$

$$L_S = (365)(1.26 \times 10^{-2})(216.10)(0.077)(0.877)$$

$$L_S = 67.1 \text{ lb/yr}$$

4. Calculate working loss. Since the parameters for working loss do not depend on diameter or vapor space height, the working loss for a horizontal tank of the same capacity as the tank in Example 1 will be the same.

$$L_W = 13.9 \text{ lb/yr}$$

5. Calculate total emissions.

$$L_T = L_S + L_W$$

$$L_T = 67.1 + 13.9 = 81 \text{ lb/yr}$$

Example 3 - Chemical Mixture in an External Floating Roof Tank - Determine the yearly emission rate of a mixture that is 75 percent benzene, 15 percent toluene, and 10 percent cyclohexane, by weight, from a 100,000-gallon external floating roof tank with a pontoon roof. The tank is 20 feet in diameter. The tank has 10 turnovers per year. The tank has a mechanical shoe seal (primary seal) and a shoe-mounted secondary seal. The tank is made of welded steel and has a light rust covering the inside surface of the shell. The tank shell is painted white, and the tank is located in Newark, New Jersey. The floating deck is equipped with the following fittings: (1) an ungasketed access hatch with an unbolted cover, (2) an unspecified number of ungasketed vacuum breakers with weighted mechanical actuation, and (3) ungasketed gauge hatch/sample ports with weighted mechanical actuation.

Solution:

1. Determine tank type. The tank is an external floating roof storage tank.
2. Determine estimating methodology. The product consists of three organic liquids, all of which are miscible in each other, which make a homogenous mixture if the material is well mixed. The tank emission rate will be based upon the properties of the mixture. Because the components have similar structures and molecular weights, Raoult's Law is assumed to apply to the mixture.
3. Select equations to be used. For an external floating roof tank,

$$L_T = L_{WD} + L_R + L_F + L_D \quad (2-1)$$

$$L_{WD} = (0.943) Q C W_L / D \quad (2-4)$$

$$L_R = (K_{Ra} + K_{Rb} v^n) P^* D M_V K_C \quad (2-2)$$

$$L_F = F_F P^* M_V K_C \quad (2-5)$$

$$L_D = K_D S_D D^2 P^* M_V K_C \quad (2-9)$$

where:

L_T = total loss, lb/yr

L_{WD} = withdrawal loss, lb/yr

L_R = rim seal loss from external floating roof tanks, lb/yr

L_F = deck fitting loss, lb/yr

L_D = deck seam loss, lb/yr = 0 for external floating roof tanks

Q = product average throughput, bbl/yr

C = product withdrawal shell clingage factor, bbl/1,000 ft²; see Table 7.1-10

W_L = density of liquid, lb/gal

D = tank diameter, ft

K_{Ra} = zero wind speed rim seal loss factor, lb-mole/ft·yr; see Table 7.1-8

K_{Rb} = wind speed dependent rim seal loss factor, lb-mole/(mph)ⁿft·yr; see Table 7.1-8

v = average ambient wind speed for the tank site, mph

n = seal wind speed exponent, dimensionless

P^* = the vapor pressure function, dimensionless

$$= (P_{VA}/P_A)/(1 + [1-(P_{VA}/P_A)]^{0.5})^2$$

where:

P_{VA} = the true vapor pressure of the materials stored, psia

P_A = atmospheric pressure, psia = 14.7

M_V = molecular weight of product vapor, lb/lb-mole

K_C = product factor, dimensionless

F_F = the total deck fitting loss factor, lb-mole/yr

$$= \sum_{i=1}^{n_f} (N_{Fi} K_{Fi}) = [(N_{F1} K_{F1}) + (N_{F2} K_{F2}) + \dots + N_{F_{nf}} K_{F_{nf}}]$$

where:

N_{Fi} = number of fittings of a particular type, dimensionless. N_{Fi} is determined for the specific tank or estimated from Tables 7.1-12, 7.1-13, or 7.1-14

K_{Fi} = deck fitting loss factor for a particular type of fitting, lb-mole/yr. K_{Fi} is determined for each fitting type from Equation 2-7 and the loss factors in Table 7.1-12

n_f = number of different types of fittings, dimensionless; $n_f = 3$ (given)

K_D = deck seam loss per unit seam length factor, lb-mole/ft/yr

S_D = deck seam length factor, ft/ft²

4. Identify parameters to be calculated/determined from tables. In this example, the following parameters are not specified: W_L , F_F , C , K_{Ra} , K_{Rb} , v , n , P_{VA} , P^* , M_V , and K_C . The following values are obtained from tables or assumptions:

$K_C = 1.0$ for volatile organic liquids (given in Section 7.1.3.2)

$C = 0.0015 \text{ bbl}/1,000 \text{ ft}^2$ for tanks with light rust (from Table 7.1-10)

$K_{Ra} = 1.6$ (from Table 7.1-8)

$K_{Rb} = 0.3$ (from Table 7.1-8)

$n = 1.6$ (from Table 7.1-8)

Since the wind speed for the actual tank site is not specified, the wind speed for Newark, New Jersey is used:

$v = 10.2 \text{ mph}$ (see Table 7.1-9)

F_F , W_L , P_{VA} , P^* , and M_V still need to be calculated.

F_F is estimated by calculating the individual K_{Fi} and N_{Fi} for each of the three types of deck fittings used in this example. For the ungasketed access hatches with unbolted covers, the K_F value can be calculated using information from Table 7.1-12. For this fitting, $K_{Fa} = 36$, $K_{Fb} = 5.9$, and $m = 1.2$. The value for K_V for external floating roof tanks is 0.7 (see Section 7.1.3, Equation 2-7). There is normally one access hatch. So,

$$\begin{aligned} K_{F\text{access hatch}} &= K_{Fa} + K_{Fb}(K_V v)^m \\ &= 36 + 5.9 [(0.7)(10.2)]^{1.2} \end{aligned}$$

$$K_{F\text{access hatch}} = 98.4 \text{ lb-mole/yr}$$

$$N_{F\text{access hatch}} = 1$$

The number of vacuum breakers can be taken from Table 7.1-13. For a tank with a diameter of 20 feet and a pontoon roof, the typical number of vacuum breakers is one. Table 7.1-12 provides fitting factors for weighted mechanical actuation, ungasketed vacuum breakers when the average wind speed is 10.2 mph. Based on this table, $K_{Fa} = 7.8$, $K_{Fb} = 0.01$, and $m = 4$. So,

$$\begin{aligned} K_{F\text{vacuum breaker}} &= K_{Fa} + K_{Fb}(K_V v)^m \\ K_{F\text{vacuum breaker}} &= 7.8 + 0.01 [(0.7)(10.2)]^4 \end{aligned}$$

$$K_{F\text{vacuum breaker}} = 33.8 \text{ lb-mole/yr}$$

$$N_{F\text{vacuum breaker}} = 1$$

For the ungasketed gauge hatch/sample ports with weighted mechanical actuation, Table 7.1-12 indicates that floating roof tanks normally have only one. This table also indicates that $K_{Fa} = 2.3$, $K_{Fb} = 0$, and $m = 0$. Therefore,

$$K_{F_{\text{gauge hatch/sample port}}} = K_{Fa} + K_{Fb} (K_v v)^m$$

$$K_{F_{\text{gauge hatch/sample port}}} = 2.3 + 0$$

$$K_{F_{\text{gauge hatch/sample port}}} = 2.3 \text{ lb-mole/yr}$$

$$N_{F_{\text{gauge hatch/sample port}}} = 1$$

F_F can be calculated from Equation 2-6:

$$\begin{aligned} F_F &= \sum_{i=1}^3 (K_{F_i})(N_{F_i}) \\ &= (98.4)(1) + (33.8)(1) + (2.3)(1) \\ &= 134.5 \text{ lb-mole/yr} \end{aligned}$$

5. Calculate mole fractions in the liquid. The mole fractions of components in the liquid must be calculated in order to estimate the vapor pressure of the liquid using Raoult's Law. For this example, the weight fractions (given as 75 percent benzene, 15 percent toluene, and 10 percent cyclohexane) of the mixture must be converted to mole fractions. First, assume that there are 1,000 lb of liquid mixture. Using this assumption, the mole fractions calculated will be valid no matter how many pounds of liquid actually are present. The corresponding amount (pounds) of each component is equal to the product of the weight fraction and the assumed total pounds of mixture of 1,000. The number of moles of each component is calculated by dividing the weight of each component by the molecular weight of the component. The mole fraction of each component is equal to the number of moles of each component divided by the total number of moles. For this example the following values are calculated:

Component	Weight fraction	Weight, lb	Molecular weight, M_i , lb/lb-mole	Moles	Mole fraction
Benzene	0.75	750	78.1	9.603	0.773
Toluene	0.15	150	92.1	1.629	0.131
Cyclohexane	0.10	100	84.2	1.188	0.096
Total	1.00	1,000		12.420	1.000

For example, the mole fraction of benzene in the liquid is $9.603/12.420 = 0.773$.

6. Determine the daily average liquid surface temperature. The daily average liquid surface temperature is equal to:

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

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

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

For Newark, New Jersey (see Table 7.1-7):

$$T_{AX} = 62.5^\circ\text{F} = 522.2^\circ\text{R}$$

$$T_{AN} = 45.9^\circ\text{F} = 505.6^\circ\text{R}$$

$$I = 1,165 \text{ Btu/ft}^2\cdot\text{d}$$

From Table 7.1-6, $\alpha = 0.17$

Therefore;

$$T_{AA} = (522.2 + 505.6)/2 = 513.9^\circ\text{R}$$

$$T_B = 513.9^\circ\text{R} + 6(0.17) - 1 = 513.92^\circ\text{R}$$

$$T_{LA} = 0.44(513.9) + 0.56(513.92) + 0.0079(0.17)(1,165)$$

$$= 515.5^\circ\text{R} = 55.8^\circ\text{F} = 56^\circ\text{F}$$

7. Calculate partial pressures and total vapor pressure of the liquid. The vapor pressure of each component at 56°F can be determined using Antoine's equation. Since Raoult's Law is assumed to apply in this example, the partial pressure of each component is the liquid mole fraction (x_i) times the vapor pressure of the component (P).

Component	P at 56°F	x_i	P_{partial}
Benzene	1.04	0.773	0.80
Toluene	0.29	0.131	0.038
Cyclohexane	1.08	0.096	0.104
Totals		1.00	0.942

The total vapor pressure of the mixture is estimated to be 0.942 psia.

8. Calculate mole fractions in the vapor. The mole fractions of the components in the vapor phase are based upon the partial pressure that each component exerts (calculated in Step 7).

So for benzene:

$$y_{\text{benzene}} = P_{\text{partial}}/P_{\text{total}} = 0.80/0.942 = 0.85$$

where:

$$y_{\text{benzene}} = \text{mole fraction of benzene in the vapor}$$

P_{partial} = partial pressure of benzene in the vapor, psia

P_{total} = total vapor pressure of the mixture, psia

Similarly,

$$y_{\text{toluene}} = 0.038/0.942 = 0.040$$

$$y_{\text{cyclohexane}} = 0.104/0.942 = 0.110$$

The vapor phase mole fractions sum to 1.0.

9. Calculate molecular weight of the vapor. The molecular weight of the vapor depends upon the mole fractions of the components in the vapor.

$$M_V = \sum M_i y_i$$

where:

M_V = molecular weight of the vapor, lb/lb-mole

M_i = molecular weight of component i, lb/lb-mole

y_i = mole fraction of component i in the vapor, lb-mole/lb-mole

Component	M_i	y_i	$M_V = \sum (M_i)(y_i)$
Benzene	78.1	0.85	66.39
Toluene	92.1	0.040	3.68
Cyclohexane	84.2	0.110	9.26
Total		1.00	79.3

The molecular weight of the vapor is 79.3 lb/lb-mole.

10. Calculate weight fractions of the vapor. The weight fractions of the vapor are needed to calculate the amount (in pounds) of each component emitted from the tank. The weight fractions are related to the mole fractions calculated in Step 7 and total molecular weight calculated in Step 9:

$$Z_{V_i} = \frac{y_i M_i}{M_V}$$

$$Z_{V_i} = \frac{(0.85)(78.1)}{79.3} = 0.84 \text{ for benzene}$$

$$Z_{V_i} = \frac{(0.040)(92.1)}{79.3} = 0.04 \text{ for toluene}$$

$$Z_{V_i} = \frac{(0.110)(84.2)}{79.3} = 0.12 \text{ for cyclohexane}$$

11. Calculate total VOC emitted from the tank. The total VOC emitted from the tank is calculated using the equations identified in Step 3 and the parameters calculated in Steps 4 through 9.

$$L_T = L_{WD} + L_R + L_F$$

a. Calculate withdrawal losses:

$$L_{WD} = 0.943 \text{ QCW}_L / D$$

where:

$$\begin{aligned} Q &= 100,000 \text{ gal} \times 10 \text{ turnovers/yr (given)} \\ &= 1,000,000 \text{ gal} \times 2.381 \text{ bbl/100 gal} = 23,810 \text{ bbl/yr} \end{aligned}$$

$$C = 0.0015 \text{ bbl/10}^3 \text{ ft}^2 \text{ (from Table 7.1-10)}$$

$$W_L = 1 / [\sum (\text{wt fraction in liquid}) / (\text{liquid component density from Table 7.1-3})]$$

Weight fractions

Benzene = 0.75 (given)
Toluene = 0.15 (given)
Cyclohexane = 0.10 (given)

Liquid densities

Benzene = 7.4 (see Table 7.1-3)
Toluene = 7.3 (see Table 7.1-3)
Cyclohexane = 6.5 (see Table 7.1-3)

$$\begin{aligned} W_L &= 1 / [(0.75/7.4) + (0.15/7.3) + (0.10/6.5)] \\ &= 1 / (0.101 + 0.0205 + 0.0154) \\ &= 1/0.1369 \end{aligned}$$

$$= 7.3 \text{ lb/gal}$$

$$D = 20 \text{ ft (given)}$$

$$L_{WD} = 0.943 \text{ QCW}_L/D$$

$$= [0.943(23,810)(0.0015)(7.3)/20]$$

$$= 12 \text{ lb of VOC/yr from withdrawal losses}$$

b. Calculate rim seal losses:

$$L_R = (K_{Ra} + K_{Rb}v^n)DP^*M_VK_C$$

where:

$$K_{Ra} = 1.6 \text{ (from Step 4)}$$

$$K_{Rb} = 0.3 \text{ (from Step 4)}$$

$$v = 10.2 \text{ mph (from Step 4)}$$

$$n = 1.6 \text{ (from Step 4)}$$

$$K_C = 1 \text{ (from Step 4)}$$

$$P_{VA} = 0.942 \text{ psia (from Step 7) (formula from Step 3)}$$

$$D = 20 \text{ ft}$$

$$P^* = (P_{VA}/P_A)/(1 + [1-(P_{VA}/P_A)]^{0.5})^2$$

$$= (0.942/14.7)/(1+[1-(0.942/14.7)]^{0.5})^2 = 0.017$$

$$M_V = 79.3 \text{ lb/lb-mole (from Step 9)}$$

$$L_R = [(1.6 + (0.3)(10.2)^{1.6}](0.017)(20)(79.3)(1.0)$$

$$= 376 \text{ lb of VOC/yr from rim seal losses}$$

c. Calculate deck fitting losses:

$$L_F = F_F P^* M_V K_C$$

where:

$$F_F = 134.5 \text{ lb-mole/yr (from Step 4)}$$

$$P^* = 0.017$$

$$M_V = 79.3 \text{ lb/lb-mole}$$

$$K_C = 1.0 \text{ (from Step 4)}$$

$$L_F = (134.5)(0.017)(79.3)(1.0)$$

$$= 181 \text{ lb/yr of VOC emitted from deck fitting losses}$$

d. Calculate total losses:

$$L_T = L_{WD} + L_R + L_F$$

$$= 12 + 376 + 181$$

$$= 569 \text{ lb/yr of VOC emitted from tank}$$

12. Calculate amount of each component emitted from the tank. For an external floating roof tank, the individual component losses are determined by Equation 4-2:

$$L_{Ti} = (Z_{Vi})(L_R + L_F) + (Z_{Li})(L_{WD})$$

Therefore,

$$L_{T\text{benzene}} = (0.84)(557) + (0.75)(12) = 477 \text{ lb/yr benzene}$$

$$L_{T\text{toluene}} = (0.040)(557) + (0.15)(12) = 24 \text{ lb/yr toluene}$$

$$L_{T\text{cyclohexane}} = (0.12)(557) + (0.10)(12) = 68 \text{ lb/yr cyclohexane}$$

Example 4 - Gasoline in an Internal Floating Roof Tank - Determine emissions of product from a 1 million gallon, internal floating roof tank containing gasoline (RVP 13). The tank is painted white and is located in Tulsa, Oklahoma. The annual number of turnovers for the tank is 50. The tank is 70 ft in diameter and 35 ft high and is equipped with a liquid-mounted primary seal plus a secondary seal. The tank has a column-supported fixed roof. The tank's deck is welded and equipped with the following: (1) two access hatches with unbolted, ungasketed covers; (2) an automatic gauge float well with an unbolted, ungasketed cover; (3) a pipe column well with a flexible fabric sleeve seal; (4) a sliding cover, gasketed ladder well; (5) adjustable deck legs; (6) a slotted sample pipe well with a gasketed sliding cover; and (7) a weighted, gasketed vacuum breaker.

Solution:

1. Determine tank type. The following information must be known about the tank in order to use the floating roof equations:

- the number of columns
- the effective column diameter
- the rim seal description (vapor- or liquid-mounted, primary or secondary seal)
- the deck fitting types and the deck seam length

Some of this information depends on specific construction details, which may not be known. In these instances, approximate values are provided for use.

2. Determine estimating methodology. Gasoline consists of many organic compounds, all of which are miscible in each other, which form a homogenous mixture. The tank emission rate will be based on the properties of RVP 13 gasoline. Since vapor pressure data have already been compiled, Raoult's Law will not be used. The molecular weight of gasoline also will be taken from a table and will not be calculated. Weight fractions of components will be assumed to be available from SPECIATE data base.

3. Select equations to be used.

$$L_T = L_{WD} + L_R + L_F + L_D \quad (2-1)$$

$$L_{WD} = \frac{(0.943) QCW_L}{D} \left[1 + \left(\frac{N_C F_C}{D} \right) \right] \quad (2-4)$$

$$L_R = (K_{Ra} + K_{Rb} v^n) DP^* M_V K_C \quad (2-2)$$

$$L_F = F_F P^* M_V K_C \quad (2-5)$$

$$L_D = K_D S_D D^2 P^* M_V K_C \quad (2-9)$$

where:

- L_T = total loss, lb/yr
- L_{WD} = withdrawal loss, lb/yr
- L_R = rim seal loss, lb/yr
- L_F = deck fitting loss, lb/yr

L_D = deck seam loss, lb/yr

Q = product average throughput (tank capacity [bbl] times turnovers per year),
bbl/yr

C = product withdrawal shell clingage factor, bbl/1,000 ft²

W_L = density of liquid, lb/gal

D = tank diameter, ft

N_C = number of columns, dimensionless

F_C = effective column diameter, ft

K_{Ra} = zero wind speed rim seal loss factor, lb-mole/ft·yr

K_{Rb} = wind speed dependent rim seal loss factor, lb-mole/(mph)ⁿft·yr

v = average ambient site wind speed (zero for internal floating roof tanks), mph

M_V = the average molecular weight of the product vapor, lb/lb-mole

K_C = the product factor, dimensionless

P^* = the vapor pressure function, dimensionless

$$= (P_{VA}/P_A) / [1 + (1 - (P_{VA}/P_A))^{0.5}]^2$$

and

P_{VA} = the vapor pressure of the material stored, psia

P_A = average atmospheric pressure at tank location, psia

F_F = the total deck fitting loss factor, lb-mole/yr

$$= \sum_{i=1}^{n_f} (N_{F_i} K_{F_i}) = [(N_{F_1} K_{F_1}) + (N_{F_2} K_{F_2}) + \dots + (N_{F_{n_f}} K_{F_{n_f}})]$$

and:

N_{F_i} = number of fittings of a particular type, dimensionless. N_{F_i} is determined
for the specific tank or estimated from Table 7.1-12

K_{F_i} = deck fitting loss factor for a particular type of deck fitting, lb-mole/yr.
 K_{F_i} is determined for each fitting type using Table 7.1-12

n_f = number of different types of fittings, dimensionless

K_D = the deck seam loss factor, lb-mole/ft·yr

= 0.14 for nonwelded decks

= 0 for welded decks

S_D = deck seam length factor, ft/ft²

$$= L_{\text{seam}}/A_{\text{deck}}$$

and:

L_{seam} = total length of deck seams, ft

$$A_{\text{deck}} = \text{area of deck, ft}^2 = \pi D^2/4$$

4. Identify parameters to be calculated or determined from tables. In this example, the following parameters are not specified: N_C , F_C , P , M_V , K_{Ra} , K_{Rb} , v , P^* , K_C , F_F , K_D , and S_D . The density of the liquid (W_L) and the vapor pressure of the liquid (P) can be read from tables and do not need to be calculated. Also, the weight fractions of components in the vapor can be obtained from speciation manuals. Therefore, several steps required in preceding examples will not be required in this example. In each case, if a step is not required, the reason is presented.

The following parameters can be obtained from tables or assumptions:

K_C = 1.0 for volatile organic liquids

N_C = 1 (from Table 7.1-11)

F_C = 1.0 (assumed)

K_{Ra} = 0.3 (from Table 7.1-8)

K_{Rb} = 0.6 (from Table 7.1-8)

v = 0 for internal floating roof tanks

M_V = 62 lb/lb-mole (from Table 7.1-2)

W_L = 5.6 lb/gal (from Table 7.1-2)

C = 0.0015 bbl/1,000 ft² (from Table 7.1-10)

K_D = 0 for welded decks so S_D is not needed

$$F_F = \sum (K_{F_i} N_{F_i})$$

5. Calculate mole fractions in the liquid. This step is not required because liquid mole fractions are only used to calculate liquid vapor pressure, which is given in this example.

6. Calculate the daily average liquid surface temperature. The daily average liquid surface temperature is equal to:

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

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

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

For Tulsa, Oklahoma (see Table 7.1-7):

$$T_{AX} = 71.3^\circ\text{F} = 530.97^\circ\text{R}$$

$$T_{AN} = 49.2^\circ\text{F} = 508.87^\circ\text{R}$$

$$I = 1,373 \text{ Btu/ft}^2\cdot\text{d}$$

From Table 7.1-6, $\alpha = 0.17$

Therefore,

$$T_{AA} = (530.97 + 508.87)/2 = 519.92^\circ\text{R}$$

$$T_B = 519.92 + 6(0.17) - 1 = 519.94^\circ\text{R}$$

$$T_{LA} = 0.44 (519.92) + 0.56 (519.94) + 0.0079(0.17)(1,373)$$

$$T_{LA} = 228.76 + 291.17 + 1.84$$

$$T_{LA} = 521.77^\circ\text{R} \text{ or } 62^\circ\text{F}$$

7. Calculate partial pressures and total vapor pressure of the liquid. The vapor pressure of gasoline RVP 13 can be interpolated from Table 7.1-2. The interpolated vapor pressure at 62°F is equal to 7.18 psia. Therefore,

$$P^* = \frac{P_{VA}/P_A}{[1 + (1 - [P_{VA}/P_A])^{0.5}]^2}$$

$$P^* = (7.18/14.7)/[1 + (1 - (7.18/14.7))^{0.5}]^2$$

$$P^* = 0.166$$

8. Calculate mole fractions of components in the vapor. This step is not required because vapor mole fractions are needed to calculate the weight fractions and the molecular weight of the vapor, which are already specified.

9. Calculate molecular weight of the vapor. This step is not required because the molecular weight of gasoline vapor is already specified.

10. Calculate weight fractions of components of the vapor. The weight fractions of components in gasoline vapor can be obtained from a VOC speciation manual.

11. Calculate total VOC emitted from the tank. The total VOC emitted from the tank is calculated using the equations identified in Step 3 and the parameters specified in Step 4.

$$L_T = L_{WD} + L_R + L_F + L_D$$

a. Calculate withdrawal losses:

$$L_{WD} = [(0.943)QCW_L]/D [1 + (N_C F_C)/D]$$

where:

$$Q = (1,000,000 \text{ gal})(50 \text{ turnovers/yr})$$

$$= (50,000,000 \text{ gal})(2.381 \text{ bbl/100 gal}) = 1,190,500 \text{ bbl/yr}$$

$$C = 0.0015 \text{ bbl/1,000 ft}^2$$

$$W_L = 5.6 \text{ lb/gal}$$

$$D = 70 \text{ ft}$$

$$N_C = 1$$

$$F_C = 1$$

$$L_{WD} = [(0.943)(1,190,500)(0.0015)(5.6)]/70[1 + (1)(1)/70] = 137 \text{ lb/yr VOC for withdrawal losses}$$

b. Calculate rim seal losses:

$$L_R = (K_{Ra} + K_{Rb}v^n)DP^*M_VK_C$$

Since $v = 0$ for IFRT's:

$$L_R = K_{Ra}DP^*M_VK_C$$

where:

$$K_{Ra} = 0.3 \text{ lb-mole/ft}\cdot\text{yr}$$

$$D = 70 \text{ ft}$$

$$P^* = 0.166$$

$$M_V = 62 \text{ lb/lb-mole}$$

$$K_C = 1.0$$

$$L_R = (0.3)(0.166)(70)(62)(1.0) = 216 \text{ lb/yr VOC from rim seals}$$

c. Calculate deck fitting losses:

$$L_F = F_F P^* M_V K_C$$

where:

$$F_F = \sum (K_{F_i} N_{F_i})$$

$K_{F_i} = K_{Fa_i}$ for internal floating roof tanks since the wind speed is zero (see Equation 2-8). Substituting values for K_{Fa_i} taken from Tables 7.1-12 and 7.1-15 for access hatches, gauge float well, pipe column well, ladder well, deck legs, sample pipe well, and vacuum breaker, respectively, yields:

$$F_F = (36)(2) + (14)(1) + (10)(1) + (56)(1) + 7.9[5 + (70/10) + (70^2/600)] + (43.1)(1) + (6.2)(1)$$

$$= 361 \text{ lb-mole/yr}$$

$$P^* = 0.166$$

$$M_V = 62 \text{ lb/lb-mole}$$

$$K_C = 1$$

$$L_F = (361)(0.166)(62)(1.0) = 3,715 \text{ lb/yr VOC from deck fittings}$$

d. Calculate deck seam losses:

$$L_D = K_D S_D D^2 P^* M_V K_C$$

Since $K_D = 0$ for IFRT's with welded decks,

$$L_D = 0 \text{ lb/yr VOC from deck seams}$$

e. Calculate total losses:

$$L_T = L_{WD} + L_R + L_F + L_D$$

$$= 137 + 216 + 3,715 + 0 = 4,068 \text{ lb/yr of VOC emitted from the tank}$$

12. Calculate amount of each component emitted from the tank. The individual component losses are equal to:

$$L_{T_i} = (Z_{V_i})(L_R + L_F + L_D) + (Z_{L_i})(L_{WD})$$

Since the liquid weight fractions are unknown, the individual component losses are calculated based on the vapor weight fraction and the total losses. This procedure should yield approximately the same values as the above equation because withdrawal losses are typically low for floating roof tanks. The amount of each component emitted is the weight fraction of that component in the vapor (obtained from a VOC species data manual and shown below) times the total amount of VOC emitted from the tank. The table below shows the amount emitted for each component in this example.

Constituent	Weight Percent In Vapor	Emissions, lb/yr
Air toxics		
Benzene	0.77	31.3
Toluene	0.66	26.8
Ethylbenzene	0.04	1.6
O-xylene	0.05	2.0
Nontoxics		
Isomers of pentane	26.78	1,089
N-butane	22.95	934
Iso-butane	9.83	400
N-pentane	8.56	348
Isomers of hexane	4.78	194
3-methyl pentane	2.34	95.2
Hexane	1.84	74.9
Others	21.40	871
Total	100	4,068

Source: SPECIATE Data Base Management System, Emission Factor and Inventory Group, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1993.

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8.8 Nitric Acid

8.8.1 General¹⁻²

In 1991, there were approximately 65 nitric acid (HNO₃) manufacturing plants in the U. S. with a total capacity of 11 million tons of HNO₃ per year. The plants range in size from 6,000 to 700,000 tons per year. About 70 percent of the nitric acid produced is consumed as an intermediate in the manufacture of ammonium nitrate (NH₄NO₃), which in turn is used in fertilizers. The majority of the nitric acid plants are located in agricultural regions such as the Midwest, South Central, and Gulf States because of the high demand for fertilizer in these areas. Another 5 to 10 percent of the nitric acid produced is used for organic oxidation in adipic acid manufacturing. Nitric acid is also used in organic oxidation to manufacture terephthalic acid and other organic compounds. Explosive manufacturing utilizes nitric acid for organic nitrations. Nitric acid nitrations are used in producing nitrobenzene, dinitrotoluenes, and other chemical intermediates.¹ Other end uses of nitric acid are gold and silver separation, military munitions, steel and brass pickling, photoengraving, and acidulation of phosphate rock.

8.8.2 Process Description^{1,3-4}

Nitric acid is produced by 2 methods. The first method utilizes oxidation, condensation, and absorption to produce a weak nitric acid. Weak nitric acid can have concentrations ranging from 30 to 70 percent nitric acid. The second method combines dehydrating, bleaching, condensing, and absorption to produce a high-strength nitric acid from a weak nitric acid. High-strength nitric acid generally contains more than 90 percent nitric acid. The following text provides more specific details for each of these processes.

8.8.2.1 Weak Nitric Acid Production^{1,3-4} -

Nearly all the nitric acid produced in the U. S. is manufactured by the high-temperature catalytic oxidation of ammonia as shown schematically in Figure 8.8-1. This process typically consists of 3 steps: (1) ammonia oxidation, (2) nitric oxide oxidation, and (3) absorption. Each step corresponds to a distinct chemical reaction.

Ammonia Oxidation -

First, a 1:9 ammonia/air mixture is oxidized at a temperature of 1380 to 1470°F as it passes through a catalytic convertor, according to the following reaction:



The most commonly used catalyst is made of 90 percent platinum and 10 percent rhodium gauze constructed from squares of fine wire. Under these conditions the oxidation of ammonia to nitric oxide (NO) proceeds in an exothermic reaction with a range of 93 to 98 percent yield. Oxidation temperatures can vary from 1380 to 1650°F. Higher catalyst temperatures increase reaction selectivity toward NO production. Lower catalyst temperatures tend to be more selective toward less useful products: nitrogen (N₂) and nitrous oxide (N₂O). Nitric oxide is considered to be a criteria pollutant and nitrous oxide is known to be a global warming gas. The nitrogen dioxide/dimer mixture then passes through a waste heat boiler and a platinum filter.

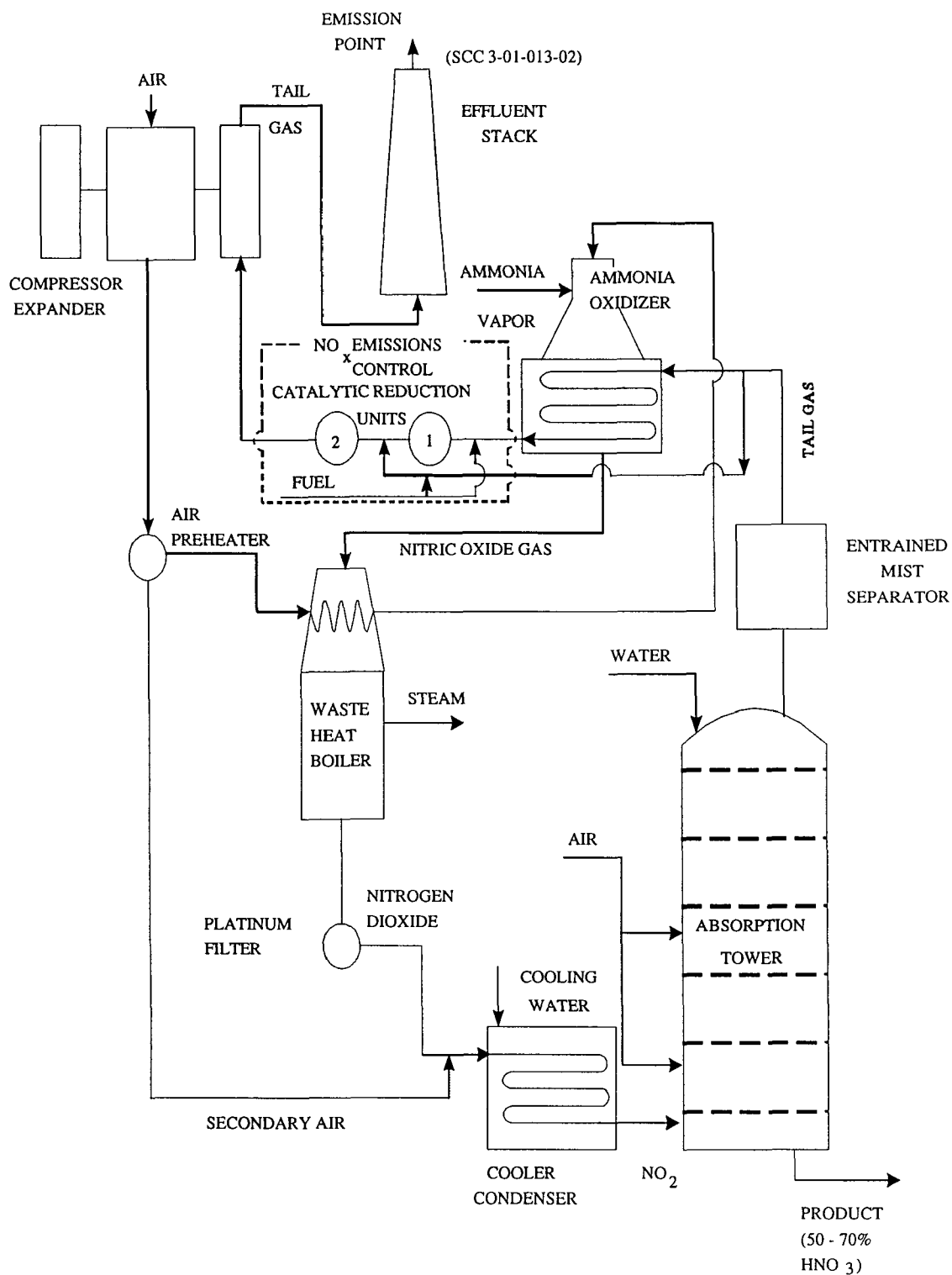


Figure 8.8-1. Flow diagram of typical nitric acid plant using single-pressure process (high-strength acid unit not shown).
(Source Classification Codes in parentheses.)

Nitric Oxide Oxidation -

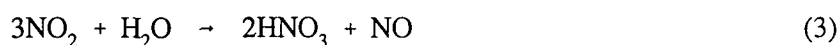
The nitric oxide formed during the ammonia oxidation must be oxidized. The process stream is passed through a cooler/condenser and cooled to 100°F or less at pressures up to 116 pounds per square inch absolute (psia). The nitric oxide reacts noncatalytically with residual oxygen to form nitrogen dioxide (NO₂) and its liquid dimer, nitrogen tetroxide:



This slow, homogeneous reaction is highly temperature- and pressure-dependent. Operating at low temperatures and high pressures promotes maximum production of NO₂ within a minimum reaction time.

Absorption -

The final step introduces the nitrogen dioxide/dimer mixture into an absorption process after being cooled. The mixture is pumped into the bottom of the absorption tower, while liquid dinitrogen tetroxide is added at a higher point. Deionized process water enters the top of the column. Both liquids flow countercurrent to the nitrogen dioxide/dimer gas mixture. Oxidation takes place in the free space between the trays, while absorption occurs on the trays. The absorption trays are usually sieve or bubble cap trays. The exothermic reaction occurs as follows:



A secondary air stream is introduced into the column to re-oxidize the NO that is formed in Reaction 3. This secondary air also removes NO₂ from the product acid. An aqueous solution of 55 to 65 percent (typically) nitric acid is withdrawn from the bottom of the tower. The acid concentration can vary from 30 to 70 percent nitric acid. The acid concentration depends upon the temperature, pressure, number of absorption stages, and concentration of nitrogen oxides entering the absorber.

There are 2 basic types of systems used to produce weak nitric acid: (1) single-stage pressure process, and (2) dual-stage pressure process. In the past, nitric acid plants have been operated at a single pressure, ranging from atmospheric pressure to 14.7 to 203 psia. However, since Reaction 1 is favored by low pressures and Reactions 2 and 3 are favored by higher pressures, newer plants tend to operate a dual-stage pressure system, incorporating a compressor between the ammonia oxidizer and the condenser. The oxidation reaction is carried out at pressures from slightly negative to about 58 psia, and the absorption reactions are carried out at 116 to 203 psia.

In the dual-stage pressure system, the nitric acid formed in the absorber (bottoms) is usually sent to an external bleacher where air is used to remove (bleach) any dissolved oxides of nitrogen. The bleacher gases are then compressed and passed through the absorber. The absorber tail gas (distillate) is sent to an entrainment separator for acid mist removal. Next, the tail gas is reheated in the ammonia oxidation heat exchanger to approximately 392°F. The final step expands the gas in the power-recovery turbine. The thermal energy produced in this turbine can be used to drive the compressor.

8.8.2.2 High-Strength Nitric Acid Production^{1,3} -

A high-strength nitric acid (98 to 99 percent concentration) can be obtained by concentrating the weak nitric acid (30 to 70 percent concentration) using extractive distillation. The weak nitric acid cannot be concentrated by simple fractional distillation. The distillation must be carried out in the presence of a dehydrating agent. Concentrated sulfuric acid (typically 60 percent sulfuric acid) is most commonly used for this purpose. The nitric acid concentration process consists of feeding strong sulfuric acid and 55 to 65 percent nitric acid to the top of a packed dehydrating column at approximately atmospheric pressure. The acid mixture flows downward, countercurrent to ascending vapors. Concentrated nitric acid leaves the top of the column as 99 percent vapor, containing a small amount of NO₂ and oxygen (O₂) resulting from dissociation of nitric acid. The concentrated acid vapor leaves the column and goes to a bleacher and a countercurrent condenser system to effect the condensation of strong nitric acid and the separation of oxygen

and oxides of nitrogen (NO_x) byproducts. These byproducts then flow to an absorption column where the nitric oxide mixes with auxiliary air to form NO_2 , which is recovered as weak nitric acid. Inert and unreacted gases are vented to the atmosphere from the top of the absorption column. Emissions from this process are relatively minor. A small absorber can be used to recover NO_2 . Figure 8.8-2 presents a flow diagram of high-strength nitric acid production from weak nitric acid.

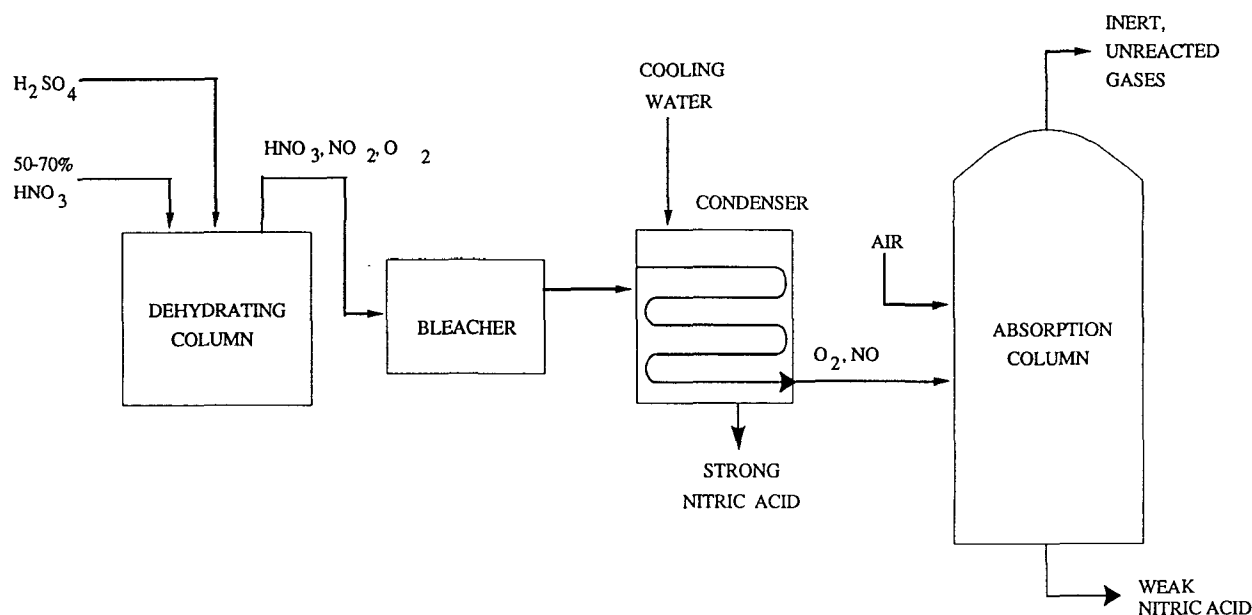


Figure 8.8-2. Flow diagram of high-strength nitric acid production from weak nitric acid.

8.8.3 Emissions And Controls³⁻⁵

Emissions from nitric acid manufacture consist primarily of NO , NO_2 (which account for visible emissions), trace amounts of HNO_3 mist, and ammonia (NH_3). By far, the major source of nitrogen oxides (NO_x) is the tailgas from the acid absorption tower. In general, the quantity of NO_x emissions is directly related to the kinetics of the nitric acid formation reaction and absorption tower design. NO_x emissions can increase when there is (1) insufficient air supply to the oxidizer and absorber, (2) low pressure, especially in the absorber, (3) high temperatures in the cooler-condenser and absorber, (4) production of an excessively high-strength product acid, (5) operation at high throughput rates, and (6) faulty equipment such as compressors or pumps that lead to lower pressures and leaks, and decrease plant efficiency.

The 2 most common techniques used to control absorption tower tail gas emissions are extended absorption and catalytic reduction. Extended absorption reduces NO_x emissions by increasing the efficiency of the existing process absorption tower or incorporating an additional absorption tower. An efficiency increase is achieved by increasing the number of absorber trays, operating the absorber at higher pressures, or cooling the weak acid liquid in the absorber. The existing tower can also be replaced with a single tower of a larger diameter and/or additional trays. See Reference 5 for the relevant equations.

In the catalytic reduction process (often termed catalytic oxidation or incineration), tail gases from the absorption tower are heated to ignition temperature, mixed with fuel (natural gas, hydrogen, propane, butane, naphtha, carbon monoxide, or ammonia) and passed over a catalyst bed. In the presence of the catalyst, the fuels are oxidized and the NO_x are reduced to N_2 . The extent of reduction of NO_2 and NO to N_2 is a function of plant design, fuel type, operating temperature and pressure, space velocity through the

reduction catalytic reactor, type of catalyst, and reactant concentration. Catalytic reduction can be used in conjunction with other NO_x emission controls. Other advantages include the capability to operate at any pressure and the option of heat recovery to provide energy for process compression as well as extra steam. Catalytic reduction can achieve greater NO_x reduction than extended absorption. However, high fuel costs have caused a decline in its use.

Two seldom-used alternative control devices for absorber tailgas are molecular sieves and wet scrubbers. In the molecular sieve adsorption technique, tailgas is contacted with an active molecular sieve that catalytically oxidizes NO to NO_2 and selectively adsorbs the NO_2 . The NO_2 is then thermally stripped from the molecular sieve and returned to the absorber. Molecular sieve adsorption has successfully controlled NO_x emissions in existing plants. However, many new plants elect not to install this method of control because its implementation incurs high capital and energy costs. Molecular sieve adsorption is a cyclic system, whereas most new nitric acid plants are continuous systems. Sieve bed fouling can also cause problems.

Wet scrubbers use an aqueous solution of alkali hydroxides or carbonates, ammonia, urea, potassium permanganate, or caustic chemicals to "scrub" NO_x from the absorber tailgas. The NO and NO_2 are absorbed and recovered as nitrate or nitrate salts. When caustic chemicals are used, the wet scrubber is referred to as a caustic scrubber. Some of the caustic chemicals used are solutions of sodium hydroxide, sodium carbonate, or other strong bases that will absorb NO_x in the form of nitrate or nitrate salts. Although caustic scrubbing can be an effective control device, it is often not used due to its incurred high costs and the necessity of treating its spent scrubbing solution.

Comparatively small amounts of nitrogen oxides are also lost from acid concentrating plants. These losses (mostly NO_2) are from the condenser system, but the emissions are small enough to be controlled easily by inexpensive absorbers.

Acid mist emissions do not occur from the tailgas of a properly operated plant. The small amounts that may be present in the absorber exit gas streams are removed by a separator or collector prior to entering the catalytic reduction unit or expander.

The acid production system and storage tanks are the only significant sources of visible emissions at most nitric acid plants. Emissions from acid storage tanks may occur during tank filling.

Nitrogen oxides and N_2O emission factors shown in Table 8.8-1 vary considerably with the type of control employed and with process conditions. For comparison purposes, the New Source Performance Standard on nitrogen emissions expressed as NO_2 for both new and modified plants is 3.0 pounds of NO_2 emitted per ton (lb/ton) of 100 percent nitric acid produced.

8.8.4 Changes Since July, 1993

- Reformatted for the Fifth Edition, released in January 1995
- Supplement D update (February 1998) - added a N_2O emission factor for weak acid plant tailgas.

Table 8.8-1. NITROGEN OXIDE EMISSIONS FROM
NITRIC ACID PLANTS

EMISSION FACTOR RATING: E

Source	Control Efficiency %	NO _x , lb/ton Nitric Acid Produced ^a	N ₂ O, lb/ton Nitric Acid Produced ^m
Weak acid plant tailgas Uncontrolled ^{b,c}	0	57	11.70
Catalytic reduction ^c			
Natural gas ^d	99.1	0.4	ND
Hydrogen ^e	97 - 98.5	0.8	ND
Natural gas/hydrogen (25%/75%) ^f	98 - 98.5	0.9	ND
Extended absorption			
Single-stage process ^g	95.8	1.9	ND
Dual-stage process ^h		2.1	ND
Chilled absorption and caustic scrubber ^j	ND	2.2	ND
High-strength acid plant ^k	ND	10	ND

^a Assumes 100% acid. Production rates are in terms of total weight of product (water and acid). A plant producing 500 tons per day of 55 weight % nitric acid is calculated as producing 275 tons/day of 100% acid. To convert lb/ton to kg/Mg, multiply by 0.5. ND = no data.

^b Reference 6. Based on a study of 12 plants, with average production rate of 230 tons (100% HNO₃)/day (range 55 - 750 tons) at average rated capacity of 97% (range 72 - 100%).

^c Single-stage pressure process.

^d Reference 4. Fuel is assumed to be natural gas. Based on data from 7 plants, with average production rate of 340 tons (100% HNO₃)/day (range 55 - 1077 tons).

^e Reference 6. Based on data from 2 plants, with average production rate of 160 tons (100% HNO₃)/day (range 120 - 210 tons) at average rated capacity of 98% (range 95 - 100%). Average absorber exit temperature is 85°F (range 78 - 90°F), and the average exit pressure is 85 psig (range 80 - 94 psig).

^f Reference 6. Based on data from 2 plants, with average production rate of 230 tons (100% HNO₃)/day (range 185 - 279 tons) at average rated capacity of 110% (range 100 - 119%). Average absorber exit temperature is 91°F (range 83 - 98°F), and average exit pressure is 79 psig (range 79 - 80 psig).

^g Reference 4. Based on data from 5 plants, with average production rate of 540 tons (100% HNO₃)/day (range 210 - 1050 tons).

^h Reference 4. Based on data from 3 plants, with average production rate of 590 tons (100% HNO₃)/day (range 315 - 940 tons).

^j Reference 4. Based on data from 1 plant, with a production rate of 700 tons (100% HNO₃)/day.

^k Reference 2. Based on data from 1 plant, with a production rate of 1.5 tons (100% HNO₃)/hour at 100% rated capacity, of 98% nitric acid.

^m Reference 7.

References For Section 8.8

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4. Marvin Drabkin, *A Review Of Standards Of Performance For New Stationary Sources — Nitric Acid Plants*, EPA-450/3-79-013, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1979.
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9.9.1 Grain Elevators And Processes

9.9.1.1 Process Description¹⁻¹⁴

Grain elevators are facilities at which grains are received, stored, and then distributed for direct use, process manufacturing, or export. They can be classified as either "country" or "terminal" elevators, with terminal elevators further categorized as inland or export types. Operations other than storage, such as cleaning, drying, and blending, often are performed at elevators. The principal grains and oilseeds handled include wheat, corn, oats, rice, soybeans, and sorghum.

Country elevators are generally smaller elevators that receive grain by truck directly from farms during the harvest season. These elevators sometimes clean or dry grain before it is transported to terminal elevators or processors. Terminal elevators dry, clean, blend, and store grain before shipment to other terminals or processors, or for export. These elevators may receive grain by truck, rail, or barge, and generally have greater grain handling and storage capacities than do country elevators. Export elevators are terminal elevators that load grain primarily onto ships for export.

Regardless of whether the elevator is a country or terminal, there are two basic types of elevator design: traditional and modern. Traditional grain elevators are typically designed so the majority of the grain handling equipment (e.g., conveyors, legs, scales, cleaners) are located inside a building or structure, normally referred to as a headhouse. The traditional elevator often employs belt conveyors with a movable tripper to transfer the grain to storage in concrete or steel silos. The belt and tripper combination is located above the silos in an enclosed structure called the gallery or bin deck. Grain is often transported from storage using belt conveyors located in an enclosed tunnel beneath the silos. Particulate emissions inside the elevator structure may be controlled using equipment such as cyclones, fabric filters, dust covers, or belt wipers; grain may be oil treated to reduce emissions. Controls are often used at unloading and loading areas and may include cyclones, fabric filters, baffles in unloading pits, choke unloading, and use of deadboxes or specially designed spouts for grain loading. The operations of traditional elevators are described in more detail in Section 2.2.1. Traditional elevator design is generally associated with facilities built prior to 1980.

Country and terminal elevators built in recent years have moved away from the design of the traditional elevators. The basic operations performed at the elevators are the same; only the elevator design has changed. Most modern elevators have eliminated the enclosed headhouse and gallery (bin decks). They employ a more open structural design, which includes locating some equipment such as legs, conveyors, cleaners, and scales, outside of an enclosed structure. In some cases, cleaners and screens may be located in separate buildings. The grain is moved from the unloading area using enclosed belt or drag conveyors and, if feasible, the movable tripper has been replaced with enclosed distributors or turn-heads for direct spouting into storage bins and tanks. The modern elevators are also more automated, make more use of computers, and are less labor-intensive. Some traditional elevators have also been partially retrofitted or redesigned to incorporate enclosed outside legs, conveyors, cleaners, and other equipment. Other techniques used to reduce emissions include deepening the trough of the open-belt conveyors and slowing the conveyor speed, and increasing the size of leg belt buckets and slowing leg velocity. At loading and unloading areas of modern elevators, the controls cited above for traditional elevators can also be used to reduce emissions.

The first step at a grain elevator is the unloading of the incoming truck, railcar, or barge. A truck or railcar discharges its grain into a hopper, from which the grain is conveyed to the main part of the elevator. Barges are unloaded by a bucket elevator (marine leg) that is extended down into the barge hold or by cranes using clam shell buckets. The main building at an elevator, where grain is elevated and distributed, is called

the "headhouse". In the headhouse, grain is lifted on one of the elevator legs and is typically discharged onto the gallery belt, which conveys the grain to the storage bins. A "tripper" diverts grain off the belt and into the desired bin. Other modes of transfer include augers and screw conveyors. Grain is often cleaned, dried, and cooled for storage. Once in storage, grain may be transferred one or more times to different storage bins or may be emptied from a bin, treated or dried, and stored in the same or a different bin. For shipping, grain is discharged from bins onto the tunnel belt below, which conveys it to the scale garner and to the desired loadout location (possibly through a surge bin). Figure 9.9.1-1 presents the major process operations at a grain elevator.

A grain processing plant or mill receives grain from an elevator and performs various manufacturing steps that produce a finished food product. The grain receiving and handling operations at processing plants and mills are basically the same as at grain elevators. Examples of processing plants are flour mills, oat mills, rice mills, dry corn mills, and animal feed mills. The following subsections describe the processing of the principal grains. Additional information on grain processing may be found in AP-42 Section 9.9.2, Cereal Breakfast Food, and AP-42 Section 9.9.7, Corn Wet Milling.

9.9.1.1.1 Flour Milling^{2,5} -

Most flour mills produce wheat flour, but durum wheat and rye are also processed in flour mills. The wheat flour milling process consists of 5 main steps: (1) grain reception, preliminary cleaning, and storage; (2) grain cleaning; (3) tempering or conditioning; (4) milling the grain into flour and its byproducts; and (5) storage and/or shipment of finished product. A simplified diagram of a typical flour mill is shown in Figure 9.9.1-2. Wheat arrives at a mill and, after preliminary cleaning, is conveyed to storage bins. As grain is needed for milling, it is withdrawn and conveyed to the mill area where it first enters a separator (a vibrating screen), then, an aspirator to remove dust and lighter impurities, and then passes over a magnetic separator to remove iron and steel particles. From the magnetic separator, the wheat enters a disc separator designed to catch individual grains of wheat and reject larger or smaller material and then to a stoner for removal of stones, sand, flints, and balls of caked earth or mud. The wheat then moves into a scourer which buffs each kernel and removes more dust and loose bran (hull or husk). Following the scouring step, the grain is sent to the tempering bins where water is added to raise the moisture of the wheat to make it easier to grind. When the grain reaches the proper moisture level, it is passed through an impact machine as a final cleaning step. The wheat flows into a grinding bin and then into the mill itself.

The grain kernels are broken open in a system of breaks by sets of corrugated rolls, each set taking feed from the preceding one. After each break, the grain is sifted. The sifting system is a combination of sieving operations (plansifters) and air aspiration (purifiers). The flour then passes through the smooth reducing rolls, which further reduce the flour-sized particles and facilitate the removal of the remaining bran and germ particles. Plansifters are used behind the reducing rolls to divide the stock into over-sized particles, which are sent back to the reducing rolls, and flour, which is removed from the milling system. Flour stock is transported from the milling system to bulk storage bins and subsequently packaged for shipment.

Generally, durum wheat processing comprises the same steps as those used for wheat flour milling. However, in the milling of durum, middlings rather than flour are the desired product. Consequently, the break system, in which middlings are formed, is emphasized over the part of the reduction system in which flour is formed. Grain receiving, cleaning, and storage are essentially identical for durum and flour milling. The tempering step varies only slightly between the two processes. The tempering of durum uses the same equipment as wheat, but the holding times are shorter. Only the grain milling step differs significantly from the comparable flour milling step.

The break system in a durum mill generally has at least five sets of rolls for a gradual reduction of the stock to avoid producing large amounts of break flour. The rolls in the reduction system are used for

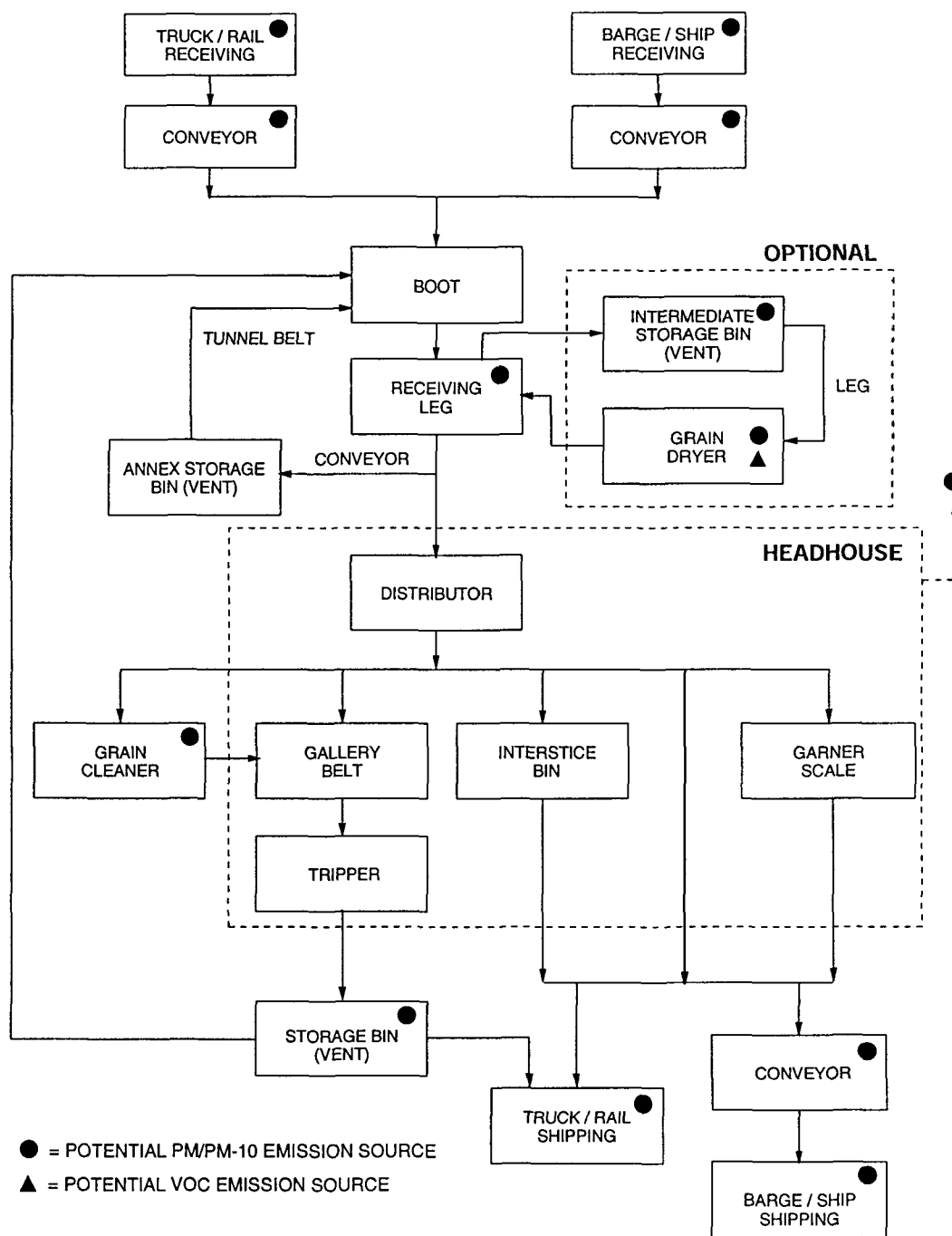


Figure 9.9.1-1. Major process operations at a grain elevator.

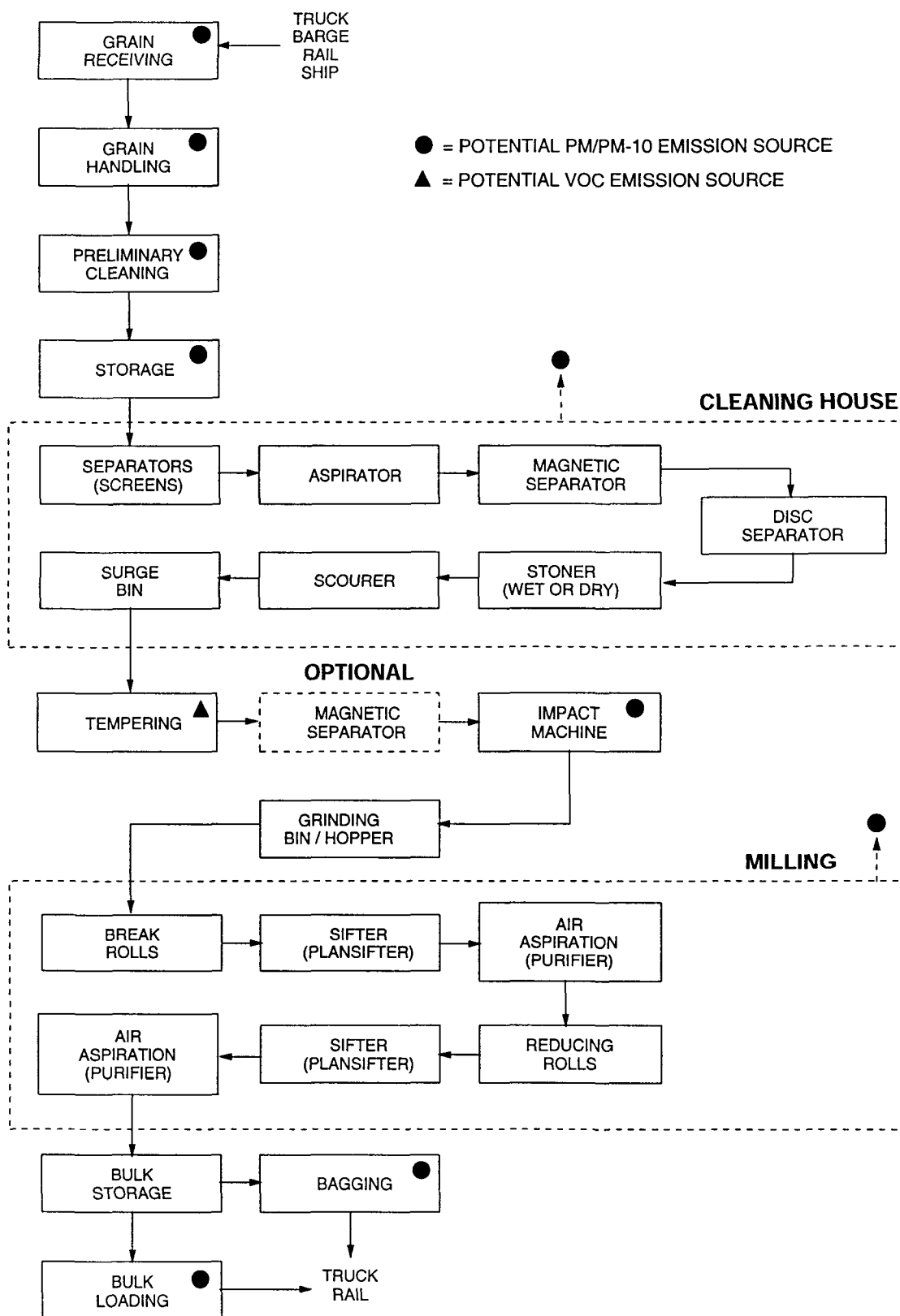


Figure 9.9.1-2. Simplified process flow diagram of a typical flour mill.

sizing only, and not to produce flour. The sizing produces a uniform product for sale. The sifting system differs from that in a wheat flour mill in that it relies heavily on purifiers. In place of plansifters, conventional sieves are more common and are used to make rough separations ahead of the purifiers.

Rye milling and wheat flour milling are quite similar processes. The purpose of both processes is to make flour that is substantially free of bran and germ. The same basic machinery and process are employed. The flow through the cleaning and tempering portions of a rye mill is essentially the same as the flow through the wheat flour mill. However, because rye is more difficult to clean than wheat, this cleaning operation must be more carefully controlled.

In contrast to wheat milling, which is a process of gradual reduction with purification and classification, rye milling does not employ gradual reduction. Both the break and reduction roller mills in a rye mill are corrugated. Following grinding, the screening systems employ plansifters like those used in wheat flour mills. There is little evidence of purifier use in rye mills.

The wheat milling and rye milling processes are very similar because flour is the product of the break rolling system. In durum wheat flour milling, the intent is to produce as little flour as possible on the break rolls. As in wheat flour milling, the intent in rye milling is to make as much rye flour as possible on the break rolls. Consequently, there are more break rolls in proportion to reduction rolls in a rye mill than in a durum wheat flour mill.

9.9.1.1.2 Oat Milling^{2,7} -

The milling process for oats consists of the following steps: (1) reception, preliminary cleaning, and storage; (2) cleaning; (3) drying and cooling; (4) grading and hulling; (5) cutting; (6) steaming; and (7) flaking. A simplified flow diagram of the oat milling process is shown in Figure 9.9.1-3. The receiving and storage operations are comparable to those described for grain elevators and for the wheat flour milling process. Preliminary cleaning removes coarse field trash, dust, loose chaff, and other light impurities before storage. After the oats are removed from storage, they flow to a milling separator combining coarse and fine screening with an efficient aspiration. In the next sequence of specialized cleaning operations, the oats are first routed to a disk separator for stick removal, and then are classified into three size categories. Each size category is subjected to a variety of processes (mechanical and gravitational separation, aspiration, and magnetic separation) to remove impurities. Large and short hulled oats are processed separately until the last stages of milling.

The next step in the oat processing system is drying and cooling. Oats are dried using pan dryers, radiator column dryers, or rotary steam tube dryers. Oats typically reach a temperature of 88° to 98°C (190° to 200°F) here, and the moisture content is reduced from 12 percent to 7 to 10 percent. After drying and cooling, the oats are ready for hulling; hulled oats are called groats. Some mills are now hulling oats with no drying or conditioning, then drying the groats separately to develop a toasted flavor. Hulling efficiency can be improved by prior grading or sizing of the oats. The free hulls are light enough that aspirators remove them quite effectively.

Generally, the final step in the large oat system is the separation of groats totally free of whole oats that have not had the hulls removed. These groats bypass the cutting operation and are directed to storage prior to flaking. The rejects are sent to the cutting plant. The cutting plant is designed to convert the groats into uniform pieces while producing a minimum of flour. The cut material is now ready for the flaking plant. First, the oats are conditioned by steaming to soften the groats thereby promoting flaking with a minimum of breakage. The steamed groats pass directly from the steamer into the flaking rolls. Shakers under the rolls remove fines and overcooked pieces are scalped off. The flakes generally pass

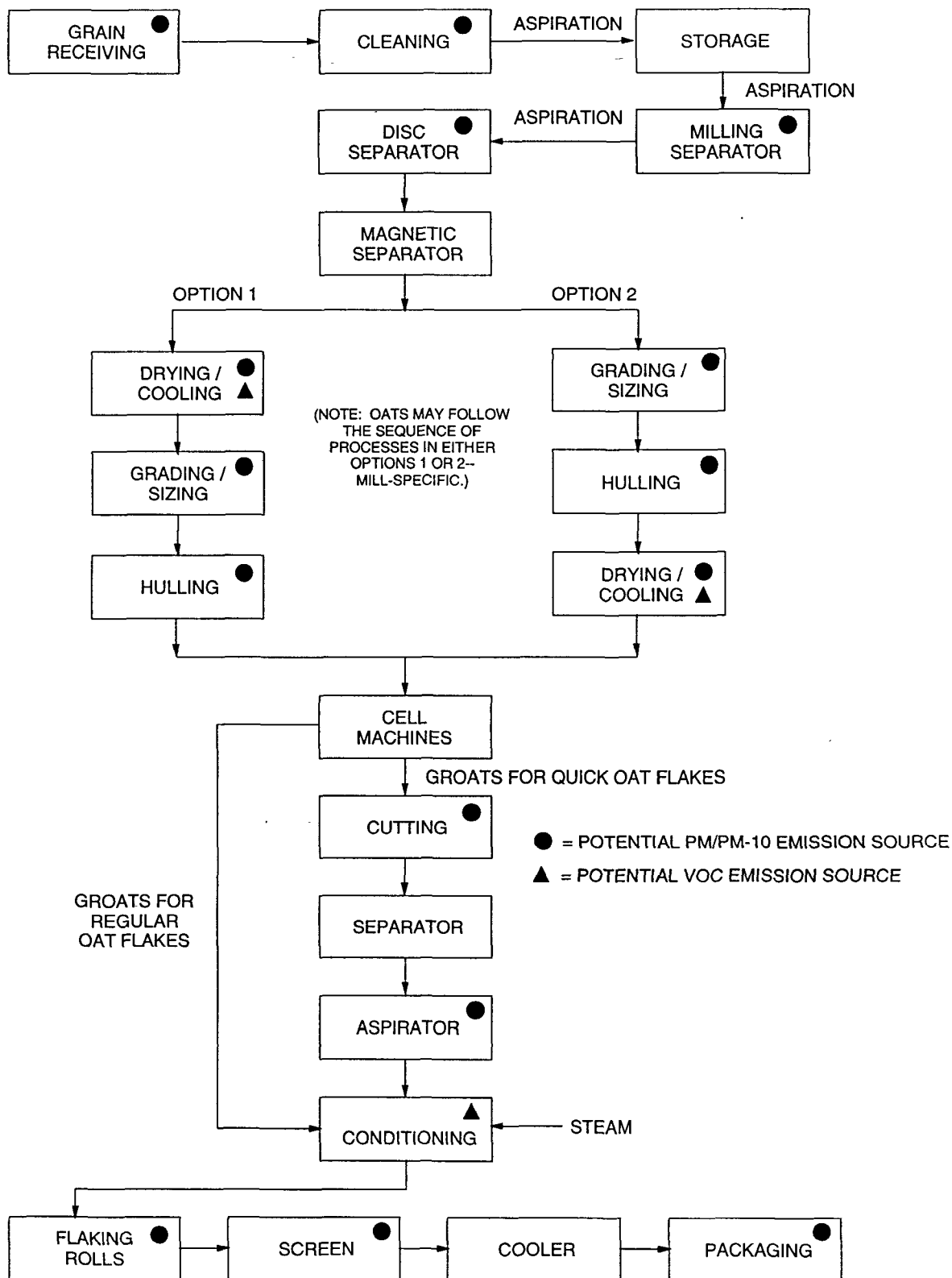


Figure 9.9.1-3. Flow diagram for oat processing operations.⁸

through a dryer and cooler to quickly reduce moisture content and temperature which ensures acceptable shelf life. The cooled flakes are then conveyed to the packaging system.

9.9.1.1.3 Rice Milling^{2,8-10}

The first step in rice processing after harvest is drying using either fixed-bed or continuous-flow dryers to reduce the wet basis moisture content (MCwb) from 24 to 25 percent to 13 to 14 percent MCwb. Essentially all of the rice is dried either on the farm or at commercial drying facilities prior to shipping to the rice mill. After the rice is dried, it is stored and subsequently shipped to either conventional or parboil rice mills for further processing. There are three distinct stages in both mills: (1) rough rice receiving, cleaning, drying, and storage; (2) milling; and (3) milled rice and byproduct bagging, packaging, and shipping. A simplified flow diagram of the rice milling process is shown in Figure 9.9.1-4.

Grain is received primarily by truck and rail. The rough rice is precleaned using combinations of scalpels, screens, aspirators, and magnetic separators and then passed through a stoner, or gravity separator, to remove stones from the grain. The cleaned rice is transported to a disk huller where the rice is dehulled. The rice then passes through a sieve to remove bran and small broken and to an aspirator to remove hulls. The unshelled rice grains (commonly called paddy) and brown rice are separated in a paddy separator. The unshelled paddy is then fed into another pair of shellers set closer together than the first set, and the process of shelling, aspiration, and separation is repeated.

From the paddy machines, the rice is conveyed to a sequence of milling machines called whitening cones, which scour off the outer bran coats and the germ from the rice kernels. Milling may be accomplished by a single pass through a mill or by consecutive passages through multiple whitening cones. The discharge from each stage is separated by a sieve. After the rice is milled, it passes through a polishing cone, which removes the inner bran layers and the proteinaceous aleurone layer. Because some of the kernels are broken during milling, a series of classifiers, known as trieurs, is used to separate the different size kernels. The rice may be sold at this point as polished, uncoated rice, or it may be conveyed to machines known as trumbels, in which the rice is coated with talc and glucose to give the surface a gloss. The rice is transferred to bulk storage prior to packing and shipping. For packing, the rice is transported to a packing machine where the product is weighed and placed in burlap sacks or other packaging containers.

In parboiling mills, the cleaned rough rice is steamed and dried prior to the milling operations. Pressure vessels are used for the steaming step, and steam tube dryers are used to dry the rice to 11 to 13 percent MCwb. Following the drying step, the rice is milled in conventional equipment to remove hull (bran), and germ.

9.9.1.1.4 Corn Dry Milling^{2,12-13}

Corn is dry milled by either a degerming or a nondegerming system. Because the degerming system is the principal system used in the United States, it will be the focus of the dry corn milling process description here. A simplified flow diagram of the corn dry milling process is shown in Figure 9.9.1-5. The degerming dry corn milling process is more accurately called the tempering degerminating (TD) system. The degerming system involves the following steps after receiving the grain: (1) dry cleaning, and if necessary, wet cleaning; (2) tempering; (3) separation of hull, germ, and tip cap from the endosperm in the degerminator; (4) drying and cooling of degermer product; (5) multistep milling of degermer product through a series of roller mills, sifters, aspirators, and purifiers; (6) further drying of products, if necessary; (7) processing of germ fraction for recovery of crude corn oil; and (8) packaging and shipping of products.

Unloading and dry cleaning of corn is essentially the same as described for wheat. However, for corn, surface dirt and spores can best be removed by wet cleaning, which involves a washing-destoning unit followed by a mechanical dewatering unit. After cleaning, the corn is sent through the tempering or



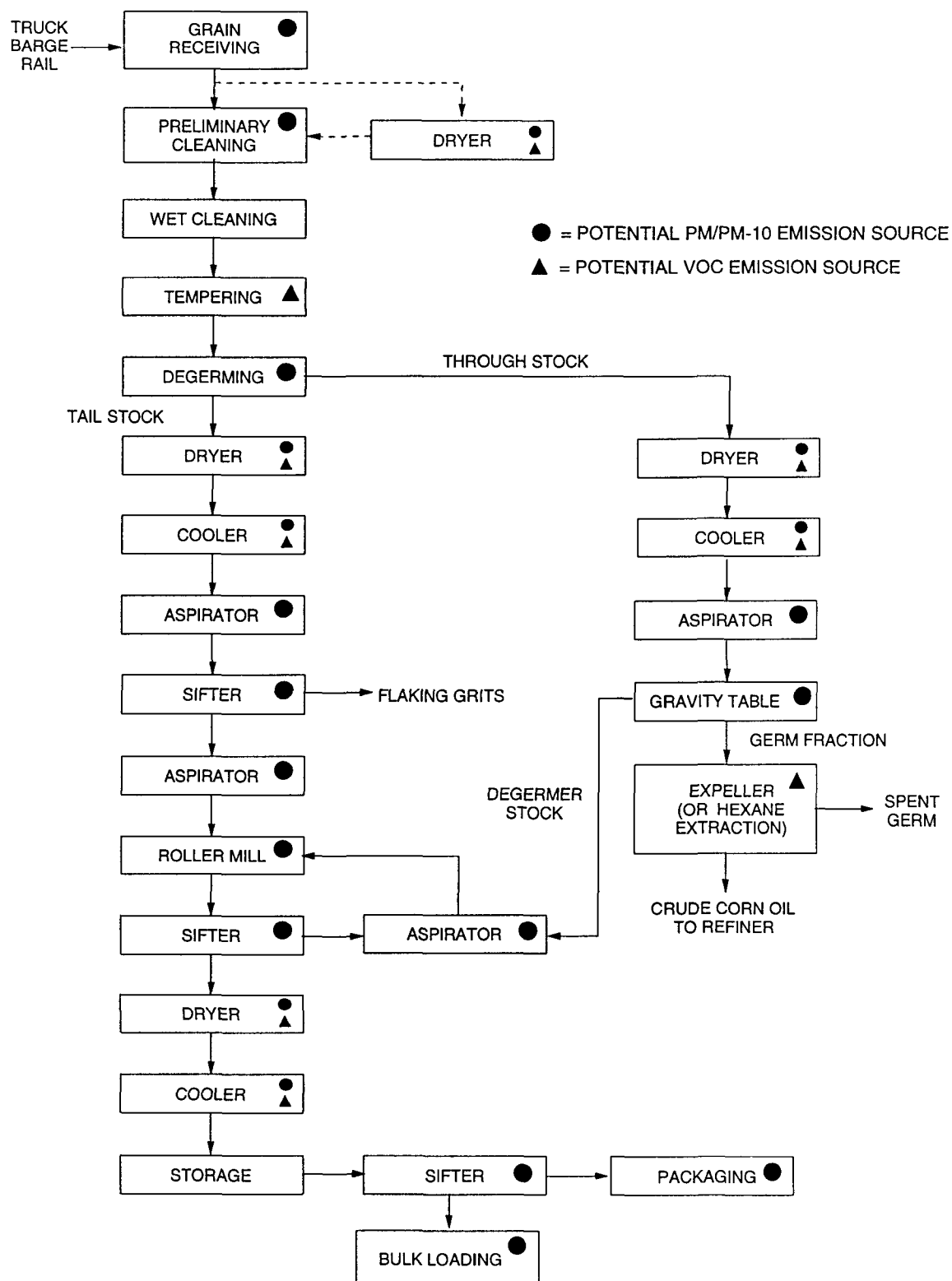


Figure 9.9.1-5. Simplified process flow diagram for a corn dry milling operation with degerming.

conditioning step, which raises the moisture content of the corn to 21 to 25 percent. After tempering, the corn is degermed, typically in a Beall degermer and corn huller. The Beall degermer is essentially an attrition device built in the form of a cone mill. The product exits in two streams, thru-stock and tail stock. Rotary steam-tube dryers are often used to dry the degermer product, because its moisture content must be in the 15 to 18 percent range for proper milling. After drying, the product is cooled to 32° to 37°C (90° to 100°F). After drying and cooling, the degermer stock is sifted or classified by particle size and is fed into the conventional milling system.

The milling section in a dry corn mill consists of sifting, classifying, milling, purifying, aspirating, and possibly, final drying operations. The feed to each pair of rolls consists of selected mill streams produced during the steps of sifting, aspirating, roller milling, and gravity table separating. For the production of specific products, various streams are withdrawn at appropriate points in the milling process. A number of process streams are often blended to produce a specific product. The finished products are stored temporarily in working bins, dried and cooled if necessary, and rebolted (sifted) before packaging or shipping in bulk.

Oil is recovered from the germ fraction either by mechanical screw presses or by a combination of screw presses and solvent extraction. A more detailed discussion of the corn oil extraction process is included in AP-42 Section 9.11.1, Vegetable Oil Processing.

9.9.1.1.5 Animal Feed Mills^{2,5,14} -

The manufacture of feed begins with receiving of ingredients at the mill. A simplified flow diagram of the animal feed manufacturing process is shown in Figure 9.9.1-6. Over 200 ingredients may be used in feed manufacture, including grain, byproducts (e.g., meat meal, bone meal, beet and tomato pulp), and medicinals, vitamins, and minerals (used in very small portions). Grain is usually received at the mill by hopper bottom truck and/or rail cars, or in some cases, by barge. Most mills pass selected feed ingredients, primarily grains, through cleaning equipment prior to storage. Cleaning equipment includes scalpels to remove coarse materials before they reach the mixer. Separators, which perform a similar function, often consist of reciprocating sieves that separate grains of different sizes and textures. Magnets are installed ahead of the grinders and at other critical locations in the mill system to remove pieces of metal, bits of wire, and other foreign metallic matter, which could harm machinery and contaminate the finished feed. From the cleaning operation, the ingredients are directed to storage.

Upon removal from storage, the grain is transferred to the grinding area, where selected whole grains, primarily corn, are ground prior to mixing with other feed components. The hammermill is the most widely used grinding device. The pulverized material is forced out of the mill chamber when it is ground finely enough to pass through the perforations in the mill screen.

Mixing is the most important process in feed milling and is normally a batch process. Ingredients are weighed on bench or hopper scales before mixing. Mixers may be horizontal or vertical type, using either screws or paddles to move the ingredients. The material leaving the mixer is meal, or mash, and may be marketed in this form. If pellets are to be made, the meal is conditioned with steam prior to being pelleted.

Pelleting is a process in which the conditioned meal is forced through dies. Pellets are usually 3.2 to 19 mm (1/8 to 3/4 in.) in diameter. After pelleting, pellets are dried and cooled in pellet coolers. If pellets are to be reduced in size, they are passed through a crumbler, or granulator. This machine is a roller mill with corrugated rolls. Crumbles must be screened to remove fines and oversized materials. The product is sent to storage bins and then bagged or shipped in bulk.

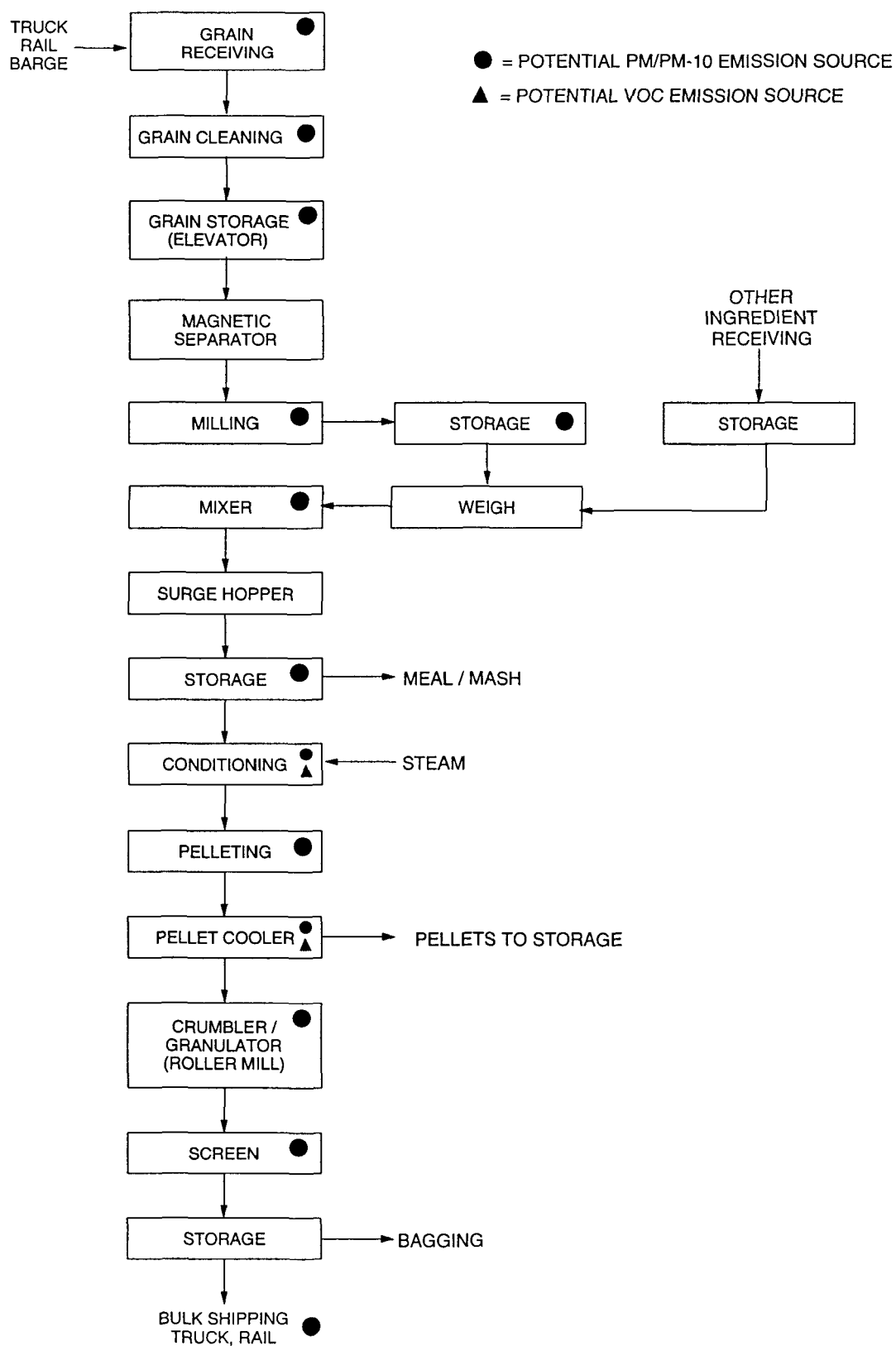


Figure 9.9.1-6. Typical animal feed milling process flow diagram.

In modern feed mills, transport equipment is connected with closed spouting and turnheads, covered drag and screw conveyors, and tightly sealed transitions between adjoining equipment to reduce internal dust loss and consequent housekeeping costs. Also many older facilities have upgraded to these closed systems.

9.9.1.1.6 Malted Barley Production³⁶⁻³⁷ -

Barley is shipped by railcar or truck to malting facilities. A screw conveyor or bucket elevator typically transports barley to storage silos or to the cleaning and sizing operations. The barley is cleaned and separated by size (using screens) and is then transferred to a malthouse where it is rinsed in steeping tanks (steeped) and is allowed to germinate. Following steeping and germination, "green" malt is dried, typically in an indirect-, natural gas-fired malt kiln. Malt kilns typically include multiple levels, called beds or layers. For a two-level kiln, green malt, with a moisture content of about 45 percent, enters the upper deck of the kiln and is dried, over a 24-hour period, to between 15 and 20 percent. The barley is then transferred to the lower deck of the kiln, where it is dried to about 4 percent over a second 24-hour period. Some facilities burn sulfur in a sulfur stove and exhaust the stove into the kiln at selected times during the kiln cycle. The sulfur dioxide serves as a fungicide, bactericide, and preservative. Malted barley is then transferred by screw conveyor to a storage elevator until it is shipped.

9.9.1.2 Emissions And Controls^{2,5,14-39}

The main pollutant of concern in grain storage, handling, and processing facilities is particulate matter (PM). Organic emissions (e.g., hexane) from certain operations at corn oil extraction facilities may also be significant. These organic emissions (and related emissions from soybean and other oilseed processing) are discussed in AP-42 Section 9.11.1. Also, direct fired grain drying operations and product dryers in grain processing plants may emit small quantities of VOC's and other combustion products; no data are currently available to quantify the emission of these pollutants. The following sections focus primarily on PM sources at grain elevators and grain milling/processing facilities.

9.9.1.2.1 Grain Elevators -

Except for barge and ship unloading and loading activities, the same basic operations take place at country elevators as at terminal elevators, only on a smaller scale and with a slower rate of grain movement. Emission factors for various grain elevator operations are presented later in this subsection. Because PM emissions at both types of elevators are similar, they will be discussed together in this subsection.

In trying to characterize emissions and evaluate control alternatives, potential PM emission sources can be classified into three groups. The first group includes external emission sources (grain receiving and grain shipping), which are characterized by direct release of PM from the operations to the atmosphere. These operations are typically conducted outside elevator enclosures or within partial enclosures, and emissions are quickly dispersed by wind currents around the elevator. The second group of sources are process emission sources that may or may not be vented to the atmosphere and include grain cleaning and headhouse and internal handling operations (e.g., garner and scale bins, elevator legs, and transfer points such as the distributor and gallery and tunnel belts). These operations are typically located inside the elevator structure. Dust may be released directly from these operations to the internal elevator environment, or aspiration systems may be used to collect dust generated from these operations to improve internal housekeeping. If aspiration systems are used, dust is typically collected in a cyclone or fabric filter before the air stream is discharged to the atmosphere. Dust emitted to the internal environment may settle on internal elevator surfaces, but some of the finer particles may be emitted to the environment through doors and windows. For operations not equipped with aspiration systems the quantity of PM emitted to the atmosphere depends on the tightness of the enclosures around the operation and internal elevator housekeeping practices. The third group of sources includes those processes that emit PM to the atmosphere in a well-defined exhaust stream (grain drying and storage bin vents). Each of these operations is discussed in the paragraphs below.

The amount of dust emitted during the various grain-handling operations may depend upon the type of grain being handled, the quality or grade of the grain, the moisture content of the grain, the speed of the belt conveyors used to transport the grain, and the extent and efficiency of dust containment systems (i.e., hoods, sheds, etc.) in use at an elevator. Part of the dust liberated during the handling of grain at elevators gets into the grain during the harvesting operation. However, most of these factors have not been studied in sufficient detail to permit the delineation of their relative importance to dust generation rates.

Grain dust emitted from grain elevator handling operations comprises about 70 percent organic material, about 17 percent free silica (silicon dioxide), and specific materials in the dust, which may include particles of grain kernels, spores of smuts and molds, insect debris, pollens, and field dust. Data recently collected on worker exposure to grain dust indicate that the characteristics of the dust released from processing operations to the internal elevator environment vary widely.¹⁵ The fraction of respirable dust (i.e., those dust particles equal to or less than 10 μm in diameter) ranged from about 1 percent to over 60 percent with an average of 20 and 26 percent for country and export elevators respectively. Those elevators handling primarily wheat had an average respirable fraction of about 30 percent while those handling primarily corn and soybeans had an average respirable fraction of slightly less than 20 percent. Because these dusts have a high organic content and a substantial suspendible fraction, concentrations above the minimum explosive concentration (MEC) pose an explosion hazard. Housekeeping practices instituted by the industry have reduced explosion hazards, and this situation is rarely encountered in work areas.

Elevators in the United States receive grain by truck, railroad hopper car, and barge. The two principal factors that contribute to dust generation during bulk unloading are wind currents and dust generated when a falling stream of grain strikes the receiving pit. Falling or moving streams of grain initiate a column of air moving in the same direction. Grain unloading is an intermittent source of dust occurring only when a truck or car is unloaded. For country elevators it is a significant source during the harvest season and declines sharply or is nonexistent during other parts of the year. At terminal elevators, however, unloading is a year-round operation.

Trucks, except for the hopper (gondola) type, are generally unloaded by the use of some type of truck dumping platform. Hopper trucks discharge through the bottom of the trailer. Elevators are often designed with the truck unloading dump located in a drive-through tunnel. These drive-through areas are sometimes equipped with a roll-down door on one end, although, more commonly they are open at both ends so that the trucks can enter and leave as rapidly as possible. The drive-through access can act as a "wind-tunnel" in that the air may blow through the unloading area at speeds greater than the wind in the open areas away from the elevator. However, the orientation of the facility to the prevailing wind direction can moderate this effect. Many facilities have installed either roll-down or bi-fold doors to eliminate this effect. The use of these doors can greatly reduce the "wind tunnel" effect and enhance the ability to contain and capture the dust.

The unloading pit at a grain elevator usually consists of a heavy grate approximately 3.05 m x 3.05 m (10 ft x 10 ft) through which the grain passes as it falls into the receiving pit. This pit will often be partially filled with grain as the truck unloads because the conveyor beneath the pit does not carry off the grain as fast as it enters. The dust-laden air emitted by the truck unloading operation results from displacement of air out of the pit plus the aspiration of air caused by the falling stream of grain. The dust itself is composed of field dirt and grain particles. Unloading grain from hopper trucks with choke flow-practices can provide a substantial reduction in dust emissions.

Similarly, a hopper railcar can be unloaded with minimal dust generation if the material is allowed to form a cone around the receiving grate (i.e., choke feed to the receiving pit). This situation will occur when either the receiving pit or the conveying system serving the pit are undersized in comparison to the rate at which material can be unloaded from the hopper car. In such cases, dust is generated primarily during the

initial stage of unloading, prior to establishment of the choked-feed conditions. Dust generated by wind currents can be minimized by the use of a shed enclosed on two sides with a manual or motorized door on one end or a shroud around the hopper discharge.

In most cases, barges are unloaded by means of a retractable bucket type elevator that is lowered into the hold of the barge. There is some generation of dust in the hold as the grain is removed and also at the top of the leg where the grain is discharged onto the transfer belt. This latter source is more appropriately designated a transfer point.

The loadout of grain from elevators into railcar, truck, barge, or ship is another important source of PM emissions and is difficult to control. Gravity is usually used to load grain from bins above the loading station or from the scale in the headhouse. The main causes of dust emissions when loading bulk grain by gravity into trucks or railcars is the wind blowing through the loading sheds and dust generated when the falling stream of grain strikes the truck or railcar hopper. The grain leaving the loading spout is often traveling at relatively high velocity and librates a considerable amount of dust as the grain is deposited in the car or truck. Dust emitted during loading of barges and ships can be at least equal to, or maybe greater than, PM generated during loading of trucks or railcars. The openings for the holds in these vessels are large, making it very hard to effectively capture the emissions. The use of deadboxes, aspiration, socks, tents, or other means are often used to reduce dust emissions.

Grain dryers present a difficult problem for air pollution control because of the large volumes of air exhausted from the dryer, the large cross-sectional area of the exhaust, the low specific gravity of the emitted dust, and the high moisture content of the exhaust stream. The rate of emission of PM from grain dryers is primarily dependent upon the type of grain, the dustiness of the grain, and the dryer configuration (rack or column type). The particles emitted from the dryers, although relatively large, may be very light and difficult to collect. However, during corn drying the characteristic "bees wing" is emitted along with normal grain dust. "Bees wing," a light flaky material that breaks off from the corn kernel during drying and handling, is a troublesome PM emission. Essentially, all bees wing emissions are over 50 μm in diameter, and the mass mean diameter is probably in the region of 150 μm . In addition to the bees wings, the dust discharged from grain dryers consists of hulls, cracked grain, weed seeds, and field dust. Effluent from a corn dryer may consist of 25 percent bees wing, which has a specific gravity of about 0.70 to 1.2. Approximately 95 percent of the grain dust is larger than 50 μm .²

Cross-flow column dryers have a lower emission rate than rack dryers because some of the dust is trapped by the column of grain. In order to control the dust emitted from the columns, it is necessary to build an enclosure. This enclosure also serves as a relatively inefficient settling chamber. New grain dryers being sold today do not require the use of enclosures. In rack dryers, the emission rate is higher because the turning motion of the grain generates more bees wings and the design facilitates dust escape. Some rack dryers are exhausted only from one or two points and are thus better suited for control device installation. The EPA's New Source Performance Standards (NSPS) for grain elevators established visible emission limits for grain dryers by requiring 0 percent opacity for emissions from column dryers with column plate perforations not to exceed 2.4 mm diameter (0.094 in.) or rack dryers with a screen filter not to exceed 50 mesh openings.

Equipment used to clean grain varies from simple screening devices to aspiration-type cleaners. Both types of systems potentially generate substantial quantities of PM depending on the design and extent of enclosure.

Both country and terminal elevators are usually equipped with garner and scale bins for weighing of grain. A country elevator may have only one garner bin and scale bin. However, a terminal elevator has multiple scale and garner bin systems, each with a capacity ranging from 42.3 to 88.1 m^3 (1,200 to 2,500 bu)

to process 1,233 to 2,643 m³/hr (35,000 to 75,000 bu/hr). Dust may be emitted from both the scale and garner bin whenever grain is admitted. The incoming stream of grain displaces air from the bin, and the displaced air entrains dust. The potential for emissions depends on the design of the system. For example, some facilities employ a relief duct that connects the two pieces of equipment to provide a path for displaced air. Also, in some cases, the bins are completely open at the top while some systems are completely enclosed.

The leg may be aspirated to remove dust created by the motion of the buckets and the grain flow. A variety of techniques are used to aspirate elevator legs. For example, some are aspirated at both the top and bottom; others are fitted with ducting from the top to the bottom in order to equalize the pressure, sometimes including a small blower to serve this purpose. The collected dust is discharged to a cyclone or filter. Leg vents may emit small amounts of dust under some operating conditions. However, these vents are often capped or sealed to prevent dust emissions. The sealing or capping of the vent is designed to act as an explosion relief vent after a certain internal pressure is reached to prevent damage to the equipment.

When grain is handled, the kernels scrape and strike against each other and the conveying medium. This action tends to rub off small particles of chaff and to fragment some kernels. Dust is continuously generated, and the grain is never absolutely clean. Belt conveyors have less rubbing friction than either screw or drag conveyors, and therefore, generate less dust. Dust emissions usually occur at belt transfer points as materials fall onto or away from a belt. Belt speed has a strong effect on dust generation at transfer points. Examples of transfer points are the discharge from one belt conveyor or the discharge from a bin onto a tunnel belt.

Storage bin vents, which are small screen-covered openings located at the top of the storage bins, are used to vent air from the bins as the grain enters. The grain flow into a bin induces a flow of air with the grain, and the grain also displaces air out of the bin. The air pressure that would be created by these mechanisms is relieved through the vents. The flow of grain into the bin generates dust that may be carried out with the flow of air through the bin vents. The quantity of dust released through the vents increases as the level of the grain in the bin increases. Bin vents are common to both country and terminal elevators, although the quantity of dust emitted is a function of the grain handling rate, which is considerably higher in terminal elevators.

The three general types of measures that are available to reduce emissions from grain handling and processing operations are process modifications designed to prevent or inhibit emissions, capture/ collection systems, and oil suppression systems that inhibit release of dust from the grain streams. The following paragraphs describe the general approaches to process controls, capture systems, and oil suppression. The characteristics of the collection systems most frequently applied to grain handling and processing plants (cyclones and fabric filters) are then described, and common operation and maintenance problems found in the industry are discussed.

Because emissions from grain handling operations are generated as a consequence of mechanical energy imparted to the dust by the operations themselves and local air currents in the vicinity of the operations, an obvious control strategy is to modify the process or facility to limit the effects of those factors that generate emissions. The primary preventive measures that facilities have used are construction and sealing practices that limit the effect of air currents and minimizing grain free fall distances and grain velocities during handling and transfer. Some construction and sealing practices that minimize emissions are enclosing the receiving area to the degree practicable, preferably with doors at both ends of a receiving shed; specifying dust-tight cleaning and processing equipment; using lip-type shaft seals at bearings on conveyor

and other equipment housings; using flanged inlets and outlets on all spouting, transitions, and miscellaneous hoppers; and fully enclosing and sealing all areas in contact with products handled.

A substantial reduction in emissions from receiving, shipping, handling, and transfer areas can be achieved by reducing grain free fall distances and grain velocities. Choke unloading reduces free fall distance during hopper car unloading. The same principle can be used to control emissions from grain transfer onto conveyor belts and from loadout operations. An example of a mechanism that is used to reduce grain velocities is a "dead box" spout, which is used in grain loadout (shipping) operations. The dead box spout slows down the flow of grain and stops the grain in an enclosed area. The dead box is mounted on a telescoping spout to keep it close to the grain pile during operation. In principle, the grain free falls down the spout to an enclosed impact dead box, with grain velocity going to zero. It then falls onto the grain pile. Typically, the entrained air and dust liberated at the dead box is aspirated back up the spout to a dust collector. Finally, several different types of devices are available that, when added to the end of the spout, slow the grain flow and compress the grain discharge stream. These systems entrap the dust in the grain stream, thereby providing a theoretical reduction in PM emissions. There are few, if any, test data from actual ship or barge loading operations to substantiate this theoretical reduction in emissions.

While the preventive measures described above can minimize emissions, most facilities also require ventilation, or capture/collection, systems to reduce emissions to acceptable levels. In fact, air aspiration (ventilation) is a part of the dead box system described above. Almost all grain handling and processing facilities, except relatively small grain elevators, use capture/collection on the receiving pits, cleaning operations, and elevator legs. Generally, milling and pelletizing operations at processing plants are ventilated, and some facilities use hooding systems on all handling and transfer operations.

Grain elevators that rely primarily on aspiration typically duct many of the individual dust sources to a common dust collector system, particularly for dust sources in the headhouse. Thus, aspiration systems serving elevator legs, transfer points, bin vents, etc., may all be ducted to one collector in one elevator and to two or more individual systems in another. Because of the myriad possibilities for ducting, it is nearly impossible to characterize a "typical" grain elevator from the standpoint of delineating the exact number and types of air pollution sources and the control configurations for those sources.

The control devices typically used in the grain handling and processing industry are cyclones (or mechanical collectors) and fabric filters. Cyclones are generally used only on country elevators and small processing plants located in sparsely populated areas. Terminal elevators and processing plants located in densely populated areas, as well as some country elevators and small processing plants, normally use fabric filters for control. Both of these systems can achieve acceptable levels of control for many grain handling and processing sources. Although cyclone collectors can achieve acceptable performance in some scenarios, and fabric filters are highly efficient, both devices are subject to failure if they are not properly operated and maintained. Also, malfunction of the ventilation system can lead to increased emissions at the source.

The emission control methods described above rely on either process modifications to reduce dust generation or capture collection systems to control dust emissions after they are generated. An alternative control measure that has developed over the last 10 years is dust suppression by oil application. The driving forces for developing most such dust suppression systems have been grain elevator explosion control as well as emission control. Consequently, few data have been published on the amount of emission reduction achieved by such systems. Recent studies, however, have indicated that a PM reduction of approximately 60 to 80 percent may be achievable (see References 57 and 61 in Section 4 of the Background Report).

Generally, these oil application dust suppression systems use either white mineral oil, soybean oil, or some other vegetable oil. Currently the Food and Drug Administration restricts application rates of mineral

oil to 0.02 percent by weight. Laboratory testing and industry experience have shown that oil additives applied at a rate of 60 to 200 parts per million by weight of grain, or 0.5 to 1.7 gallons of oil per thousand bushels of grain can provide effective dust control.³⁹ The effectiveness of the oil suppression system depends to some extent on how well the oil is dispersed within the grain stream after it is applied. Several options are available for applying oil additives.

1. As a top dressing before grain enters the bucket elevator or at other grain transfer points.
2. From below the grain stream at a grain transfer point using one or more spray nozzles.
3. In the boot of the bucket elevator leg.
4. At the discharge point from a receiving pit onto a belt or other type conveyor.
5. In a screw conveyor.

9.9.1.2.2 Grain Processing Plants -

Several grain milling operations, such as receiving, conveying, cleaning, and drying, are similar to those at grain elevators. In addition, applications of various types of grinding operations to the grain, grain products, or byproducts are further sources of emissions. The hammermill is the most widely used grinding device at feed mills. Some product is recovered from the hammermill with a cyclone collector or baghouse. Mills, similar to elevators, use a combination of cyclones and fabric filters to conserve product and to control emissions. Several types of dryers are used in mills, including the traditional rack or column dryers, fluidized bed dryers (soybean processing), and flash-fired or direct-fired dryers (corn milling). These newer dryer types might have lower emissions, but data are insufficient at this time to quantify the difference. The grain precleaning often performed before drying also likely serves to reduce emissions.

Because of the operational similarities, emission control methods used in grain milling and processing plants are similar to those in grain elevators. Cyclones or fabric filters are often used to control emissions from the grain handling operations (e. g., unloading, legs, cleaners, etc.) and also from other processing operations. Fabric filters are used extensively in flour mills. However, certain operations within milling operations are not amenable to the use of these devices and alternatives are needed. Wet scrubbers, for example, are applied where the effluent gas stream has a high moisture content. A few operations have been found to be difficult to control by any method. Various emission control systems have been applied to operations within the grain milling and processing industry.²

Grain processing facilities also have the potential to emit gaseous pollutants. Natural gas-fired dryers and boilers are potential sources of combustion byproducts and VOC. The production of various modified starches has the potential for emissions of hydrochloric acid or ethylene oxide. However, no data are available to confirm or quantify the presence of these potential emissions. Neither are there any data available concerning the control of these potential emissions.

Table 9.9.1-1 presents emission factors for filterable PM and PM-10 emissions from grain elevators. Table 9.9.1-2 presents emission factors for filterable PM; PM-10; inorganic, organic and total condensable PM emissions from grain processing facilities.

The most recent source test data for grain elevators either does not differentiate between country and inland terminal elevators or does not show any significant difference in emission factors between these two types of elevators. There are no current emission source test data for export terminal elevators. Because there is no significant difference in emission factors between different types of elevators, the emission factors presented in Table 9.9.1-1 are for grain elevators, without any distinction between elevator types.

Table 9.9.1-1. PARTICULATE EMISSION FACTORS FOR GRAIN ELEVATORS^a

Emission Source	Type of Control	Filterable ^b			EMISSION FACTOR RATING
		PM	EMISSION FACTOR RATING	PM-10 ^c	
Grain receiving (SCC 3-02-005-05)	None	ND		ND	
Trucks (unspecified) (SCC 3-02-005-50)	None	0.18 ^d	E	0.059 ^e	E
Straight truck (SCC 3-02-005-51)	None	0.035 ^d	E	0.0078 ^e	E
Hopper truck (SCC 3-02-005-52)	None	0.032 ^e	E	0.0078 ^e	E
Railcar (SCC 3-02-005-53)	None	(f)		(f)	
Barge (SCC 3-02-005-54)	None	(f)		(f)	
Ships (SCC 3-02-005-55)	None				
Grain cleaning (SCC 3-02-005-03)	Cyclone	0.075 ^g	E	(j)	
Internal vibrating (SCC 3-02-005-37)	None	ND		ND	
Stationary enclosed (SCC 3-02-005-38)	None				
Grain drying (SCC 3-02-005-04)	None	0.22 ^h	E	(j)	
Column dryer (SCC 3-02-005-27)	None	3.0 ^h	E	(j)	
Rack dryer (SCC 3-02-005-28)	Self-cleaning screens (<50 mesh)	0.47 ^h	E	(j)	
Headhouse and internal handling (SCC 3-02-005-30) (legs, belts, distributor, scale, etc.)	None	0.061 ^e	E	0.034 ^e	E
Storage bin (vent) (SCC 3-02-005-40)	None	ND		ND	

Table 9.9.1-1 (cont.).

Emission Source	Type of Control	Filterable ^b		
		PM	EMISSION FACTOR RATING	PM-10 ^c
Grain shipping (SCC 3-02-005-06)				
Truck (unspecified) (SCC 3-02-005-60)	None	0.086 ^d	E	0.029 ^e
Railcar (SCC 3-02-005-63)	None	0.027 ^e	E	0.0022 ^e
Barge (SCC 3-02-005-64)		(f)		(f)
Ship (SCC 3-02-005-05)		(f)		(f)

^a Specific sources of emission factors are cited in Reference 1, Table 4-16 and supporting tables. Factors are in units of lb/ton of grain handled or processed. Lb/ton divided by 2 gives kg/Mg. SCC = Source Classification Code. ND = no data available.

^b Weight of total filterable PM, regardless of size, per unit weight of grain throughput.

^c Weight of PM $\leq 10\mu\text{m}$ in aerodynamic diameter per unit weight of grain throughput.

^d Mean of two values from References 18 and 19.

^e Reference 19.

^f No data are available that represent current loading and unloading practices for ships and barges.

^g Mean of six A- and C-rated data points from References 20, 21, 22, 23, and 24.

^h Mean of two D-rated data points from Reference 2.

^j PM-10 test data are not available. PM-10 emission factors can be estimated by taking 25 percent of the filterable PM emission factor.

Table 9.9.1-2. PARTICULATE EMISSION FACTORS FOR GRAIN PROCESSING FACILITIES^a

Type of Facility/ Emission Source	Type of Control	Filterable ^b				Condensible PM ^c		
		PM	EMISSION FACTOR RATING	PM-10 ^d	EMISSION FACTOR RATING	Inorganic	Organic	Total
Animal feed mills Grain receiving (SCC 3-02-008-02)	None	0.017 ^e	E	0.0025 ^e	E			
Grain cleaning (SCC 3-02-008-07)	Cyclone	(f)		(f)				
Storage	None	ND		ND				
Grain milling (SCC 3-02-008-15)								
Hammermill (SCC 3-02-008-17)	Cyclone	0.067 ^h	E	(g)				
	Baghouse	0.012 ^j	E	(y)				
Flaker (SCC 3-02-008-18)	Cyclone	0.15 ^k	E	(g)				
Grain cracker (SCC 3-02-008-19)	Cyclone	0.024 ^k	E	(g)				
Mixer	None	ND		ND				
Conditioning	None	ND		ND				
Pelletizing								
Pellet cooler ^m (SCC 3-02-008-16)	Cyclone	0.36 ⁿ	E	(g)		--	--	0.059 ^p
	High efficiency cyclone ^r	0.15 ^q	E	(g)				
Feed shipping (SCC 3-02-008-03)	None	0.0033 ^e	E	0.0008 ^e	E			
Wheat flour mills Grain receiving (SCC 3-02-007-31)	None	(f)		(f)				
Grain handling (SCC 3-02-007-32) (legs, belts, etc.)	None	(f)		(f)				

Table 9.9.1-2 (cont.).

Type of Facility/ Emission Source	Type of Control	Filterable ^b				Condensable PM ^c		
		PM	EMISSION FACTOR RATING	PM-10 ^d	EMISSION FACTOR RATING	Inorganic	Organic	Total
Cleaning house separators (SCC 3-02-007-33)	Cyclone	0.012 ^s	E	(g)				
Wheat milling (SCC 3-02-007-34) (roller mill)	None	70 ^s	E	(g)				
Bulk loading		ND		ND				
Corn dry mills								
Grain receiving (SCC 3-02-007-41)	None	(f)		(f)				
Grain drying (SCC 3-02-007-42)	None	(f)		(f)				
Grain handling (SCC 3-02-007-43) (legs, belts, etc.)	None	(f)		(f)				
Grain cleaning (SCC 3-02-007-44)	None	(f)		(f)				
Degermer/milling (SCC 3-02-007-45)		ND		ND				
Bulk loading		ND		ND				
Rice Mills								
Grain receiving (SCC 3-02-007-71)	None	ND		ND				
Precleaning/handling (SCC 3-02-007-72)		ND		ND				
Rice drying (SCC 3-02-007-73)	None	0.063 ^t	E	(g)				
Cleaning house (SCC 3-02-007-74)		ND		ND				

Table 9.9.1-2 (cont.).

Type of Facility/ Emission Source	Type of Control	Filterable ^b				Condensable PM ^c		
		PM	EMISSION FACTOR RATING	PM-10 ^d	EMISSION FACTOR RATING	Inorganic	Organic	Total
Parboiling	None	ND		ND				
Mill house (SCC 3-02-007-76)	Fabric filter	0.27 ^u	E	(y)				
Paddy cleaner (SCC 3-02-007-75)	Fabric filter	0.0031 ^u	E	(y)				
Aspirator (SCC 3-02-007-77)	Fabric filter	0.0030 ^u	E	(y)				
Bran handling (SCC 3-02-007-78)	Fabric filter	0.017 ^u	E	(y)				
Trumbel	None	ND		ND				
Trieurs	None	ND		ND				
Packaging/Shipping		ND		ND				
Durum Mills Grain receiving (SCC 3-02-007-11)		(f)		(f)				
Grain precleaning/ handling (SCC 3-02-007-12)		ND		ND				
Cleaning house (SCC 3-02-007-13)		ND		ND				
Durum milling (SCC 3-02-007-14)		ND		ND				
Bulk loading		ND		ND				

Table 9.9.1-2 (cont.).

Type of Facility/ Emission Source	Type of Control	Filterable ^b				Condensable PM ^c		
		PM	EMISSION FACTOR RATING	PM-10 ^d	EMISSION FACTOR RATING	Inorganic	Organic	Total
<u>Rye Mills</u> Grain receiving (SCC 3-02-007-21)		(f)		(f)				
Grain precleaning/ handling (SCC 3-02-007-22)		(f)		(f)				
Cleaning house (SCC 3-02-007-23)		ND		ND				
Rye milling (SCC 3-02-007-24)		ND		ND				
Bulk loading		ND		ND				
<u>Oat Mills</u> (SCC 3-02-007-60)								
Grain receiving		(f)		(f)				
Grain cleaning		(f)		(f)				
Separators		ND		ND				
Drying/cooling		ND		ND				
Grading/sizing		ND		ND				
Hulling		ND		ND				
Cutting		ND		ND				
Steaming/conditioning		ND		ND				
Flaking		ND		ND				
Screening		ND		ND				
Packaging		ND		ND				

Table 9.9.1-2 (cont.).

Type of Facility/ Emission Source	Type of Control	Filterable ^b				Condensible PM ^c		
		PM	EMISSION FACTOR RATING	PM-10 ^d	EMISSION FACTOR RATING	Inorganic	Organic	Total
Barley Malting Grain receiving (SCC 3-02-007-08)	Fabric filter	0.016 ^v	E	(y)				
Gas-fired malt kiln (SCC 3-02-007-09)	None	0.19 ^w	E	0.17 ^x (PM-2.5 =0.075)	E	0.075 ^x	0.013 ^x	0.088 ^x

^a Specific sources of emission factors are cited in Reference 1, Table 4-17 and supporting tables. Factors are in unit of lb/ton of grain handled or processed. Lb/ton divided by 2 gives kg/Mg. SCC = Source Classification Code. ND = no data available.

^b Weight of total filterable PM, regardless of size, per unit weight of grain throughput.

^c Condensible PM is material collected in the impinger portion of a PM sampling train.

^d Weight of PM $\leq 10\mu\text{m}$ in aerodynamic diameter per unit weight of grain throughput.

^e Reference 38. Feed shipping emission factor based on data for loading of bulk feed (not pellets).

^f See emission factors for grain elevators, Table 9.9.1-1.

^g PM-10 test data are not available. PM-10 emission factors can be estimated by taking 50 percent of the filterable PM emission factor.

^h Mean of two values from References 26 and 27.

ⁱ Mean of two B-rated values from References 28, 29, and 30.

^j Reference 31.

^m Includes column and pan dryers.

ⁿ Mean of 11 A-, B-, and C-rated values from References 26, 27, 31, and 32.

^p Mean of three B- and C-rated values from References 26 and 32.

^q Mean of two B-rated values from References 29, 30, and 31.

^r Equivalent to triple cycle or modern high efficiency cyclone.

^s Reference 2.

^t Mean of five D-rated values from Reference 34.

^u Reference 35.

^v Reference 36.

^w Mean of two values from References 36 and 37. Value converted from bushels to tons using a conversion factor of 50 bu/ton.

^x Reference 37.

^y PM-10 test data are not available. PM-10 emission factors can be estimated by taking 100 percent of the filterable PM emission factor.

In Tables 9.9.1-1 and 9.9.1-2, a number of potential emission sources are presented for each type of facility. The number and type of processes that occur within a specific elevator or grain processing plant will vary considerably from one facility to another. The total emissions from a specific facility will be dependent upon the different types of processes and the number of times a process or operation occurs within each facility. Not all processes occur at every facility; therefore, the specific emission sources and number of sources must be determined for each individual facility. It is not appropriate to sum emission factors for all sources and assume that total factor for all facilities.

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10.5 Plywood Manufacturing

10.5.1 General

Plywood is a building material consisting of veneers (thin wood layers or plies) bonded with an adhesive. The outer layers (face and back) surround a core that is usually lumber, veneer, or particleboard. Plywood has many uses, including wall siding, sheathing, roof decking, concrete formboards, floors, and containers.

10.5.2 Process Description^{1-3,15}

The manufacture of plywood consists of seven main processes: log debarking and bucking, heating the logs, peeling the logs into veneers, drying the veneers, gluing the veneers together, pressing the veneers in a hot press, and finishing processes such as sanding and trimming. Figure 10.5-1 provides a generic process flow diagram for a plywood mill.

The initial step of debarking is accomplished by feeding logs through one of several types of debarking machines. The purpose of this operation is to remove the outer bark of the tree without substantially damaging the wood. Although the different types of machines function somewhat differently, emissions from the different machines are comparable. After the bark is removed, the logs are cut to appropriate lengths in a step known as bucking.

The logs (now referred to as blocks) then are heated to improve the cutting action of the veneer lathe or slicer, thereby generating a product from the lathe or slicer with better surface finish. Blocks are heated to around 93°C (200°F) using a variety of methods--hot water baths, steam heat, hot water spray, or a combination of the three.

After heating, the logs are processed to generate veneer. For most applications, a veneer lathe is used, but some decorative, high quality veneer is generated with a veneer slicer. The slicer and veneer lathe both work on the same principle; the wood is compressed with a nosebar while the veneer knife cuts the blocks into veneers that are typically 3 mm (1/8 in.) thick. These pieces are then clipped to a useable width, typically 1.37 m (54 in.), to allow for shrinkage and trim.

Veneers are taken from the clipper to a veneer dryer where they are dried to moisture contents that range from less than 1 to 15 percent. Target moisture contents depend on the type of resin used in subsequent gluing steps. The typical drying temperature ranges from 150° to 200°C (300° to 400°F). The veneer dryer may be a longitudinal dryer, which circulates air parallel to the veneer, or a jet dryer. The jet driers direct hot, high velocity air at the surface of the veneers in order to create a more turbulent flow of air. The increased turbulence provides more effective use of dryer energy, thereby reducing drying time. In direct-heated wood-fired dryers, the combustion gases are blended with recirculated exhaust from the dryer to reduce the combustion gas temperature. In such cases, the gases entering the dryer generally are maintained in the range of 316° to 427°C (600° to 800°F).

When the veneers have been dried to their specified moisture content, they are glued together with a thermosetting resin. The two main types of resins are phenol-formaldehyde, which is used for softwood and exterior grades of hardwood, and urea-formaldehyde, which is used to glue interior grades of hardwood. The resins are applied by glue spreaders, curtain coaters, or spray systems. Spreaders have a

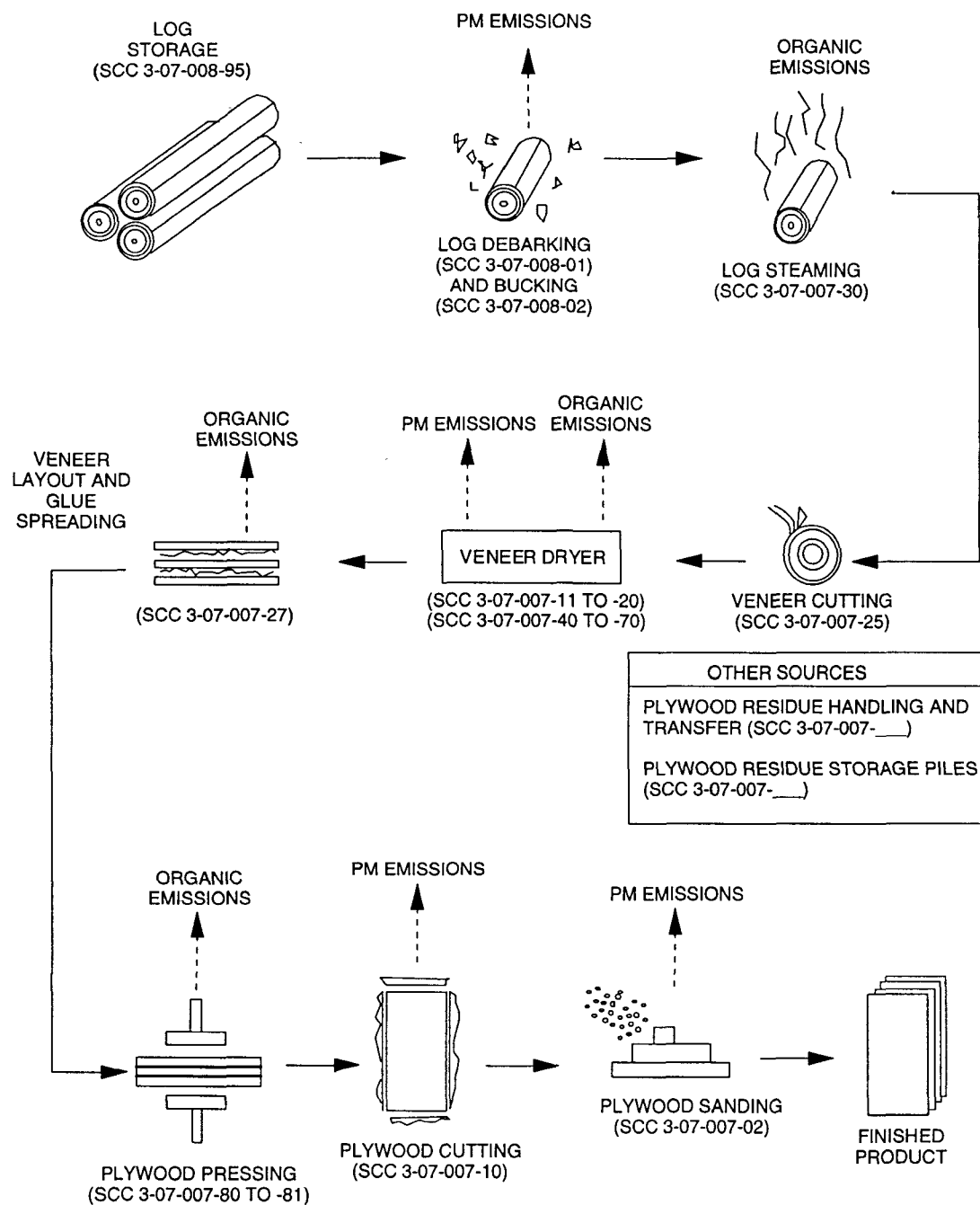


Figure 10.5-1. Generic process flow diagram for a plywood mill.
(SCC = Source Classification Code.)

series of rubber-covered grooved application rolls that apply the resin to the sheet of veneer. Generally, resin is spread on two sides of one ply of veneer, which is then placed between two plies of veneer that are not coated with resin.

Assembly of the plywood panels must be symmetrical on either side of a neutral center in order to avoid excessive warpage. For example, a five-ply panel would be laid up in the following manner. A back, with the grain direction parallel to the long axis of the panel, is placed on the assembly table. The next veneer has a grain direction perpendicular to that of the back, and is spread with resin on both sides. Then, the center is placed, with no resin, and with the grain perpendicular to the previous veneer (parallel with the back). The fourth veneer has a grain perpendicular to the previous veneer (parallel with the short axis of the panel) and is spread with resin on both sides. The final, face, veneer with no resin is placed like the back with the grain parallel to the long axis of the plywood panel.

The laid-up assembly of veneers then is sent to a hot press in which it is consolidated under heat and pressure. Hot pressing has two main objectives: (1) to press the glue into a thin layer over each sheet of veneer; and (2) to activate the thermosetting resins. Typical press temperatures range from 132° to 165°C (270° to 330°F) for softwood plywood, and 107° to 135°C (225° to 275°F) for hardwood plywood. Press times range from 2 to 7 minutes. The time and temperature vary depending on the wood species used, the resin used, and the press design.

The plywood then is taken to a finishing process where edges are trimmed; the face and back may or may not be sanded smooth. The type of finishing depends on the end product desired.

10.5.3 Emissions and Controls²⁻²⁰

The primary emissions from the manufacture of plywood include filterable particulate matter (PM) and PM less than 10 micrometers in aerodynamic diameter (PM-10) from log debarking and bucking, and plywood cutting and sanding; filterable and condensible PM/PM-10 from drying and pressing; organic compounds from steaming and drying operations; and organic compounds, including formaldehyde and other hazardous air pollutants (HAPs), from gluing and hot pressing. However, trace amounts of combustion by-products, which may include HAPs (e. g., aldehydes), may be present in direct-fired, veneer dryer exhausts as a result of fossil fuel or wood combustion gases being passed through the dryer. Fuel combustion for material drying also can generate carbon monoxide (CO), carbon dioxide (CO₂), sulfur dioxide (SO₂), and nitrogen oxide (NO_x) emissions.

The main source of emissions is the veneer dryer, which emits significant quantities of organic compounds. The quantity and type of organic compounds emitted varies depending on the wood species, the dryer type, and its method of operation. The two discernible fractions released from the dryer are condensibles and volatiles. The condensible organic compounds consist largely of sesqui-terpenes, resin acids, fatty acids, and alcohols. As these condensible compounds cool after being emitted from the stack, they often combine with water vapor to form aerosols, which can cause a blue haze. The other fraction, volatile organic compounds (VOCs), comprises terpenes along with small quantities of volatile combustion by-products where direct-fired dryers are used.

Measurement of VOC and condensible PM emission rates are highly dependent on stack gas and sampling train filter temperatures. When the sampling train filter temperature is higher than the stack gas temperature, the rate of VOC and condensible PM emissions measured will increase with increasing filter temperature, because as filter temperature increases less organic material will condense on the sampling train filter. The available data are inadequate to determine the effect on emissions of recirculating the exhaust from wood-fired veneer dryers to a combustion gas blend box.

The hot pressing operation is also a source of organic emissions. The quantity and composition of emissions from this operation are expected to vary with wood species and resin components. However, few test data are available for hot presses to characterize this variability.

Significant quantities of sawdust and other small wood particles are generated by plywood cutting and sanding operations. Sanders and trim saws typically have control devices to recover the material for use as a fuel in the dryer or boiler. However, small amounts of PM may be released from cutting and sanding. Log debarking, log bucking, and sawdust handling are additional sources of PM emissions. Finally, fugitive dust emissions are generated from open sources such as sawdust storage piles and vehicular traffic. Emissions from these operations are discussed in more detail in AP-42 Chapter 13.

Particulate matter and PM-10 emissions from log debarking, sawing, sanding, and material handling operations can be controlled through capture in an exhaust system connected to a sized cyclone and/or fabric filter collection system. These wood dust capture and collection systems are used not only to control atmospheric emissions, but also to collect the dust as a by-product fuel for a boiler or dryer.

Methods of controlling PM emissions from the veneer dryer include multiple spray chambers, a packed tower combined with a cyclonic collector, a sand filter scrubber, an ionizing wet scrubber (IWS), an electrified filter bed (EFB), and a wet electrostatic precipitator (WESP). The first three devices are older technologies that are being replaced with newer technologies that combine electrostatic processes with other scrubbing or filtration processes. Wet PM controls, such as IWS and WESP systems also may reduce VOC emissions from veneer dryers, but to a lesser extent than PM emissions are reduced by such systems.

In multiple spray chamber systems, the dryer exhaust is routed through a series of chambers in which water is used to capture pollutants. The water is then separated from the exhaust stream in a demisting zone. Multiple spray chambers are the most common control technology used on veneer dryers today. However, because they provide only limited removal of PM, PM-10, and condensible organic emissions, they are being replaced with newer, more effective techniques. The packed tower/cyclonic collector comprises a spray chamber, a cyclonic collector, and a packed tower in series. Applications of this system are also limited as newer, more efficient controls are applied. The sand filter scrubber incorporates a wet scrubbing section followed by a wet-sand filter and mist eliminator. The larger PM is removed in the scrubber, while a portion of the remaining organic material is collected in the filter bed or the mist eliminator. This scrubbing system is also becoming obsolete as newer, more efficient controls are applied.

Three newer technologies for controlling veneer dryer emissions are the IWS, the EFB, and the WESP. Because applications of these systems are relatively recent, there are limited data on their performance for veneer dryer emission control. The IWS combines electrostatic forces with packed bed scrubbing techniques to remove pollutants from the exhaust stream. The EFB uses electrostatic forces to attract pollutants to an electrically charged gravel bed. The WESP uses electrostatic forces to attract pollutants to either a charged metal plate or a charged metal tube. The collecting surfaces are continually rinsed with water to wash away the pollutants.

Little information is available on control devices for plywood pressing operations, as these operations are generally uncontrolled. However, one test report indicates that hot press emissions at one facility are captured by a large hood placed over and around the hot press and cooling station. The captured emissions are ducted to a packed-bed caustic scrubber. Formaldehyde collected in the scrubber is converted to sodium formate and discharged to the sewer.

A VOC control technology gaining popularity in the wood products industry for controlling both dryer and press exhaust gases is regenerative thermal oxidation. Thermal oxidizers destroy VOCs, CO, and

condensable organics by burning them at high temperatures. Regenerative thermal oxidizers (RTOs) are designed to preheat the inlet emission stream with heat recovered from the incineration exhaust gases. Up to 98 percent heat recovery is possible, although 95 percent is typically specified. Gases entering an RTO are heated by passing through pre-heated beds packed with a ceramic media. A gas burner brings the preheated emissions up to an incineration temperature between 788° and 871°C (1450° and 1600°F) in a combustion chamber with sufficient gas residence time to complete the combustion. Combustion gases then pass through a cooled ceramic bed where heat is extracted. By reversing the flow through the beds, the heat transferred from the combustion exhaust air preheats the gases to be treated, thereby reducing auxiliary fuel requirements. Industry experience has shown that RTOs typically achieve 95 percent reduction for VOC (except at inlet concentrations below 20 parts per million by volume as carbon [ppm-vC]), 70 to 80 percent reduction for CO, and typical NO_x increase of 10 to 20 ppm.

Biofiltration systems can be used effectively for control of a variety of pollutants including organic compounds (including formaldehyde and benzene), NO_x, CO, and PM from both dryer and press exhaust streams. Data from pilot plant studies in U. S. oriented strandboard mills indicate that biofilters can achieve VOC control efficiencies of 70 to 90 percent, formaldehyde control efficiencies of 85 to 98 percent, CO control efficiencies of 30 to 50 percent, NO_x control efficiencies of 80 to 95 percent, and resin/fatty acid control efficiencies of 83 to 99 percent.

Other potential control technologies for plywood veneer dryers and presses include exhaust gas recycle, regenerative catalytic oxidation (RCO), absorption systems (scrubbers), and adsorption systems.

Table 10.5-1 presents emission factors for veneer dryer emissions of PM, including filterable PM and condensable PM. Table 10.5-2 presents emission factors for veneer dryer emissions of SO₂, NO_x, CO, and CO₂. Table 10.5-3 presents emission factors for veneer dryer emissions of organic pollutants. Table 10.5-4 presents emission factors for plywood press emissions of PM, including filterable PM and condensable PM. Table 10.5-5 presents emission factors for plywood press emissions of formaldehyde and VOC. Table 10.5-6 presents emission factors for plywood manufacturing miscellaneous sources.

Table 10.5-1. EMISSION FACTORS FOR PLYWOOD VENEER DRYERS--
PARTICULATE MATTER^a

Source	Emission Control ^c	Filterable ^b				Condensible ^d	EMISSION FACTOR RATING
		PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING		
Direct wood-fired							
Douglas fir (SCC-3-07-007-47)	WESP	0.26	D	ND		0.045	D
Direct natural gas-fired							
Unspecified pines ^e (SCC-3-07-007-50)	None	0.079	E	ND		0.42	E
Indirect heated							
Unspecified pines ^e (SCC-3-07-007-60)	None	0.35	D	ND		1.0	D
Douglas fir (SCC-3-07-007-67)	None	0.070 ^f	D	ND		0.82 ^f	D
Douglas fir (SCC-3-07-007-67)	WESP	0.040	E	ND		0.11	E
Unspecified firs ^g (SCC-3-07-007-66)	WESP	0.034	E	ND		0.065	E
Radio frequency heated							
Unspecified pines ^e (SCC-3-07-007-70)	None	0.0050	E	ND		0.0060	E

^a Emission factor units are pounds per thousand square feet of 3/8-inch thick veneer (lb/MSF 3/8). One lb/MSF 3/8 = 0.5 kg/m³. SCC = source classification code. Reference 19 except where noted otherwise. ND = no data available.

^b Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

^c Emission control device: WESP = wet electrostatic precipitator.

^d Condensible PM is that PM collected in the impinger portion of a PM sampling train.

^e Based on data on the drying of mixed pine species or the drying of veneers which are identified only as pines.

^f References 11,14.

^g Based on data on the drying of mixed fir species or the drying of veneers which are identified only as firs.

Table 10.5-2. EMISSION FACTORS FOR PLYWOOD VENEER DRYERS--SO₂, NO_x, CO, AND CO₂^a

Source	Emission Control	SO ₂	EMISSION FACTOR RATING	NO _x	EMISSION FACTOR RATING	CO	EMISSION FACTOR RATING	CO ₂ ^c	EMISSION FACTOR RATING
Direct wood-fired (SCC-3-07-007-40 to -46)	None	0.058	D	0.24	D	5.1	D	ND	
Direct natural gas-fired (SCC-3-07-007-50)	None	ND		0.012	E	0.57	E	ND	
Indirect heated (SCC-3-07-007-60 to -69)	None	NA		NA		NA		ND	
Radio-frequency heated (SCC-3-07-007-70)	None	ND		ND		ND		ND	

^a Factors represent uncontrolled emissions. SCC = Source Classification Code. ND = no data available. NA = not applicable. All emission factors in units of pounds per thousand square feet of 3/8-inch thick veneer (lb/MSF 3/8). One lb/MSF 3/8 = 0.5 kg/m³. Reference 19.

Table 10.5-3. EMISSION FACTORS FOR PLYWOOD VENEER DRYERS--ORGANICS^a

Source	Emission Control ^b	VOC ^c	EMISSION FACTOR RATING	Formaldehyde	EMISSION FACTOR RATING
Direct wood-fired					
Unspecified pines ^d (SCC 3-07-007-40)	None	3.3 ^e	E	ND	
Hemlock (SCC 3-07-007-44)	None	0.70 ^{e,f}	E	ND	
Douglas fir (SCC 3-07-007-47)	WESP	0.50 ^e	D	ND	
Unspecified firs ^g (SCC 3-07-007-46)	IWS	0.61 ^{e,f}	E	ND	
Direct natural gas-fired					
Unspecified pines ^d (SCC 3-07-007-50)	None	2.1 ^e	E	ND	
Indirect heated					
Unspecified pines ^d (SCC 3-07-007-60)	None	2.7 ^{e,h}	D	ND	
Douglas fir (SCC 3-07-007-67)	None	1.3 ^{e,j}	D	ND	
Poplar (SCC 3-07-007-69)	None	0.033 ^{k,m}	E	0.0023 ^k	E
Radio-frequency heated					
Unspecified pines ^d (SCC 3-07-007-70)	None	0.22 ^e	E	ND	

^a Factors represent uncontrolled emissions unless noted. SCC = Source Classification Code. ND = no data available. All emission factors in units of pounds per thousand square feet of 3/8-inch thick veneer (lb/MSF 3/8). One lb/MSF 3/8 = 0.5 kg/m³. Reference 19 except where noted.

^b Emission control device: WESP = wet electrostatic precipitator; IWS = ionizing wet scrubber.

^c Volatile organic compounds as propane.

^d Based on data on the drying of mixed pine species or on the drying of veneers which are identified only as pines.

^e Emission factor may not account for formaldehyde, which is suspected to be present; VOC factor indicated is likely to be biased low.

^f Reference 10.

^h References 10,19.

^j References 10,14.

^g Based on data on the drying of mixed fir species or on the drying of veneers which are identified only as firs.

^k Reference 12.

^m Emission factor calculated as the sum of the factor for VOC and the factor for formaldehyde, based on a separate measurement.

Table 10.5-4. EMISSION FACTORS FOR PLYWOOD PRESSES--PARTICULATE MATTER^a

Source	Filterable ^b				Condensible ^c	EMISSION FACTOR RATING
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING		
Plywood press PF resin (SCC 3-07-007-80)	0.12	D	ND		0.083	D

^a Reference 19. Emission factors units are pounds per thousand square feet of 3/8-inch thick panel (lb/MSF 3/8). One lb/MSF 3/8 = 0.5 kg/m³. SCC = Source Classification Code. ND = no data available. Factors represent uncontrolled emissions. PF = phenol-formaldehyde.

^b Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

^c Condensible PM is that PM collected in the impinger portion of a PM sampling train.

Table 10.5-5. EMISSION FACTORS FOR PLYWOOD PRESSES--FORMALDEHYDE AND VOC^a

Source	FORMALDEHYDE	EMISSION FACTOR RATING	VOC ^b	EMISSION FACTOR RATING
Plywood press				
PF resin (SCC 3-07-007-80)	ND		0.33 ^{c,d}	D
UF resin (SCC 3-07-007-81)	0.0042	E	0.021 ^e	E
UF resin, wet scrubber (SCC 3-07-007-81)	0.0025	E	0.018 ^e	E

^a Factors represent uncontrolled emissions unless noted. SCC = Source Classification Code. Reference 12 unless otherwise noted. ND = no data available. Emission factor units are pounds per thousand square feet of 3/8-inch thick panel (lb/MSF 3/8). One lb/MSF 3/8 = 0.5 kg/m³. PF = phenol-formaldehyde; UF = urea-formaldehyde.

^b Volatile organic compounds on a propane basis.

^c Reference 19.

^d Emission factor may not account for formaldehyde, which is suspected to be present; VOC factor indicated is likely to be biased low.

^e Emission factor calculated as the sum of the factor for VOC and the factor for formaldehyde, based on a separate measurement.

Table 10.5-6. EMISSION FACTORS FOR PLYWOOD MANUFACTURING--
MISCELLANEOUS SOURCES^a

Source	Pollutant	Emission factor	EMISSION FACTOR RATING
Log storage (SCC 3-07-008-95)	ND		
Log debarking (SCC 3-07-008-01)	ND		
Log bucking (SCC 3-07-008-02)	ND		
Log steaming (SCC 3-07-007-30)	ND		
Veneer cutting (SCC 3-07-007-25)	ND		
Veneer layout and glue spreading (SCC 3-07-007-27)	ND		
Plywood cutting (SCC 3-07-007-10)	ND		
Plywood sanding (SCC 3-07-007-02)	ND		
Plywood residue handling and transfer (SCC 3-07-007-___)	ND		
Plywood residue storage piles (SCC 3-07-007-___)	ND		

^a SCC = Source Classification Code; ND = no data available.

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APPENDIX A

EMISSION FACTOR CALCULATION SPREADSHEETS

This appendix presents printouts of the detailed spreadsheets that were constructed in order to calculate emission factors for plywood veneer dryers and presses. Table A-1 presents the calculations for plywood veneer dryers. Table A-2 presents the calculations for plywood presses. Table A-3 presents a summary of Method 25 and Method 25A VOC data and available formaldehyde data for plywood veneer dryers and presses.

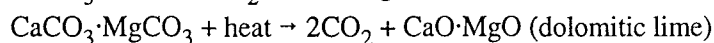
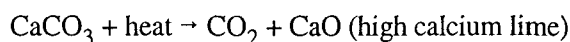
As discussed in Section 4.3.1 of this report, the data available for some of the specific emission factors developed included the results of multiple tests on the same emission source. In such cases, the test-specific emission factors for the same source were averaged first, and that average emission factor then was averaged with the factors for the other sources to yield the candidate emission factors for AP-42. In Table A-1, the emission factor column is divided into two subcolumns, "Test," and "Dryer". The emission factor column labeled "Test" includes the available test-specific emission factors. The emission factor column labeled "Dryer" includes averages of test-specific emission factors for the same dryer. For dryers where only one test-specific emission factor was available, that emission factor appears in both the "Test" and "Dryer" columns. The AP-42 candidate emission factors were developed by averaging the dryer average emission factors in the "Dryer" column. A parallel structure applies to Table A-2 for plywood presses.

11.17 Lime Manufacturing

11.17.1 Process Description¹⁻⁵

Lime is the high-temperature product of the calcination of limestone. Although limestone deposits are found in every state, only a small portion is pure enough for industrial lime manufacturing. To be classified as limestone, the rock must contain at least 50 percent calcium carbonate. When the rock contains 30 to 45 percent magnesium carbonate, it is referred to as dolomite, or dolomitic limestone. Lime can also be produced from aragonite, chalk, coral, marble, and sea shells. The Standard Industry Classification (SIC) code for lime manufacturing is 3274. The six-digit Source Classification Code (SCC) for lime manufacturing is 3-05-016.

Lime is manufactured in various kinds of kilns by one of the following reactions:



In some lime plants, the resulting lime is reacted (slaked) with water to form hydrated lime. The basic processes in the production of lime are: (1) quarrying raw limestone; (2) preparing limestone for the kilns by crushing and sizing; (3) calcining limestone; (4) processing the lime further by hydrating; and (5) miscellaneous transfer, storage, and handling operations. A generalized material flow diagram for a lime manufacturing plant is given in Figure 11.17-1. Note that some operations shown may not be performed in all plants.

The heart of a lime plant is the kiln. The prevalent type of kiln is the rotary kiln, accounting for about 90 percent of all lime production in the United States. This kiln is a long, cylindrical, slightly inclined, refractory-lined furnace, through which the limestone and hot combustion gases pass countercurrently. Coal, oil, and natural gas may all be fired in rotary kilns. Product coolers and kiln feed preheaters of various types are commonly used to recover heat from the hot lime product and hot exhaust gases, respectively.

The next most common type of kiln in the United States is the vertical, or shaft, kiln. This kiln can be described as an upright heavy steel cylinder lined with refractory material. The limestone is charged at the top and is calcined as it descends slowly to discharge at the bottom of the kiln. A primary advantage of vertical kilns over rotary kilns is higher average fuel efficiency. The primary disadvantages of vertical kilns are their relatively low production rates and the fact that coal cannot be used without degrading the quality of the lime produced. There have been few recent vertical kiln installations in the United States because of high product quality requirements.

Other, much less common, kiln types include rotary hearth and fluidized bed kilns. Both kiln types can achieve high production rates, but neither can operate with coal. The "calcimatic" kiln, or rotary hearth kiln, is a circular kiln with a slowly revolving doughnut-shaped hearth. In fluidized bed kilns, finely divided limestone is brought into contact with hot combustion air in a turbulent zone, usually above a perforated

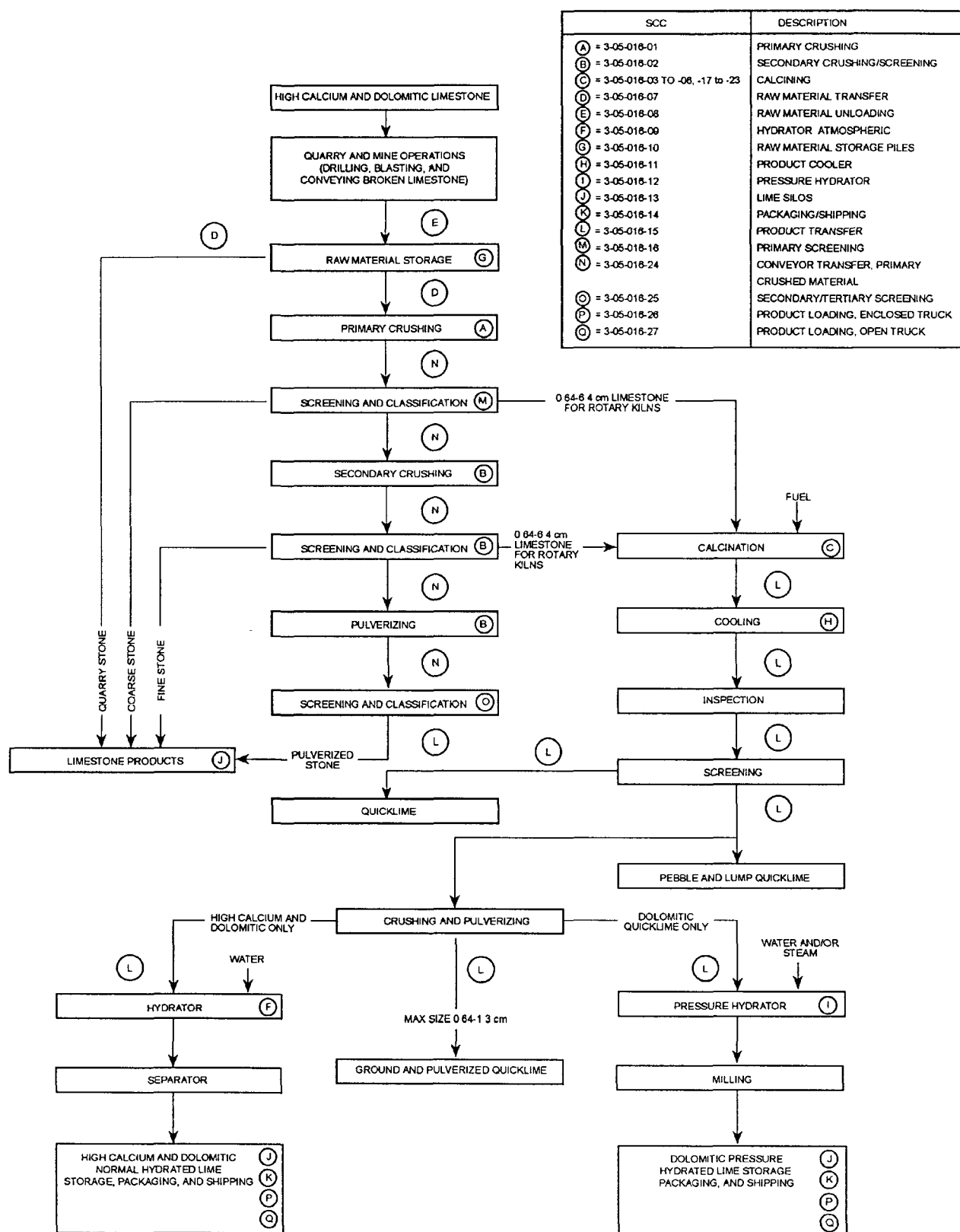


Figure 11.17-1. Process flow diagram for lime manufacturing.⁴
(SCC = Source Classification Code.)

grate. Because of the amount of lime carryover into the exhaust gases, dust collection equipment must be installed on fluidized bed kilns for process economy.

Another alternative process that is beginning to emerge in the United States is the parallel flow regenerative (PR) lime kiln. This process combines 2 advantages. First, optimum heating conditions for lime calcining are achieved by concurrent flow of the charge material and combustion gases. Second, the multiple-chamber regenerative process uses the charge material as the heat transfer medium to preheat the combustion air. The basic PR system has 2 shafts, but 3 shaft systems are used with small size grains to address the increased flow resistance associated with smaller feed sizes.

In the 2-shaft system, the shafts alternate functions, with 1 shaft serving as the heating shaft and the other as the flue gas shaft. Limestone is charged alternatively to the 2 shafts and flows downward by gravity flow. Each shaft includes a heating zone, a combustion/burning zone, and a cooling zone. The 2 shafts are connected in the middle to allow gas flow between them. In the heating shaft, combustion air flows downward through the heated charge material. After being preheated by the charge material, the combustion air combines with the fuel (natural gas or oil), and the air/fuel mixture is fired downward into the combustion zone. The hot combustion gases pass from the combustion zone in the heating shaft to the combustion zone in the flue gas shaft. The heated exhaust gases flow upward through the flue gas shaft combustion zone and into the preheating zone where they heat the charge material. The function of the 2 shafts reverses on a 12-minute cycle. The bottom of both shafts is a cooling zone. Cooling air flows upward through the shaft countercurrently to the flow of the calcined product. This air mixes with the combustion gases in the crossover area providing additional combustion air. The product flows by gravity from the bottom of both shafts.

About 15 percent of all lime produced is converted to hydrated (slaked) lime. There are 2 kinds of hydrators: atmospheric and pressure. Atmospheric hydrators, the more prevalent type, are used in continuous mode to produce high-calcium and dolomitic hydrates. Pressure hydrators, on the other hand, produce only a completely hydrated dolomitic lime and operate only in batch mode. Generally, water sprays or wet scrubbers perform the hydrating process and prevent product loss. Following hydration, the product may be milled and then conveyed to air separators for further drying and removal of coarse fractions.

The major uses of lime are metallurgical (aluminum, steel, copper, silver, and gold industries), environmental (flue gas desulfurization, water softening, pH control, sewage-sludge destabilization, and hazardous waste treatment), and construction (soil stabilization, asphalt additive, and masonry lime).

11.17.2 Emissions And Controls^{1-4,6}

Potential air pollutant emission points in lime manufacturing plants are indicated by SCC in Figure 11.17-1. Except for gaseous pollutants emitted from kilns, particulate matter (PM) is the only dominant pollutant. Emissions of filterable PM from rotary lime kilns constructed or modified after May 3, 1977 are regulated to 0.30 kilograms per megagram (kg/Mg) (0.60 pounds per ton [lb/ton]) of stone feed under 40 CFR Part 60, subpart HH.

The largest ducted source of particulate is the kiln. The properties of the limestone feed and the ash content of the coal (in coal-fired kilns) can significantly affect PM emission rates. Of the various kiln types, fluidized beds have the highest levels of uncontrolled PM emissions because of the very small feed rate combined with the high air flow through these kilns. Fluidized bed kilns are well controlled for maximum product recovery. The rotary kiln is second worst in uncontrolled PM emissions because of the small feed rate and relatively high air velocities and because of dust entrainment caused by the rotating chamber. The calcimatic (rotary hearth) kiln ranks third in dust production primarily because of the larger feed rate and the

fact that, during calcination, the limestone remains stationary relative to the hearth. The vertical kiln has the lowest uncontrolled dust emissions due to the large lump feed, the relatively low air velocities, and the slow movement of material through the kiln. In coal-fired kilns, the properties of the limestone feed and the ash content of the coal can significantly affect PM emissions.

Some sort of particulate control is generally applied to most kilns. Rudimentary fallout chambers and cyclone separators are commonly used to control the larger particles. Fabric and gravel bed filters, wet (commonly venturi) scrubbers, and electrostatic precipitators are used for secondary control.

Carbon monoxide (CO), carbon dioxide (CO₂), sulfur dioxide (SO₂), and nitrogen oxides (NO_x) are all produced in kilns. Sulfur dioxide emissions are influenced by several factors, including the sulfur content of the fuel, the sulfur content and mineralogical form (pyrite or gypsum) of the stone feed, the quality of lime being produced, and the type of kiln. Due to variations in these factors, plant-specific SO₂ emission factors are likely to vary significantly from the average emission factors presented here. The dominant source of sulfur emissions is the kiln's fuel, and the vast majority of the fuel sulfur is not emitted because of reactions with calcium oxides in the kiln. Sulfur dioxide emissions may be further reduced if the pollution equipment uses a wet process or if it brings CaO and SO₂ into intimate contact.

Carbon dioxide is emitted from the kiln as a result of the carbonate in the limestone being reduced to CO₂ gas, and the carbon in the fuel oxidizing. If CO₂ emissions from the fuel combustion are estimated using data from Chapter 1 (External Combustion Sources) only non-combustion CO₂ emission factors should be used (915 kg/Mg (1830 lb/ton) lime produced for dolomitic limestone and 785 kg/Mg (1570 lb/ton) lime produced for calcitic limestone). These estimates are theoretical, based on the production of two moles of CO₂ for each mole of limestone produced. In some facilities a portion of the CO₂ generated is recovered for use in sugar refining.

In sugar refining, a suspension of hydrated lime in water is used to adjust the pH of the product stream and precipitate colloidal impurities.⁷ The lime is then removed by reaction with carbon dioxide.⁷

Product coolers are emission sources only when some of their exhaust gases are not recycled through the kiln for use as combustion air. The trend is away from the venting of product cooler exhaust, however, to maximize fuel use efficiencies. Cyclones, baghouses, and wet scrubbers have been used on coolers for particulate control.

Hydrator emissions are low because water sprays or wet scrubbers are usually installed to prevent product loss in the exhaust gases. Emissions from pressure hydrators may be higher than from the more common atmospheric hydrators because the exhaust gases are released intermittently, making control more difficult.

Other particulate sources in lime plants include primary and secondary crushers, mills, screens, mechanical and pneumatic transfer operations, storage piles, and roads. If quarrying is a part of the lime plant operation, particulate emissions may also result from drilling and blasting. Emission factors for some of these operations are presented in Sections 11.19 and 13.2 of this document.

Tables 11.17-1 (metric units) and 11.17-2 (English units) present emission factors for PM emissions from lime manufacturing calcining, cooling, and hydrating. Tables 11.17-3 (metric units) and 11.17-4 (English units) include emission factors for the mechanical processing (crushing, screening, and grinding) of limestone and for some materials handling operations. Section 11.19, Construction Aggregate Processing, also includes stone processing emission factors that are based on more recent testing, and, therefore, may be more representative of emissions from stone crushing, grinding, and screening. In addition, Section 13.2, Fugitive Dust Sources, includes emission factors for materials handling that may be more representative of materials handling emissions than the emission factors in Tables 11.17-3 and 11.17-4.

Emission factors for emissions of SO₂, NO_x, CO, and CO₂ from lime manufacturing are presented in Tables 11.17-5 and 11.17-6. Particle size distribution for rotary lime kilns is provided in Table 11.17-7.

Because of differences in the sulfur content of the raw material and fuel and in process operations, a mass balance on sulfur may yield a more representative emission factor for a specific facility than the SO₂ emission factors presented in Tables 11.17-5 and 11.17-6. In addition, CO₂ emission factors estimated using a mass balance on carbon may be more representative for a specific facility than the CO₂ emission factors presented in Tables 11.17-5 and 11.17-6. Additional information on estimating emission factors for CO₂ emissions from lime kilns can be found in the background report for this AP-42 section.

11.17.3 Updates Since the Fifth Edition

The Fifth Edition was released in January 1995. Revisions to this section since that date are summarized below. For further detail, consult the memoranda describing each supplement or the background report for this section. These and other documents can be found on the EFIG home page (<http://www.epa.gov/ttn/chief>).

Supplement D, June 1998

- Revision made to distinguish between the carbon dioxide that is emitted from a kiln as a result of the carbonate in the limestone being reduced to CO₂ gas, and the carbon in the fuel oxidizing (based on information already contained in the background report).
- Note added to indicate that some of the CO₂ created in lime manufacturing is used in sugar refining.
- The report cited for the above information was added to the reference section as reference number 7. This changed the numbering for the subsequent references.
- The background document was not revised.

Table 11.17-1 (Metric Units). EMISSION FACTORS FOR LIME MANUFACTURING CALCINING, COOLING, AND HYDRATING^a

Source	Filterable ^b			Condensable PM ^c		
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING	Inorganic	Organic
Coal-fired rotary kiln (SCC 3-05-016-18)	180 ^d	D	22 ^e	D	0.67 ^f	0.51 ^g
Coal-fired rotary kiln with large diameter cyclone (SCC 3-05-016-18)	60 ^h	D	ND		ND	ND
Coal-fired rotary kiln with fabric filter (SCC 3-05-016-18)	0.14 ^j	D	0.077 ^k	D	0.19 ^m	ND
Coal-fired rotary kiln with ESP (SCC 3-05-016-18)	4.3 ^h	D	2.2 ⁿ	D	ND	ND
Coal-fired rotary kiln with venturi scrubber (SCC 3-05-016-18)	0.72 ^p	D	ND		0.14 ^q	ND
Gas-fired rotary kiln with ESP (SCC 3-05-016-19)	0.086 ^r	E	ND		0.11 ^r	ND
Gas-fired rotary kiln with gravel bed filter (SCC 3-05-016-19)	0.51 ^s	E	ND		0.24 ^s	ND
Coal- and gas fired rotary kiln (SCC 3-05-016-20)	40 ^t	E	ND		ND	ND
Coal- and gas-fired rotary kiln with venturi scrubber (SCC 3-05-016-20)	0.44 ^t	D	ND		0.041 ^t	ND
Coal- and coke-fired rotary kiln with venturi scrubber (SCC 3-05-016-21)	0.83 ^u	D	ND		ND	ND
Coal-fired rotary preheater kiln with multiclone (SCC 3-05-016-22)	42 ^v	E	ND		0.040 ^v	ND
Coal-fired rotary preheater kiln with gravel bed filter (SCC 3-05-016-22)	0.59 ^w	E	ND		ND	ND
Coal-fired rotary preheater kiln with multiclone, water spray, and fabric filter (SCC 3-05-016-22)	0.56 ^x	E	ND		0.57 ^x	0.076 ^x
						E

Table 11.17-1 (cont.).

Source	Filterable ^b			Condensable PM ^c		
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING	Inorganic	EMISSION FACTOR RATING
Gas-fired calcinatic kiln (SCC 3-05-016-05)	48 ^y	E	ND	E	0.14 ^y	ND
Gas-fired parallel flow regenerative kiln with fabric filter (SCC 3-05-016-23)	0.051 ^z	D	ND		ND	ND
Atmospheric hydrator with wet scrubber (SCC 3-05-016-09)	0.033 ^{aa}	D	ND		0.0067 ^{aa}	ND
Product cooler (SCC 3-05-016-11)	3.4 ^y	E	ND	E	0.011 ^y	ND

^a Factors represent uncontrolled emissions unless otherwise noted. All emission factors in kg/Mg of lime produced unless noted. ND = no data.

SCC = Source Classification Code.

^b Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

^c Condensable PM is that PM collected in the impinger portion of a PM sampling train.

^d References 11-12.

^e References 4,11-12.

^f References 11,13.

^g Reference 11.

^h Reference 12.

^j References 12,20,31,33.

^k References 4,12,20,31,33.

^m References 9,20-23,33.

ⁿ References 4,12.

^p References 8,28-29.

^q References 8,15-16.

^r Reference 14.

^s References 17,32.

^t Reference 19.

^u Reference 30.

^v Reference 12.

^w Reference 18.

^x Reference 34.

^y Reference 25.

Table 11.17-2 (English Units). EMISSION FACTORS FOR LIME MANUFACTURING CALCINING, COOLING, AND HYDRATING^a

Source	Filterable ^b			Condensable PM ^c		
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING	Inorganic	Organic
Coal-fired rotary kiln (SCC 3-05-016-18)	350 ^d	D	42 ^e	D	1.3 ^f	1.0 ^g
Coal-fired rotary kiln with large diameter cyclone (SCC 3-05-016-18)	120 ^h	D	ND		ND	ND
Coal-fired rotary kiln with fabric filter (SCC 3-05-016-18)	0.28 ^j	D	0.15 ^k	D	0.38 ^m	ND
Coal-fired rotary kiln with ESP (SCC 3-05-016-18)	8.5 ^h	D	4.3 ⁿ	D	ND	ND
Coal-fired rotary kiln with venturi scrubber (SCC 3-05-016-18)	1.4 ^p	D	ND		0.28 ^q	ND
Gas-fired rotary kiln with ESP (SCC 3-05-016-19)	0.17 ^f	E	ND		0.22 ^r	ND
Gas-fired rotary kiln with gravel bed filter (SCC 3-05-016-19)	0.99 ^s	E	ND		0.48 ^s	ND
Coal- and gas fired rotary kiln (SCC 3-05-016-20)	80 ^t	E	ND		ND	ND
Coal- and gas-fired rotary kiln with venturi scrubber (SCC 3-05-016-20)	0.87 ^t	D	ND		0.082 ^t	ND
Coal- and coke-fired rotary kiln with venturi scrubber (SCC 3-05-016-21)	1.7 ^u	D	ND		ND	ND
Coal-fired rotary preheater kiln with multiclone (SCC 3-05-016-22)	84 ^v	E	ND		0.081 ^v	ND
Coal-fired rotary preheater kiln with gravel bed filter (SCC 3-05-016-22)	1.2 ^w	E	ND		ND	ND
Coal-fired rotary preheater kiln with multiclone, water spray, and fabric filter (SCC 3-05-016-22)	1.1 ^x	E	ND		1.1 ^x	0.15 ^x
Gas-fired calcimatic kiln (SCC 3-05-016-05)	97 ^y	E	ND		0.27 ^y	ND

Table 11.17-2 (cont.).

Source	Filterable ^b			Condensable PM ^c		
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING	Inorganic	Organic
Gas-fired parallel flow regenerative kiln with fabric filter (SCC 3-05-016-23)	0.026 ^z	D	ND		ND	ND
Atmospheric hydrator with wet scrubber (SCC 3-05-016-09)	0.067 ^{aa}	D	ND		0.013 ^{aa}	ND
Product cooler (SCC 3-05-016-11)	6.8 ^y	E	ND		0.023 ^y	ND

^a Factors represent uncontrolled emissions unless otherwise noted. Factors are lb/ton of lime produced unless noted. ND = no data. SCC = Source Classification Code.

^b Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

^c Condensable PM is that PM collected in the impinger portion of a PM sampling train.

^d References 11-12.

^e References 4,11-12.

^f References 9,13.

^g Reference 11.

^h Reference 12.

^j References 12,20,31,33.

^k References 4,12,20,31,33.

^m References 8,20-23,33.

ⁿ References 4,12.

^p References 10,28-29.

^q References 10,15-16.

^r Reference 14.

^s References 17,32.

^t Reference 19.

^u Reference 30.

^v Reference 13.

^w Reference 18.

^x Reference 34.

^y Reference 25.

^z Reference 35.

Table 11.17-3 (Metric Units). EMISSION FACTORS FOR LIME MANUFACTURING
RAW MATERIAL AND PRODUCT PROCESSING AND HANDLING^a

Source	Filterable ^b			
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING
Primary crusher ^c (SCC 3-05-016-01)	0.0083	E	ND	
Scalping screen and hammermill (secondary crusher) ^c (SCC 3-05-016-02)	0.31	E	ND	
Primary crusher with fabric filter ^d (SCC 3-05-016-01)	0.00021	D	ND	
Primary screen with fabric filter ^e (SCC 3-05-016-16)	0.0030	D	ND	
Crushed material conveyor transfer with fabric filter ^f (SCC 3-05-016-24)	4.4x10 ⁻⁵	D	ND	
Secondary and tertiary screen with fabric filter ^g (SCC 3-05-016-25)	6.5x10 ⁻⁵	D	ND	
Product transfer and conveying (SCC 3-05-016-15) ^h	1.1	E	ND	
Product loading, enclosed truck (SCC 3-05-016-26) ^h	0.31	D	ND	
Product loading, open truck (SCC 3-05-016-27) ^h	0.75	D	ND	

^a Factors represent uncontrolled emissions unless otherwise noted. Factors are kg/Mg of material processed unless noted. ND = no data. SCC = Source Classification Code.

^b Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

^c Reference 8; units of kg/Mg of stone processed.

^d Reference 35. Emission factors in units of kg/Mg of material processed. Includes scalping screen, scalping screen discharges, primary crusher, primary crusher discharges, and ore discharge.

^e Reference 35. Emission factors in units of kg/Mg of material processed. Includes primary screening, including the screen feed, screen discharge, and surge bin discharge.

^f Reference 35. Emission factors in units of kg/Mg of material processed. Based on average of three runs each of emissions from two conveyor transfer points on the conveyor from the primary crusher to the primary stockpile.

^g Reference 35. Emission factors in units of kg/Mg of material processed. Based on sum of emissions from two emission points that include conveyor transfer point for the primary stockpile underflow to the secondary screen, secondary screen, tertiary screen, and tertiary screen discharge.

^h Reference 12; units of kg/Mg of product loaded.

Table 11.17-4 (English Units). EMISSION FACTORS FOR LIME MANUFACTURING
RAW MATERIAL AND PRODUCT PROCESSING AND HANDLING^a

Source	Filterable ^b			
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING
Primary crusher ^c (SCC 3-05-016-01)	0.017	E	ND	
Scalping screen and hammermill (secondary crusher) (SCC 3-05-016-02) ^c	0.62	E	ND	
Primary crusher with fabric filter ^d (SCC 3-05-016-01)	0.00043	D	ND	
Primary screen with fabric filter ^e (SCC 3-05-016-16)	0.00061	D	ND	
Crushed material conveyor transfer with fabric filter ^f (SCC 3-05-016-24)	8.8x10 ⁻⁵	D	ND	
Secondary and tertiary screen with fabric filter ^g (SCC 3-05-016-25)	0.00013	D	ND	
Product transfer and conveying (SCC 3-05-016-15) ^h	2.2	E	ND	
Product loading, enclosed truck (SCC 3-05-016-26) ^h	0.61	D	ND	
Product loading, open truck (SCC 3-05-016-27) ^h	1.5	D	ND	

^a Factors represent uncontrolled emissions unless otherwise noted. Factors are lb/ton of material processed unless noted. ND = no data. SCC = Source Classification Code.

^b Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

^c Reference 8; factors are lb/ton.

^d Reference 35. Factors are lb/ton of material processed. Includes scalping screen, scalping screen discharges, primary crusher, primary crusher discharges, and ore discharge.

^e Reference 35. Factors are lb/ton of material processed. Includes primary screening, including the screen feed, screen discharge, and surge bin discharge.

^f Reference 35. Factors are lb/ton of material processed. Based on average of three runs each of emissions from two conveyor transfer points on the conveyor from the primary crusher to the primary stockpile.

^g Reference 35. Emission factors in units of kg/Mg of material processed. Based on sum of emissions from two emission points that include conveyor transfer point for the primary stockpile underflow to the secondary screen, secondary screen, tertiary screen, and tertiary screen discharge.

^h Reference 12; units are lb/ton of product loaded.

Table 11.17-5 (Metric Units). EMISSION FACTORS FOR LIME MANUFACTURING^a

Source	EMISSION FACTOR RATING		SO ₂	EMISSION FACTOR RATING		NO _x	EMISSION FACTOR RATING		CO	EMISSION FACTOR RATING		CO ₂ ^c	EMISSION FACTOR RATING	
	SO ₂ ^b													
Coal-fired rotary kiln (SCC 3-05-016-18)	2.7 ^d	D	ND		C	1.6 ^e		C	0.74 ^f	D		1,600 ^g		C
Coal-fired rotary kiln with fabric filter (SCC 3-05-016-18)	0.83 ^h	D	ND			ND			ND			ND		
Coal-fired rotary kiln with wet scrubber (SCC 3-05-016-18)	0.15 ^j	D	0.11 ^k	E		ND			ND			ND		
Gas-fired rotary kiln (SCC 3-05-016-19)	ND		ND		E	1.7 ^m		E	1.1 ⁿ	E		ND		
Coal- and gas-fired rotary kiln with venturi scrubber (SCC 3-05-016-20)	ND		ND			1.4 ⁿ		D	0.41 ⁿ	D		1,600 ⁿ		D
Coal- and coke-fired rotary kiln with venturi scrubber (SCC 3-05-016-21)	ND		ND			ND			ND			1,500 ^p		D
Coal-fired rotary preheater kiln with dry PM controls (SCC 3-05-016-22)	1.1 ^q	E	ND			ND			ND			ND		
Coal-fired rotary preheater kiln with multiclone, water spray, and fabric filter (SCC 3-05-016-22)	3.2 ^r	E	ND			ND			3.2 ^r	E		1,200 ^r		E
Gas-fired calcimatic kiln (SCC 3-05-016-05)	ND		ND		D	0.076 ^s		D	ND			1,300 ^s		E
Gas-fired parallel flow regenerative kiln with fabric filter (SCC 3-05-016-23)	0.0060 ^t	D	ND			0.12 ^t		D	0.23 ^t	D		ND		
Product cooler (SCC 3-05-016-11)	ND	ND				ND			ND			3.9 ^s		E

^a Factors represent uncontrolled emissions unless otherwise noted. Factors are kg/Mg of lime produced unless noted. ND = no data. SCC = Source Classification Code.

^b Mass balance on sulfur may yield a more representative emission factor for a specific facility.

^c Mass balance on carbon may yield a more representative emission factor for a specific facility.

^d References 11,20.

^e References 11,13,20,31,33.

^f References 20,27.

^g References 10-11,26-29,31.

^h References 20,31,33.
^j Reference 27.
^k Reference 15.
^m Reference 14.
ⁿ Reference 19.
^p Reference 30.
^q References 18,26.
^r Reference 34.
^s Reference 25.
^t Reference 35.

Table 11.17-5 (cont.).

Table 11.17-6 (English Units). EMISSION FACTORS FOR LIME MANUFACTURING^a

Source	SO ₂ ^b	EMISSION FACTOR RATING	SO ₃	EMISSION FACTOR RATING	NO _x	EMISSION FACTOR RATING	CO	EMISSION FACTOR RATING	CO ₂ ^c	EMISSION FACTOR RATING
Coal-fired rotary kiln (SCC 3-05-016-18)	5.4 ^d	D	ND		3.1 ^e	C	1.5 ^f	D	3,200 ^g	C
Coal-fired rotary kiln with fabric filter (SCC 3-05-016-18)	1.7 ^h	D	ND		ND		ND		ND	
Coal-fired rotary kiln with wet scrubber (SCC 3-05-016-18)	0.30 ^j	D	0.21 ^k	E	ND		ND		ND	
Gas-fired rotary kiln (SCC 3-05-016-19)	ND		ND		3.5 ^m	E	2.2 ^m	E	ND	
Coal- and gas fired rotary kiln with venturi scrubber (SCC 3-05-016-20)	ND		ND		2.7 ⁿ	D	0.83 ⁿ	D	3,200 ⁿ	D
Coal- and coke-fired rotary kiln with venturi scrubber (SCC 3-05-016-21)	ND		ND		ND		ND		3,000 ^p	D
Coal-fired rotary preheater kiln with dry PM controls (SCC 3-05-016-22)	2.3 ^q	E	ND		ND		ND		ND	
Coal-fired rotary preheater kiln with multiclone, water spray, and fabric filter (SCC 3-05-016-22)	6.4 ^r	E	ND		ND		6.3 ^r	E	2,400 ^r	E
Gas-fired calcimatic kiln (SCC 3-05-016-05)	ND		ND		0.15 ^s	D	ND		2,700 ^s	E
Gas-fired parallel flow regenerative kiln with fabric filter (SCC 3-05-016-23)	0.0012 ^t	D	ND		0.24 ^t	D	0.45 ^t	D	ND	
Product cooler (SCC 3-05-016-11)	ND		ND		ND		ND		7.8 ^s	E

^a Factors represent uncontrolled emissions unless otherwise noted. Factors are lb/ton of lime produced unless noted. ND = no data. SCC = Source Classification Code.

^b Mass balance on sulfur may yield a more representative emission factor for a specific facility.

^c Mass balance on carbon may yield a more representative emission factor for a specific facility.

^d References 11,20.

^e References 11,13,20,31,33.

^f References 20,27.

Table 11.17-6 (cont.).

^h	References 20,31,33.
^j	Reference 27.
^k	Reference 15.
^m	Reference 14.
ⁿ	Reference 19.
^p	Reference 30.
^q	References 18,26.
^r	Reference 34.
^s	Reference 25.
^t	Reference 35.

Table 11.17-7. AVERAGE PARTICLE SIZE DISTRIBUTION FOR ROTARY LIME KILNS^a

Particle Size (μm)	Cumulative Mass Percent Less Than Stated Particle Size			
	Uncontrolled Rotary Kiln	Rotary Kiln With Multiclone	Rotary Kiln With ESP	Rotary Kiln With Fabric Filter
2.5	1.4	6.1	14	27
5.0	2.9	9.8	ND	ND
10.0	12	16	50	55
15.0	31	23	62	73
20.0	ND	31	ND	ND

^a Reference 4, Table 4-28; based on A- and C-rated particle size data. Source Classification Codes 3-05-016-04, and -18 to -21. ND = no data.

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12.1 Primary Aluminum Production

12.1.1 General¹

Primary aluminum refers to aluminum produced directly from mined ore. The ore is refined and electrolytically reduced to elemental aluminum. There are 13 companies operating 23 primary aluminum reduction facilities in the U. S. In 1991, these facilities produced 4.5 million tons of primary aluminum.

12.1.2 Process Description²⁻³

Primary aluminum production begins with the mining of bauxite ore, a hydrated oxide of aluminum consisting of 30 to 56 percent alumina (Al_2O_3) and lesser amounts of iron, silicon, and titanium. The ore is refined into alumina by the Bayer process. The alumina is then shipped to a primary aluminum plant for electrolytic reduction to aluminum. The refining and reducing processes are seldom accomplished at the same facility. A schematic diagram of primary aluminum production is shown in Figure 12.1-1.

12.1.2.1 Bayer Process Description -

In the Bayer process, crude bauxite ore is dried, ground in ball mills, and mixed with a preheated spent leaching solution of sodium hydroxide (NaOH). Lime (CaO) is added to control phosphorus content and to improve the solubility of alumina. The resulting slurry is combined with sodium hydroxide and pumped into a pressurized digester operated at 221 to 554°F. After approximately 5 hours, the slurry of sodium aluminate (NaAl_2OH) solution and insoluble red mud is cooled to 212°F and sent through either a gravity separator or a wet cyclone to remove coarse sand particles. A flocculent, such as starch, is added to increase the settling rate of the red mud. The overflow from the settling tank contains the alumina in solution, which is further clarified by filtration and then cooled. As the solution cools, it becomes supersaturated with sodium aluminate. Fine crystals of alumina trihydrate ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$) are seeded in the solution, causing the alumina to precipitate out as alumina trihydrate. After being washed and filtered, the alumina trihydrate is calcined to produce a crystalline form of alumina, which is advantageous for electrolysis.

12.1.2.2 Hall-Heroult Process -

Crystalline Al_2O_3 is used in the Hall-Heroult process to produce aluminum metal. Electrolytic reduction of alumina occurs in shallow rectangular cells, or "pots", which are steel shells lined with carbon. Carbon electrodes extending into the pot serve as the anodes, and the carbon lining serves as the cathode. Molten cryolite (Na_3AlF_6) functions as both the electrolyte and the solvent for the alumina. The electrolytic reduction of Al_2O_3 by the carbon from the electrode occurs as follows:



Aluminum is deposited at the cathode, where it remains as molten metal below the surface of the cryolite bath. The carbon anodes are continuously depleted by the reaction. The aluminum product is tapped every 24 to 48 hours beneath the cryolite cover, using a vacuum siphon. The aluminum is then transferred to a reverberatory holding furnace where it is alloyed, fluxed, and

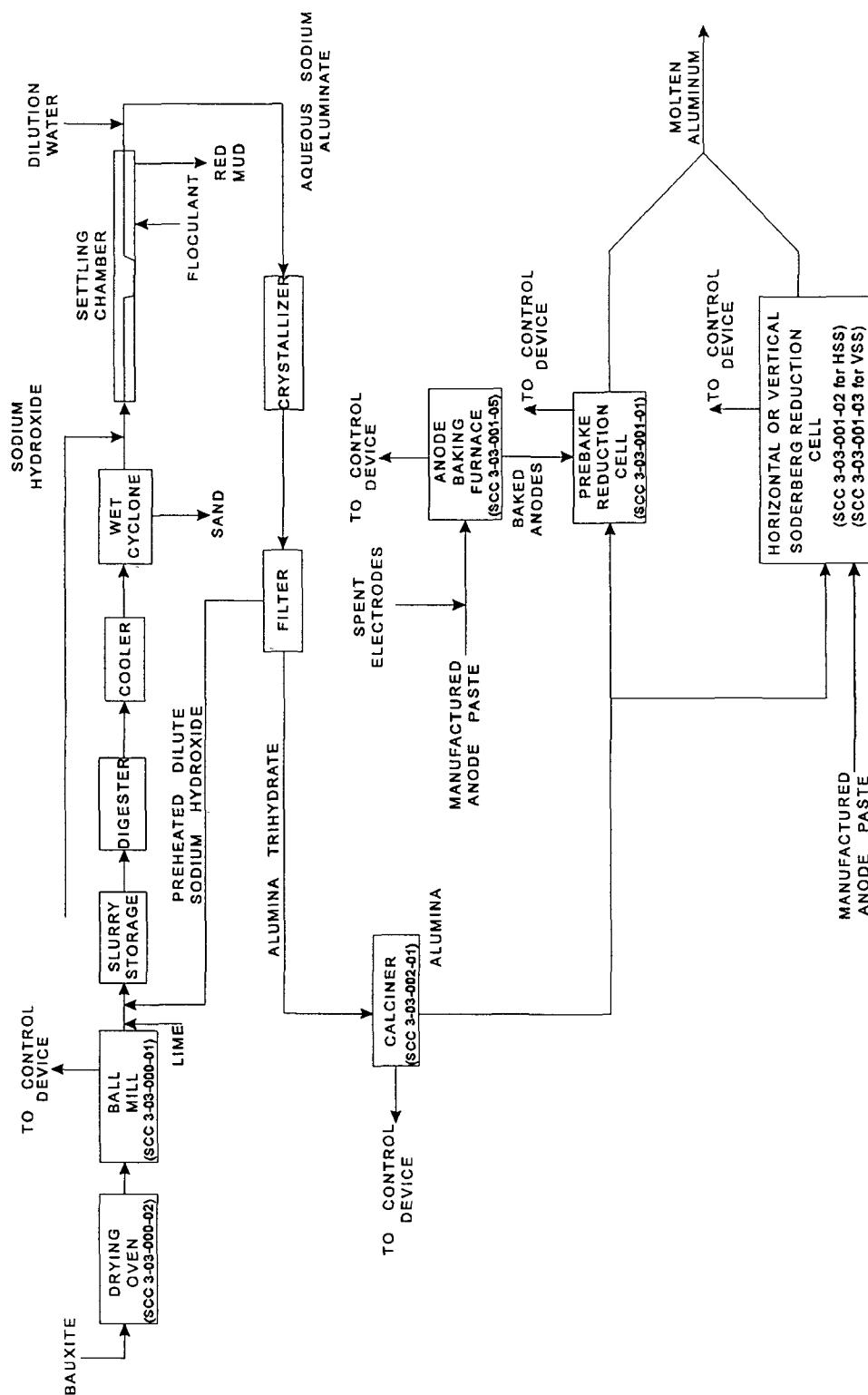


Figure 12.1-1. Schematic diagram of aluminum production process. (Source Classification Codes in parentheses.)

degassed to remove trace impurities. (Aluminum reverberatory furnace operations are discussed in detail in Section 12.8, "Secondary Aluminum Operations".) From the holding furnace, the aluminum is cast or transported to fabricating plants.

Three types of aluminum reduction cells are now in use: prebaked anode cell (PB), horizontal stud Soderberg anode cell (HSS), and vertical stud Soderberg anode cell (VSS). Most of the aluminum produced in the U. S. is processed using the prebaked cells.

All three aluminum cell configurations require a "paste" (petroleum coke mixed with a pitch binder). Paste preparation includes crushing, grinding, and screening of coke and blending with a pitch binder in a steam jacketed mixer. For Soderberg anodes, the thick paste mixture is added directly to the anode casings. In contrast, the prebaked ("green") anodes are produced as an ancillary operation at a reduction plant.

In prebake anode preparation, the paste mixture is molded into green anode blocks ("butts") that are baked in either a direct-fired ring furnace or a Reid Hammer furnace, which is indirectly heated. After baking, steel rods are inserted and sealed with molten iron. These rods become the electrical connections to the prebaked carbon anode. Prebaked cells are preferred over Soderberg cells because they are electrically more efficient and emit fewer organic compounds.

12.1.3 Emissions And Controls²⁻¹⁰

Controlled and uncontrolled emission factors for total particulate matter, gaseous fluoride, and particulate fluoride are given in Table 12.1-1. Table 12.1-2 gives available data for size-specific particulate matter emissions for primary aluminum industry processes.

In bauxite grinding, hydrated aluminum oxide calcining, and materials handling operations, various dry dust collection devices (centrifugal collectors, multiple cyclones, or Electrostatic precipitators (ESPs) and/or wet scrubbers) have been used. Large amounts of particulate are generated during the calcining of hydrated aluminum oxide, but the economic value of this dust leads to the use of extensive controls which reduce emissions to relatively small quantities.

Emissions from aluminum reduction processes are primarily gaseous hydrogen fluoride and particulate fluorides, alumina, carbon monoxide, carbon dioxide (CO₂), volatile organics, and sulfur dioxide (SO₂) from the reduction cells. The source of fluoride emissions from reduction cells is the fluoride electrolyte, which contains cryolite, aluminum fluoride (AlF₃), and fluorospar (CaF₂). The dissociation of the molten cryolite is the source of the perfluorinated carbons (PFCs) — tetrafluoromethane (CF₄) and hexafluoroethane (C₂F₆) — which are formed during anode effects. The factors related to the formation of PFCs are not currently well understood, but they can be formed either by direct reaction of the fluorine with the carbon anode or electrochemically.¹¹ The emission factors for CF₄ and C₂F₆ presented here should be used with caution due to the lack of information on their formation. Table 12.1-3 presents emission factors for greenhouse gases. The CO₂ emission factors shown in Table 12.1-3 assume that all of the carbon used in the production process is emitted as CO₂. While some of the carbon is emitted as CO, there is insufficient data to develop emission factors for CO. Therefore, the carbon emitted as CO is treated here as CO₂ because it is assumed that it will eventually be oxidized to CO₂ after being emitted. Because the primary source of carbon in the anodes is petroleum coke (some is also from the pitch binder), care must be taken not to double count CO₂ emissions in a greenhouse gas emissions inventory if the CO₂ emissions from aluminum production are also accounted for as a non-fuel use of petroleum coke.

Particulate emissions from reduction cells include alumina and carbon from anode dusting, and cryolite, aluminum fluoride, calcium fluoride, chiolite ($\text{Na}_5\text{Al}_3\text{F}_{14}$), and ferric oxide. Representative size distributions for fugitive emissions from PB and HSS plants, and for particulate emissions from HSS cells, are presented in Table 12.1-2.

Emissions from reduction cells also include hydrocarbons or organics, carbon monoxide, and sulfur oxides. These emission factors are not presented here because of a lack of data. Small amounts of hydrocarbons are released by PB pots, and larger amounts are emitted from HSS and VSS pots. In vertical cells, these organics are incinerated in integral gas burners. Sulfur oxides originate from sulfur in the anode coke and pitch, and concentrations of sulfur oxides in VSS cell emissions range from 200 to 300 parts per million. Emissions from PB plants usually have SO_2 concentrations ranging from 20 to 30 parts per million.

Emissions from anode bake ovens include the products of fuel combustion; high boiling organics from the cracking, distillation, and oxidation of paste binder pitch; sulfur dioxide from the sulfur in carbon paste, primarily from the petroleum coke; fluorides from recycled anode butts; and other particulate matter. Emission factors for these components are not included in this document due to insufficient data. Concentrations of uncontrolled SO_2 emissions from anode baking furnaces range from 5 to 47 parts per million (based on 3 percent sulfur in coke).

High molecular weight organics and other emissions from the anode paste are released from HSS and VSS cells. These emissions can be ducted to gas burners to be oxidized, or they can be collected and recycled or sold. If the heavy tars are not properly collected, they can cause plugging of exhaust ducts, fans, and emission control equipment.

A variety of control devices has been used to abate emissions from reduction cells and anode baking furnaces. To control gaseous and particulate fluorides and particulate emissions, 1 or more types of wet scrubbers (spray tower and chambers, quench towers, floating beds, packed beds, venturis) have been applied to all 3 types of reduction cells and to anode baking furnaces. In addition, particulate control methods such as wet and dry electrostatic precipitators (ESPs), multiple cyclones, and dry alumina scrubbers (fluid bed, injected, and coated filter types) are used on all 3 cell types and with anode baking furnaces.

The fluoride adsorption system is becoming more prevalent and is used on all 3 cell types. This system uses a fluidized bed of alumina, which has a high affinity for fluoride, to capture gaseous and particulate fluorides. The pot offgases are passed through the crystalline form of alumina, which was generated using the Bayer process. A fabric filter is operated downstream from the fluidized bed to capture the alumina dust entrained in the exhaust gases passing through the fluidized bed. Both the alumina used in the fluidized bed and that captured by the fabric filter are used as feedstock for the reduction cells, thus effectively recycling the fluorides. This system has an overall control efficiency of 99 percent for both gaseous and particulate fluorides. Wet ESPs approach adsorption in particulate removal efficiency, but they must be coupled to a wet scrubber or coated baghouse to catch hydrogen fluoride.

Scrubber systems also remove a portion of the SO_2 emissions. These emissions could be reduced by wet scrubbing or by reducing the quantity of sulfur in the anode coke and pitch (i.e., calcining the coke).

The molten aluminum may be batch treated in furnaces to remove oxide, gaseous impurities, and active metals such as sodium and magnesium. One process consists of adding a flux of chloride and fluoride salts and then bubbling chlorine gas, usually mixed with an inert gas, through the molten mixture. Chlorine

reacts with the impurities to form HCl, Al_2O_3 , and metal chloride emissions. A dross forms on the molten aluminum and is removed before casting.

Potential sources of fugitive particulate emissions in the primary aluminum industry are bauxite grinding, materials handling, anode baking, and the 3 types of reduction cells (see Table 12.1-1). These fugitive emissions probably have particulate size distributions similar to those presented in Table 12.1-2.

12.1.4 Changes to Section Since 10/86

- ▶ Reformatted in 1995 for the 5th Edition.
- ▶ For Supplement D to the 5th Edition, the tables with metric units were removed and some text and emission factors were added for the Greenhouse gases (CO_2 , CF_4 , and C_2F_6).

Table 12.1-1. EMISSION FACTORS FOR PRIMARY ALUMINUM
 PRODUCTION PROCESSES (lb/ton Al produced)^a
 EMISSION FACTOR RATING: A

Operation	Total Particulate ^b	Gaseous Fluoride	Particulate Fluoride	Reference
Bauxite grinding^c (SCC 3-03-000-01)				
Uncontrolled	6.0	Neg	Neg	1,3
Spray tower	1.8	Neg	Neg	1,3
Floating bed scrubber	1.7	Neg	Neg	1,3
Quench tower and spray screen	1.0	Neg	Neg	1,3
Aluminum hydroxide calcining^d (SCC 3-03-002-01)				
Uncontrolled ^e	200.0	Neg	Neg	1,3
Spray tower	60.0	Neg	Neg	1,3
Floating bed scrubber	56.0	Neg	Neg	1,3
Quench tower	34.0	Neg	Neg	1,3
ESP	4.0	Neg	Neg	1,3
Anode baking furnace (SCC 3-03-001-05)				
Uncontrolled	3.0	0.9	0.1	2,12-13
Fugitive (SCC 3-03-001-11)	ND	ND	ND	NA
Spray tower	0.75	0.04	0.03	12
ESP	0.75	0.04	0.03	2
Dry alumina scrubber	0.06	0.009	0.002	2,12
Prebake cell (SCC 3-03-001-01)				
Uncontrolled	94.0	24.0	20.0	1-2,12-13
Fugitive (SCC 3-03-001-08)	5.0	1.2	1.0	2,12
Emissions to collector	89.0	22.8	19.0	2
Multiple cyclones	19.6	22.8	4.2	2
Dry alumina scrubber	1.8	0.2	0.4	2,12
Dry ESP plus spray tower	4.5	1.4	3.4	2,12
Spray tower	112.8	1.4	3.8	2
Floating bed scrubber	112.8	0.5	3.8	2
Coated bag filter dry scrubber	1.8	3.4	0.4	2
Crossflow packed bed	26.3	6.7	5.6	12
Dry plus secondary scrubber	0.7	0.4	0.3	12

Table 12.1-1 (Cont.)

Operation	Total Particulate ^b	Gaseous Fluoride	Particulate Fluoride	Reference
Vertical Soderberg stud cell (SCC 3-03-001-03)				
Uncontrolled	78.0	33.0	11.0	2,12
Fugitive (SCC 3-03-001-10)	12.0	4.9	1.7	12
Emissions to collector	66.0	28.1	9.3	12
Spray tower	16.5	0.3	2.3	2
Venturi scrubber	2.6	0.3	0.4	2
Multiple cyclones	33.0	28.1	4.7	2
Dry alumina scrubber	1.3	0.3	0.2	2
Scrubber plus ESP plus spray screen and scrubber	7.7	1.5	1.3	2
Horizontal Soderberg stud cell (SCC 3-03-001-02)				
Uncontrolled	98.0	22.0	12.0	2,12
Fugitive (SCC 3-03-001-09)	10.0	2.2	1.2	2,12
Emissions to collector	88.0	19.8	10.8	2,12
Spray tower	22.0	7.5	2.7	2,12
Floating bed scrubber	19.4	0.4	2.4	2
Scrubber plus wet ESP	1.8	0.2	0.2	2,12
Wet ESP	1.8	1.0	0.2	12
Dry alumina scrubber	1.8	0.4	0.2	12

^a To convert from lb/ton to kg/Mg, multiply by 0.5. SCC = Source Classification Code. Neg = negligible. ND = no data. NA = not applicable. Sulfur oxides may be estimated, with an EMISSION FACTOR RATING of C, by the following calculations.

Anode baking furnace, uncontrolled SO₂ emissions (excluding furnace fuel combustion emissions):

$$40(C)(S)(1-0.01 K) \text{ lb/ton}$$

Prebake (reduction) cell, uncontrolled SO₂ emissions:

$$0.4(C)(S)(K) \text{ lb/ton}$$

where:

C = Anode consumption* during electrolysis, lb anode consumed/lb Al produced

S = % sulfur in anode before baking

K = % of total SO₂ emitted by prebake (reduction) cells.

* Anode consumption weight is weight of anode paste (coke + pitch) before baking.

^b Includes particulate fluorides, but does not include condensible organic particulate.

^c For bauxite grinding, units are lb of pollutant/ton of bauxite processed.

^d For aluminum hydroxide calcining, units are lb of pollutant/ton of alumina produced.

^e After multicyclones.

Table 12.1-2. UNCONTROLLED EMISSION FACTORS AND PARTICLE SIZE DISTRIBUTION IN ALUMINUM PRODUCTION^a

EMISSION FACTOR RATING: D (except as noted)

Particle Size ^b (µm)	Prebake Aluminum Cells ^c		HSS Aluminum Cells		HSS Reduction Cells	
	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factor (lb/ton Al produced)	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factor (lb/ton Al produced)	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factor (lb/ton Al produced)
0.625	13	0.67	8	0.8	26	25.5
1.25	18	0.92	13	1.3	32	31.4
2.5	28	1.40	17	1.7	40	39.2
5	43	2.15	23	2.3	50	49.0
10	58	2.90	31	3.1	58	56.8
15	65	3.23	39	3.9	63	61.7
Total	100	2.5	100	10.0	100	98

^a Reference 5. To convert from lb/ton to kg/Mg, multiply by 0.5.

^b Expressed as equivalent aerodynamic particle diameter.

^c EMISSION FACTOR RATING: C

Table 12.1-3. GREENHOUSE GAS EMISSION FACTORS FOR PRIMARY ALUMINUM PRODUCTION PROCESSES^a

Source Category	Pollutant	Emission Factor (lb/ton Al produced)	EMISSION FACTOR RATING	Notes
Aluminum Production — Soderberg Process ^b	CO ₂	3670	C	Assumes carbon consumption of 0.50 lb C/lb Al produced.
Aluminum Production — Prebake Process ^b	CO ₂	3080	C	Assumes carbon consumption of 0.42 lb C/lb Al produced.
Aluminum Production	CF ₄	1.2	E	Industry average. Varies with duration of anode effect, frequency, and current efficiency.
Aluminum Production	C ₂ F ₆	0.12	E	Industry average. Varies with duration of anode effect, frequency, and current efficiency.

^a References 11,14-17. To convert from lb/ton to kg/Mg, multiply by 0.5.

^b Double counting of emissions will occur if CO₂ emissions from aluminum production are also accounted for as a non-fuel use of petroleum coke in a greenhouse gas inventory.

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13.2.1 Paved Roads

13.2.1.1 General

Particulate emissions occur whenever vehicles travel over a paved surface, such as a road or parking lot. Particulate emissions from paved roads are due to direct exhaust from vehicles and resuspension of loose material on the road surface. In general terms, particulate emissions from paved roads originate from the loose material present on the surface. In turn, that surface loading, as it is moved or removed, is continuously replenished by other sources. At industrial sites, surface loading is replenished by spillage of material and trackout from unpaved roads and staging areas. Figure 13.2.1-1 illustrates several transfer processes occurring on public streets.

Various field studies have found that public streets and highways, as well as roadways at industrial facilities, can be major sources of the atmospheric particulate matter within an area.¹⁻⁹ Of particular interest in many parts of the United States are the increased levels of emissions from public paved roads when the equilibrium between deposition and removal processes is upset. This situation can occur for various reasons, including application of snow and ice controls, carryout from construction activities in the area, and wind and/or water erosion from surrounding unstabilized areas. In the absence of continuous addition of fresh material (through localized trackout or application of antiskid material), paved road surface loading should reach equilibrium values in which the amount of material resuspended matches the amount replenished. The equilibrium sL value depends upon numerous factors. It is believed that the most important factors are: mean speed of vehicles traveling the road; the average daily traffic (ADT); the number of lanes and ADT per lane; the fraction of heavy vehicles (buses and trucks); and the presence/absence of curbs, storm sewers and parking lanes.

13.2.1.2 Emissions And Correction Parameters

Dust emissions from paved roads have been found to vary with what is termed the "silt loading" present on the road surface as well as the average weight of vehicles traveling the road. The term silt loading (sL) refers to the mass of silt-size material (equal to or less than 75 micrometers [μm] in physical diameter) per unit area of the travel surface.⁴⁻⁵ The total road surface dust loading is that of loose material that can be collected by broom sweeping and vacuuming of the traveled portion of the paved road. The silt fraction is determined by measuring the proportion of the loose dry surface dust that passes through a 200-mesh screen, using the ASTM-C-136 method. Silt loading is the product of the silt fraction and the total loading, and is abbreviated "sL". Additional details on the sampling and analysis of such material are provided in AP-42 Appendices C.1 and C.2.

The surface sL provides a reasonable means of characterizing seasonal variability in a paved road emission inventory.⁹ In many areas of the country, road surface loadings are heaviest during the late winter and early spring months when the residual loading from snow/ice controls is greatest. As noted earlier, once replenishment of fresh material is eliminated, the road surface loading can be expected to reach an equilibrium value, which is substantially lower than the late winter/early spring value.

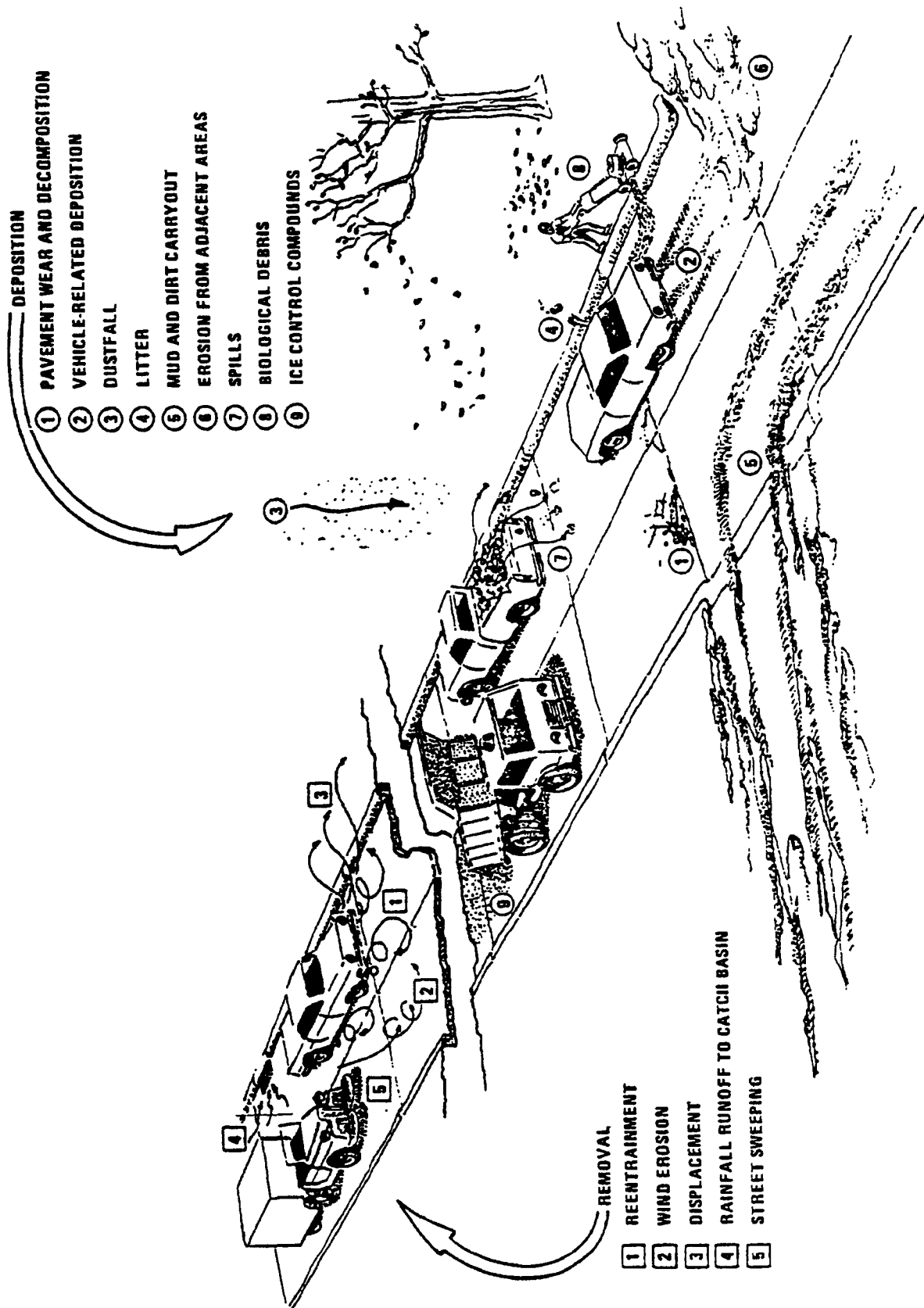


Figure 13.2.1-1. Deposition and removal processes.

13.2.1.3 Predictive Emission Factor Equations¹⁰

The quantity of dust emissions from vehicle traffic on a paved road may be estimated using the following empirical expression:

$$E = k (sL/2)^{0.65} (W/3)^{1.5} \quad (1)$$

where:

- E = particulate emission factor (having units matching the units of k)
- k = base emission factor for particle size range and units of interest (see below)
- sL = road surface silt loading (grams per square meter) (g/m²)
- W = average weight (tons) of the vehicles traveling the road

It is important to note that Equation 1 calls for the average weight of all vehicles traveling the road. For example, if 99 percent of traffic on the road are 2 Mg cars/trucks while the remaining 1 percent consists of 20 Mg trucks, then the mean weight "W" is 2.2 Mg. More specifically, Equation 1 is *not* intended to be used to calculate a separate emission factor for each vehicle weight class. Instead, only one emission factor should be calculated to represent the "fleet" average weight of all vehicles traveling the road.

The particle size multiplier (k) above varies with aerodynamic size range as shown in Table 13.2.1-1. To determine particulate emissions for a specific particle size range, use the appropriate value of k shown in Table 13.2.1-1.

Table 13.2-1.1. PARTICLE SIZE MULTIPLIERS FOR PAVED ROAD EQUATION

Size range ^a	Multiplier k ^b		
	g/VKT	g/VMT	lb/VMT
PM-2.5 ^c	1.1	1.8	0.0040
PM-10	4.6	7.3	0.016
PM-15	5.5	9.0	0.020
PM-30 ^d	24	38	0.082

^a Refers to airborne particulate matter (PM-x) with an aerodynamic diameter equal to or less than x micrometers.

^b Units shown are grams per vehicle kilometer traveled (g/VKT), grams per vehicle mile traveled (g/VMT), and pounds per vehicle mile traveled (lb/VMT). The multiplier k includes unit conversions to produce emission factors in the units shown for the indicated size range from the mixed units required in Equation 1.

^c Ratio of PM-2.5 to PM-10 taken from Reference 22.

^d PM-30 is sometimes termed "suspendable particulate" (SP) and is often used as a surrogate for TSP.

The above equation is based on a regression analysis of numerous emission tests, including 65 tests for PM-10.¹⁰ Sources tested include public paved roads, as well as controlled and uncontrolled industrial paved roads. All sources tested were of freely flowing vehicles on relatively level roads and at constant speed. No tests of "stop-and-go" traffic or vehicles under load were available for inclusion in the data base. The equations retain the quality rating of A (B for PM-2.5), if applied within the range of source conditions that were tested in developing the equation as follows:

Silt loading:	0.02 - 400 g/m ²
	0.03 - 570 grains/square foot (ft ²)
Mean vehicle weight:	1.8 - 38 megagrams (Mg)
	2.0 - 42 tons
Mean vehicle speed:	16 - 88 kilometers per hour (kph)
	10 - 55 miles per hour (mph)

To retain the quality rating for the emission factor equation when it is applied to a specific paved road, it is necessary that reliable correction parameter values for the specific road in question be determined. With the exception of limited access roadways, which are difficult to sample, the collection and use of site-specific sL data for public paved road emission inventories are strongly recommended. The field and laboratory procedures for determining surface material silt content and surface dust loading are summarized in Appendices C.1 and C.2. In the event that site-specific values cannot be obtained, an appropriate value for a paved public road may be selected from the values given in Table 13.2.1-2, but the quality rating of the equation should be reduced by 2 levels. Also, recall that Equation 1 refers to emissions due to freely flowing (not stop-and-go) traffic at constant speed on level roads.

During the preparation of the background document (Reference 10), public road silt loading values from 1992 and earlier were assembled into a data base. This data base is available in the file "oldslat.zip" located at the Internet URL "<http://www.epa.gov/ttn/chief/ap42back.html>" on the World Wide Web. Although hundreds of public paved road sL measurements had been collected, there was no uniformity in sampling equipment and analysis techniques, in roadway classification schemes, and in the types of data reported. Not surprisingly, the data set did not yield a coherent relationship between sL and road class, average daily traffic (ADT), etc., even though an inverse relationship between sL and ADT has been found for a subclass of curbed paved roads in urban areas. Further complicating the analysis is the fact that, in many parts of the country, paved road sL varies greatly over the course of the year, probably because of cyclic variations in mud/dirt carryout and in use of anti-skid materials. Although there were strong reasons to suspect that the assembled data base was skewed towards high values, independent data were not available to confirm the suspicions.

Since the time that the background document was prepared, new field sampling programs have shown that the assembled sL data set is biased high for "normal" situations. Just as importantly, however, the newer programs confirm that substantially higher than "normal" silt loadings can occur on public paved roads. As a result, two sets of default values are provided in Table 13.2.1-2, one for "normal" conditions and another for worst-case conditions (such as after winter storm seasons or in areas with substantial mud/dirt trackout). The newer sL data base is available as in the file "newsldat.zip" located at the Internet URL "<http://www.epa.gov/ttn/chief/ap42back.html>" on the World Wide Web.

Table 13.2.1-2 (Metric Units). RECOMMENDED DEFAULT SILT LOADING (g/m^2)
VALUES FOR PUBLIC PAVED ROADS^a

	High ADT roads ^b	Low ADT roads
Normal conditions	0.1	0.4
Worst-case conditions ^c	0.5	3

^a Excluding limited access roads. See discussion in text. 1 g/m^2 is equal to 1.43 grains/ft^2

^b High ADT refers to roads with at least 5,000 vehicles per day.

^c For conditions such as post-winter-storm or areas with substantial mud/dirt carryout.

The range of sL values in the data base for normal conditions is 0.01 to 1.0 for high-ADT roads and 0.054 to 6.8 for low-ADT roads. Consequently the use of a default value from Table 13.2.1-2 should be expected to yield only an order-of-magnitude estimate of the emission factor. Public paved road silt loadings are dependent upon: traffic characteristics (speed, ADT, and fraction of heavy vehicles); road characteristics (curbs, number of lanes, parking lanes); local land use (agriculture, new residential construction) and regional/seasonal factors (snow/ice controls, wind blown dust). As a result, the collection and use of site-specific silt loading data is highly recommended. In the event that default sL values are used, the quality ratings for the equation should be downgraded 2 levels.

Limited access roadways pose severe logistical difficulties in terms of surface sampling, and few sL data are available for such roads. Nevertheless, the available data do not suggest great variation in sL for limited access roadways from one part of the country to another. For annual conditions, a default value of 0.015 g/m^2 is recommended for limited access roadways.^{9,22} Even fewer of the available data correspond to worst-case situations, and elevated loadings are observed to be quickly depleted because of high traffic speeds and high ADT rates. A default value of 0.2 g/m^2 is recommended for short periods of time following application of snow/ice controls to limited access roads.²²

The limited data on silt loading values for industrial roads have shown as much variability as public roads. Because of the greater variation of traffic conditions, the use of preventive controls and the use of mitigative controls at industrial roads, the data probably do not reflect the potential extent of this variation. However, the collection of site specific silt loading data from industrial roads is easier and safer than for public roads. Therefore, the collection and use of site-specific silt loading data is preferred and is highly recommended. In the event that site-specific values cannot be obtained, an appropriate value for an industrial road may be selected from the mean values given in Table 13.2.1-3, but the quality rating of the equation should be reduced by 2 levels.

13.2.1.4 Controls^{6,23}

Because of the importance of the surface loading, control techniques for paved roads attempt either to prevent material from being deposited onto the surface (preventive controls) or to remove from the travel lanes any material that has been deposited (mitigative controls). Regulations requiring the covering of loads in trucks, or the paving of access areas to unpaved lots or construction sites, are preventive measures. Examples of mitigative controls include vacuum sweeping, water flushing, and broom sweeping and flushing.

Table 13.2.1-3 (Metric And English Units). TYPICAL SILT CONTENT AND LOADING VALUES FOR PAVED ROADS AT INDUSTRIAL FACILITIES^a

Industry	No. Of Sites	No. Of Samples	Silt Content (%)		No. Of Travel Lanes	Total Loading x 10 ⁻³			Silt Loading (g/m ²)	
			Range	Mean		Range	Mean	Units	Range	Mean
Copper smelting	1	3	15.4-21.7	19.0	2	12.9-19.5 45.8-69.2	15.9 55.4	kg/km lb/mi	188-400	292
Iron and steel production	9	48	1.1-35.7	12.5	2	0.006-4.77 0.020-16.9	0.495 1.75	kg/km lb/mi	0.09-79	9.7
Asphalt batching	1	3	2.6-4.6	3.3	1	12.1-18.0 43.0-64.0	14.9 52.8	kg/km lb/mi	76-193	120
Concrete batching	1	3	5.2-6.0	5.5	2	1.4-1.8 5.0-6.4	1.7 5.9	kg/km lb/mi	11-12	12
Sand and gravel processing	1	3	6.4-7.9	7.1	1	2.8-5.5 9.9-19.4	3.8 13.3	kg/km lb/mi	53-95	70
Municipal solid waste landfill	2	7	—	—	2	—	—	—	1.1-32.0	7.4
Quarry	1	6	—	—	2	—	—	—	2.4-14	8.2

^a References 1-2,5-6,11-13. Values represent samples collected from *industrial* roads. Public road silt loading values are presented in

Table-13.2.1-2. Dashes indicate information not available.

^b Multiply entries by 1000 to obtain stated units; kilograms per kilometer (kg/km) and pounds per mile (lb/mi).

It is particularly important to note that street sweeping of gutters and curb areas may actually increase the silt loading on the traveled portion of the road. Redistribution of loose material onto the travel lanes will actually produce a short-term increase in the emissions.

In general, preventive controls are usually more cost effective than mitigative controls. The cost-effectiveness of mitigative controls falls off dramatically as the size of an area to be treated increases. The cost-effectiveness of mitigative measures is also unfavorable if only a short period of time is required for the road to return to equilibrium silt loading condition. That is to say, the number and length of public roads within most areas of interest preclude any widespread and routine use of mitigative controls. On the other hand, because of the more limited scope of roads at an industrial site, mitigative measures may be used quite successfully (especially in situations where truck spillage occurs). Note, however, that public agencies could make effective use of mitigative controls to remove sand/salt from roads after the winter ends.

Because available controls will affect the sL, controlled emission factors may be obtained by substituting controlled silt loading values into the equation. (Emission factors from controlled industrial roads were used in the development of the equation.) The collection of surface loading samples from treated, as well as baseline (untreated), roads provides a means to track effectiveness of the controls over time.

13.2.1.5 Changes since Fifth Edition

The following changes were made since the publication of the Fifth Edition of AP-42:

- 1) The particle size multiplier was reduced by approximately 55% as a result of emission testing specifically to evaluate the PM-2.5 component of the emissions.
- 2) Default silt loading values were included in Table 13.2.1-2 replacing the Tables and Figures containing silt loading statistical information.
- 3) Editorial changes within the text were made indicating the possible causes of variations in the silt loading between roads within and among different locations. The uncertainty of using the default silt loading value was discussed.

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13.2.6 Abrasive Blasting

13.2.6.1 General¹⁻²

Abrasive blasting is the use of abrasive material to clean or texturize a material such as metal or masonry. Sand is the most widely used blasting abrasive. Other abrasive materials include coal slag, smelter slags, mineral abrasives, metallic abrasives, and synthetic abrasives. Industries that use abrasive blasting include the shipbuilding industry, automotive industry, and other industries that involve surface preparation and painting. The majority of shipyards no longer use sand for abrasive blasting because of concerns about silicosis, a condition caused by respiratory exposure to crystalline silica. In 1991, about 4.5 million tons of abrasives, including 2.5 million tons of sand, 1 million tons of coal slag, 500 thousand tons of smelter slag, and 500 thousand tons of other abrasives were used for domestic abrasive blasting operations.

13.2.6.2 Process Description¹⁻⁹

Abrasive blasting systems typically include three essential components: an abrasive container (i. e., blasting pot); a propelling device; and a blasting nozzle or nozzles. The exact equipment used depends to a large extent on the specific application and type(s) of abrasive.

Three basic methods can be used to project the abrasive towards the surface being cleaned: air pressure; centrifugal wheels; or water pressure. Air blast (or dry) systems use compressed air to propel the abrasive using either a suction-type or pressure-type process. Centrifugal wheel systems use a rotating impeller to mechanically propel the abrasive by a combination of centrifugal and inertial forces. Finally, the water (or wet) blast method uses either air pressure or water pressure to propel an abrasive slurry towards the cleaned surface.

Abrasive materials used in blasting can generally be classified as sand, slag, metallic shot or grit, synthetic, or other. The cost and properties associated with the abrasive material dictate its application. The following discusses the general classes of commonly used abrasives.

Silica sand is commonly used for abrasive blasting where reclaiming is not feasible, such as in unconfined abrasive blasting operations. Sand has a rather high breakdown rate, which can result in substantial dust generation. Worker exposure to free crystalline silica is of concern when silica sand is used for abrasive blasting.

Coal and smelter slags are commonly used for abrasive blasting at shipyards. Black BeautyTM, which consists of crushed slag from coal-fired utility boilers, is a commonly used slag. Slags have the advantage of low silica content, but have been documented to release other contaminants, including hazardous air pollutants (HAP), into the air.

Metallic abrasives include cast iron shot, cast iron grit, and steel shot. Cast iron shot is hard and brittle and is produced by spraying molten cast iron into a water bath. Cast iron grit is produced by crushing oversized and irregular particles formed during the manufacture of cast iron shot. Steel shot is produced by blowing molten steel. Steel shot is not as hard as cast iron shot, but is much more durable. These materials typically are reclaimed and reused.

Synthetic abrasives, such as silicon carbide and aluminum oxide, are becoming popular substitutes for sand. These abrasives are more durable and create less dust than sand. These materials typically are reclaimed and reused.

Other abrasives include mineral abrasives (such as garnet, olivine, and staurolite), cut plastic, glass beads, crushed glass, and nutshells. As with metallic and synthetic abrasives, these other abrasives are generally used in operations where the material is reclaimed. Mineral abrasives are reported to create significantly less dust than sand and slag abrasives.

The type of abrasive used in a particular application is usually specific to the blasting method. Dry blasting is usually done with sand, metallic grit or shot, aluminum oxide (alumina), or silicon carbide. Wet blasters are operated with either sand, glass beads, or other materials that remain suspended in water.

13.2.6.3 Emissions And Controls^{1,3,5-11}

Emissions —

Particulate matter (PM) and particulate HAP are the major concerns relative to abrasive blasting. Table 13.2.6-1 presents total PM emission factors for abrasive blasting as a function of wind speed. Higher wind speeds increase emissions by enhanced ventilation of the process and by retardation of coarse particle deposition.

Table 13.2.6-1 also presents fine particulate emission factors for abrasive blasting. Emission factors are presented for PM-10 and PM-2.5, which denote particles equal to or smaller than 10 and 2.5 microns in aerodynamic diameter, respectively. Emissions of PM of these size fractions are not significantly wind-speed dependent. Table 13.2.6-1 also presents an emission factor for controlled emissions from an enclosed abrasive blasting operation controlled by a fabric filter; the blasting media was 30/40 mesh garnet.

Limited data from Reference 3 give a comparison of total PM emissions from abrasive blasting using various media. The study indicates that, on the basis of tons of abrasive used, total PM emissions from abrasive blasting using grit are about 24 percent of total PM emissions from abrasive blasting with sand. The study also indicates that total PM emissions from abrasive blasting using shot are about 10 percent of total PM emissions from abrasive blasting with sand.

Hazardous air pollutants, typically particulate metals, are emitted from some abrasive blasting operations. These emissions are dependent on both the abrasive material and the targeted surface.

Controls —

A number of different methods have been used to control the emissions from abrasive blasting. These methods include: blast enclosures; vacuum blasters; drapes; water curtains; wet blasting; and reclaim systems. Wet blasting controls include not only traditional wet blasting processes but also high pressure water blasting, high pressure water and abrasive blasting, and air and water abrasive blasting. For wet blasting, control efficiencies between 50 and 93 percent have been reported. Fabric filters are used to control emissions from enclosed abrasive blasting operations.

Table 13.2.6-1. PARTICULATE EMISSION FACTORS FOR ABRASIVE BLASTING^a

EMISSION FACTOR RATING: E

Source	Particle size	Emission factor, lb/1,000 lb abrasive
Sand blasting of mild steel panels ^b (SCC 3-09-002-02)	Total PM	
	5 mph wind speed	27
	10 mph wind speed	55
	15 mph wind speed	91
	PM-10 ^c	13
	PM-2.5 ^c	1.3
Abrasive blasting of unspecified metal parts, controlled with a fabric filter ^d (SCC 3-09-002-04)	Total PM	0.69

a One lb/1,000 lb is equal to 1 kg/Mg. Factors represent uncontrolled emissions, unless noted.
SCC = Source Classification Code.

^b Reference 10.

^c Emissions of PM-10 and PM-2.5 are not significantly wind-speed dependent.

^d Reference 11. Abrasive blasting with garnet blast media.

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14.4 Enteric Fermentation—Greenhouse Gases

14.4.1 General

The description of this source is drawn from a report by Gibbs and Leng.¹ The methodology and factors presented in this section are drawn directly from the methodology description in the *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, prepared by the U. S. EPA Office of Policy, Planning and Evaluation (OPPE),² *International Anthropogenic Methane Emissions: Estimates for 1990*,³ and Crutzen, et al. (1986).⁴ A more detailed discussion of biology and variables affecting methane (CH₄) generation from ruminant digestion can be found in those volumes.

Enteric fermentation is fermentation that takes place in the digestive systems of animals. In particular, ruminant animals (cattle, buffalo, sheep, goats, and camels) have a large "fore-stomach," or rumen, within which microbial fermentation breaks down food into soluble products that can be utilized by the animal.^{1,2} Approximately 200 species and strains of microorganisms are present in the anaerobic rumen environment, although only a small portion, about 10 to 20 species, are believed to play an important role in ruminant digestion.⁵ The microbial fermentation that occurs in the rumen enables ruminant animals to digest coarse plant material that monogastric animals cannot digest.^a

Methane is produced in the rumen by bacteria as a by-product of the fermentation process. This CH₄ is exhaled or belched by the animal and accounts for the majority of emissions from ruminants. Methane also is produced in the large intestines of ruminants and is expelled.^{1,2}

There are a variety of factors that affect CH₄ production in ruminant animals, such as: the physical and chemical characteristics of the feed, the feeding level and schedule, the use of feed additives to promote production efficiency, and the activity and health of the animal. It has also been suggested that there may be genetic factors that affect CH₄ production. Of these factors, the feed characteristics and feed rate have the most influence.²

To describe CH₄ production by ruminant animals, it is convenient to refer to the portion of feed energy (food caloric value) intake that is converted to CH₄. Higher levels of conversion translate into higher emissions, given constant feed energy intake. Similarly, higher levels of intake translate into higher emissions, given constant conversion. There are, however, interactions between level of intake and conversion to CH₄, so these values are not independent.^{1,2}

Methane production as a fraction of the animal's gross energy intake generally will decrease as daily intake increases for the same diet, but the actual quantity of CH₄ produced may increase due to the greater amount of fermentable material. Because of the complex relationship between the quantity of feed and the CH₄ yield percentage, emission factors and straightforward emission equations can be used for general approximations only. In cases where the animal type, feed quality, and feed quantity are narrowly characterized and matched to reliable CH₄ yield percent values, CH₄ emission factors are much more accurate. In addition, feed intake changes over time with animal performance. Periodic updates to the emission factors are required to reflect changes in animal management characteristics.

As a result of the various interrelationships among feed characteristics, feed intake, and conversion rates to CH₄, most well-fed ruminant animals in temperate agriculture systems will convert about 5.5-6.5 percent of their feed energy intake to CH₄. Given this range for the rate of CH₄ formation, CH₄ emissions

^a Monogastric animals have a single-chambered stomach, unlike the multi-chambered stomachs of ruminants. Examples of monogastric animals include swine, dogs, monkeys, and humans.

can be estimated based on the feed energy consumed by the animals. Because feed energy intake is related to production level (e.g., weight gain or milk production), the feed energy intake can be estimated for these regions based on production statistics.^{1,2}

The rates of conversion of feed energy to CH₄ for non-ruminant animals are much lower than those for ruminants. For swine on good quality grain diets, about 0.6 percent of feed consumed is converted to CH₄. For horses, mules, and asses the estimate is about 2.5 percent. While these estimates are also uncertain and likely vary among regions, the global emissions from these species are much smaller than the emissions from ruminant animals. Consequently, the uncertainty in these values does not contribute significantly to the uncertainty in the estimates of total CH₄ emissions from livestock.^{2,4}

14.4.2 Emissions

Given their population and size, cattle account for the majority of CH₄ emissions in the United States for this source category. Cattle characteristics and emissions vary significantly by region. Therefore, it was important to develop a good model for cattle which takes into account the diversity of cattle types and cattle feeding systems in the United States. The variability in emission factors among regions for other animals is much smaller than the variability in emission factors for cattle.²

The emission factors presented here were developed using a validated mechanistic model^b of rumen digestion and CH₄ production for cattle feeding systems in the United States.⁵ The digestion model estimates the amount of CH₄ formed and emitted as a result of microbial fermentation in the rumen. The model is linked to an animal production model that predicts growth, pregnancy, milk production, and other production variables as a function of digestion products. The model evaluates the relationships between feed input characteristics and animal outputs including weight gain, lactation, heat production, pregnancy, and CH₄ emissions.⁵ The model has been validated for a wide range of feeding conditions encountered in the United States; a total of 32 diets were simulated for 8 animal types in 5 regions.⁵ Figure 14.4-1 shows which states are assigned to each region. Table 14.4-1 provides regional emission factors for typical types of dairy and beef cattle. The use of these emission factors requires detailed information on cattle production characteristics.²

For example, emissions from beef cattle in Kansas from a 1,000 head (animal) operation using the yearling system are calculated using the figures and tables of this section, in the following manner:

$$\begin{aligned} EF &= \frac{N * F}{2,000} \\ EF &= \frac{(1,000 \text{ head}) (103.4 \text{ lb CH}_4/\text{head-yr})}{2,000 \text{ lb/ton}} \\ EF &= 5.17 \text{ ton CH}_4/\text{year} \end{aligned}$$

where: EF = CH₄ emission factor for a livestock operation or facility (ton CH₄/yr)

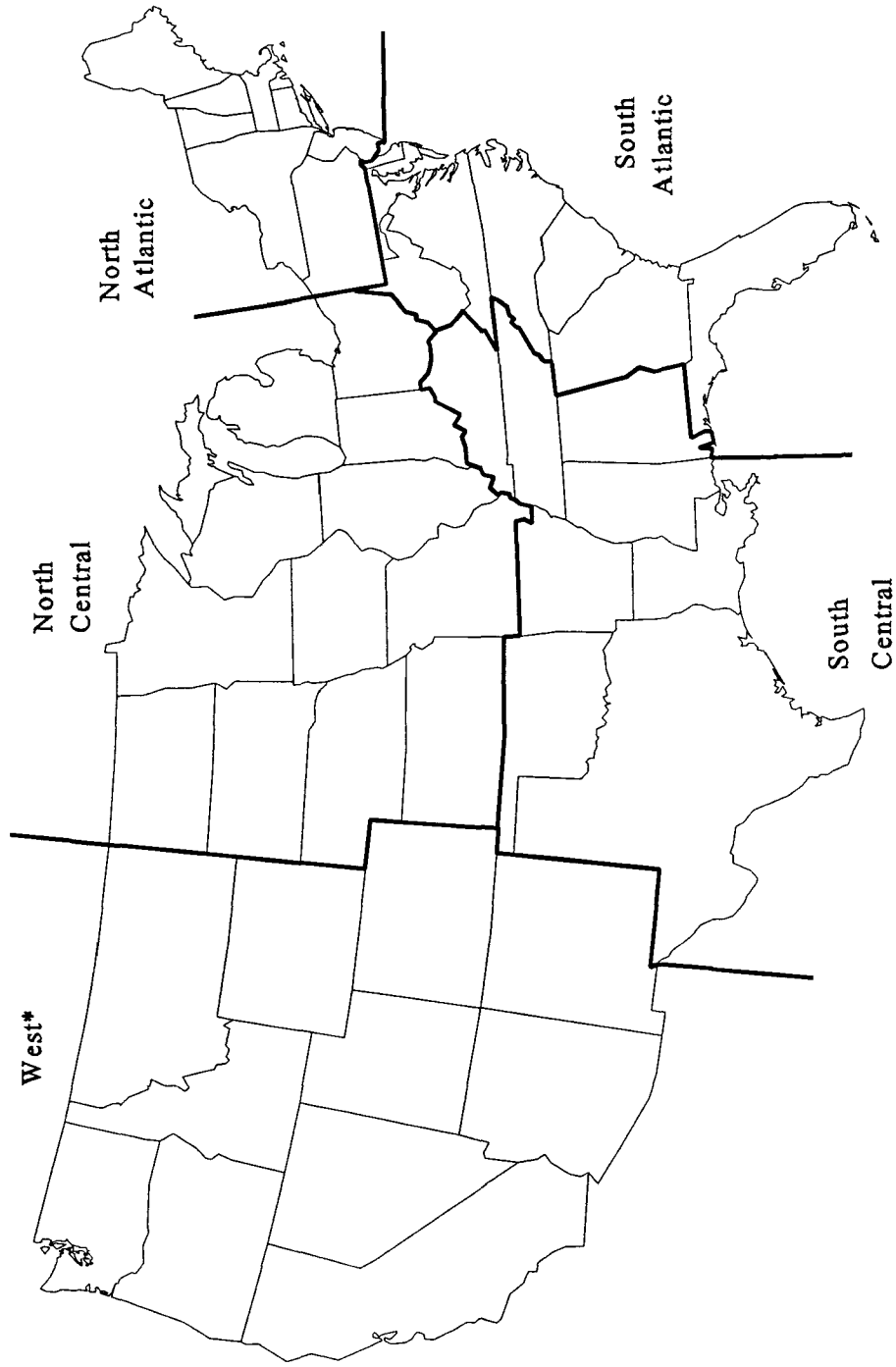
^b The mechanistic model is outlined in the U. S. EPA Report to Congress entitled "Anthropogenic Methane Emissions in the United States: Estimates for 1990."⁵

F = the individual animal methane emission factor from Table 14.4-1 and Figure 14.4-1 (lb CH₄/head-yr). In this example Kansas is in the north central zone according to Figure 14.4-1 and yearling operations in the north central zone have an "F" value of 103.4 lb CH₄ per head-yr.

Emission factors for other animals were developed using a simple functional relationship between feed intake and feed intake released as CH₄.^{3,4} This approach is reasonable given that feed characteristics of other animals are more or less homogeneous. Table 14.4-2 provides emission factors for sheep, goats, swine, horses, mules, and asses in developing and developed countries. Note that emission factors differ for sheep and swine for developed and developing countries, and the emission factor for water buffalos is unique for India.

Emission factors for cattle outside of the United States were also developed based on a model of feed intake and methane conversion. Table 14.4-3 provides emission factors for dairy cattle in Western Europe, Eastern Europe, Oceania, Latin America, Asia, Africa and the Middle East, and the Indian Subcontinent. Table 14.4-4 provides emission factors for non-dairy cattle in the same regions.

Although much study and measurement of this source has been done, the potential variation for the parameters used to develop the emission factors introduce a considerable amount of uncertainty, as would be the case for any source that relies on biological processes, which are highly variable by nature.



* Includes Alaska and Hawaii

Figure 14.4-1. Geographic Regions.²

Table 14.4-1. EMISSION FACTORS FOR U. S. CATTLE BY REGION^a

EMISSION FACTOR RATING: E

Animal Type/Region	English Emission Factors					Metric Emission Factors						
	North Atlantic	South Atlantic	North Central	South Central	West	National Average ^b	North Atlantic	South Atlantic	North Central	South Central	West	National Average ^b
Dairy Cattle												
Replacements 0-12 months ^c	42.9	45.1	41.6	44.7	45.5	43.1	19.5	20.5	18.9	20.3	20.6	19.5
Replacements 12-24 months ^c	128.5	129.1	126.3	135.7	134.6	129.4	58.3	58.6	57.3	61.5	61.0	58.7
Mature Cows	258.5	278.3	240.7	257.7	262.5	252.1	117.2	126.2	109.2	116.9	119.1	114.3
Beef Cattle												
Replacements 0-12 months ^c	42.2	49.9	44.8	51.9	49.9	49.1	19.1	22.6	20.3	23.5	22.6	22.3
Replacements 12-24 months ^c	140.4	148.5	133.8	148.9	142.7	143.0	63.7	67.4	60.7	67.5	64.7	64.9
Mature Cows	135.3	154.0	130.9	155.9	152.0	146.7	61.4	69.8	59.4	70.7	68.9	66.5
Weanling System Steers/Heifers ^d	NA ^e	NA ^e	49.7	52.8	51.7	50.8	NA ^e	NA ^e	22.5	23.9	23.4	23.0
Yearling System Steers/Heifers ^f	NA	NA	103.4	104.7	104.7	104.1	NA ^e	NA ^e	46.9	47.5	47.5	47.2
Bulls	220.0	220.0	220.0	220.0	220.0	220.0	99.8	99.8	99.8	99.8	99.8	99.8

^a Units are lbs CH₄/head/year. Metric units are kg CH₄/head/year. Reference 5.^b National averages are weighted by regional populations as of 1990.^c A portion of the offspring are retained to replace mature cows that die or are removed from the herd (culled) each year. Those that are retained are called "replacements."^d In "weanling systems," calves are moved directly from weaning to confined feeding programs. This system represents a very fast movement of cattle through to marketing. Weanling system cattle are marketed at about 420 days of age (14 months).^e These cattle types are typically not found in the North Atlantic and South Atlantic regions. If desired, it is appropriate to use the national total emission factor for these regions.^f "Yearling systems" represent a relatively slow movement of cattle through to marketing. These systems include a wintering over, followed by a summer of grazing on pasture. Yearling system cattle are marketed at 565 days of age (18.8 months). If desired, it is appropriate to use the national total emission factor for these regions.

Table 14.4-2. ENTERIC FERMENTATION EMISSION FACTORS FOR OTHER ANIMALS^a

EMISSION FACTOR RATING: E

Animal Type	Emission Factors			
	Developing Countries (lbs)	Developing Countries (kg)	Developed Countries (lbs)	Developed Countries (kg)
Sheep	11.0	5.0	17.6	8.0
Goats	11.0	5.0	11.0	5.0
Swine	2.2	1.0	3.3	1.5
Horses	39.6	18.0	39.6	18.0
Mules/Asses	22.0	10.0	22.0	10.0
Water Buffalo	116.8 ^b	53.0	127.9	58.0

^a References 3 and 4. Units are lbs/head/year or kg/head/year.^b India only. Emission factor for developed countries applies to other developing countries.Table 14.4-3. ENTERIC FERMENTATION EMISSION FACTORS FOR DAIRY CATTLE^a

EMISSION FACTOR RATING: E

Region	CH ₄ Emission Factor (lb/head/yr)	CH ₄ Emission Factor (kg/head/yr)	Average Milk Production (lb/yr)	Average Milk Production (kg/yr)
Western Europe	220	100	9240	4200
Eastern Europe	178	81	5610	2550
Oceania	150	68	3740	1700
Latin America	125	57	1760	800
Asia	123	56	3630	1650
Africa and Middle East	72	36	1045	475
Indian Subcontinent	101	46	1980	900

^a Reference 6.

Table 14.4-4. ENTERIC FERMENTATION EMISSION FACTORS
FOR NON-DAIRY CATTLE^a

EMISSION FACTOR RATING: E

Type	CH ₄ Emission Factors (lb/head/yr)	CH ₄ Emission Factors (kg/head/yr)
Western Europe		
Mature Males	132	60
Replacement/growing	185	84
Calves on milk	0	0
Calves on forage	73	6.3
Eastern Europe ^b		
Mature Females	163	73.7
Mature Males	143	65
Young	88	40.2
Oceania ^c		
Mature Females	139	63.2
Mature Males	121	54.6
Young	86	38.8
Latin America ^d		
Mature Females	128	58.2
Mature Males	125	56.7
Young	92	42.3
Asia ^e		
Mature Females — Farming	106	48.3
Mature Females — Grazing	90	41.3
Mature Males — Farming	128	57.5
Mature Males — Grazing	97	44.3
Young	68	31.2
Indian Subcontinent ^f		
Mature Females	68	30
Mature Males	90	46.1
Young	37	17
Africa		
Mature Females	68	31.2
Draft Bullocks	88	39.7
Mature Females — Grazing	101	46
Bulls — Grazing	121	55.2
Young	31	14.2

^a Reference 3.

^b Based on estimates for the former U.S.S.R.

^c Based on estimates for Australia.

^d Based on estimates for Brazil.

^e Based on estimates for China.

^f Based on estimates for India.

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