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Fifth Edition
Supplement A
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SUPPLEMENT A

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
Research Triangle Park, NC 27711

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<p>16. ABSTRACT</p> <p>This document contains emission factors and process information for more than 200 air pollution source categories. These emission factors have been compiled from source test data, material balance studies, and engineering estimates, and they can be used judiciously in making emission estimations for various purposes. When specific source test data are available, they should be preferred over the generalized factors presented in this document.</p> <p>This Supplement to AP-42 addresses pollutant-generating activity from Bituminous And Subbituminous Coal Combustion; Anthracite Coal Combustion; Fuel Oil Combustion; Natural Gas combustion; Wood Waste Combustion In Boilers; Lignite Combustion; Waste Oil Combustion; Stationary Gas Turbines For Electricity Generation; Heavy-duty Natural Gas-fired Pipeline Compressor Engines; Large Stationary Diesel And All Stationary Dual-fuel Engines; Natural Gas Processing; Organic Liquid Storage Tanks; Meat Smokehouses; Meat Rendering Plants; Canned Fruits And Vegetables; Dhydrated Fruits And Vegetables; Pickles, Sauces And Salad Dressings; Grain Elevators And Processes; Cereal Breakfast Foods; Pasta Manufacturing; Vegetable Oil Processing; Wines And Brandy; Coffee Roasting; Charcoal; Coal Cleaning; Frit Manufacturing; Sand And Gravel Processing; Diatomite Processing; Talc Processing; Vermiculite Processing; Paved Roads; and Unpaved Roads. Also included is information on Generalized Particle Size Distributions.</p>					
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Table 1.1-1 (English Units). EMISSION FACTORS FOR SULFUR OXIDES (SO_x), NITROGEN OXIDES (NO_x), AND CARBON MONOXIDE (CO) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION^a

Firing Configuration	SCC	SO _x ^b		NO _x ^c		CO ^{d,e}	
		lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
Pulverized coal fired, dry bottom, wall fired	1-01-002-02/22	38S	A	21.7	A	0.5	A
	1-02-002-02/22	(35S)					
	1-03-002-06/22						
Pulverized coal fired, dry bottom, tangentially fired	1-01-002-12/26	38S	A	14.4	A	0.5	A
	1-02-002-12/26	(35S)					
	1-03-002-16/26						
Pulverized coal fired, wet bottom	1-01-002-01/21	38S	D	34.0	C	0.5	A
	1-02-002-01/21	(35S)					
	1-03-002-05/21						
Cyclone furnace	1-01-002-03/23	38S	D	33.8	C	0.5	A
	1-02-002-03/23	(35S)					
	1-03-002-03/23						
Spreader stoker	1-01-002-04/24	38S	B	13.7	A	5	A
	1-02-002-04/24	(35S)					
	1-03-002-09/24						
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24	38S	B	13.7	A	5	A
	1-02-002-04/24	(35S)					
	1-03-002-09/24						
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24	38S	A	13.7	A	5	A
	1-02-002-04/24	(35S)					
	1-03-002-09/24						
Overfeed stoker ^f	1-01-002-05/25	38S	B	7.5	A	6	B
	1-02-002-05/25	(35S)					
	1-03-002-07/25						

Table 1.1-1 (cont.).

Firing Configuration	SCC	SO _x ^b		NO _x ^c		CO ^{d,e}	
		lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
Feed stoker, with multiple cyclones ^f	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	38S (35S)	B	7.5	A	6	B
Underfeed stoker	1-02-002-06 1-03-002-08	31S	B	9.5	A	11	B
Underfeed stoker, with multiple cyclones	1-02-002-06 1-03-002-08	31S	B	9.5	A	11	B
Hand-fed units	1-03-002-14	31S	D	9.1	E	275	E
Fluidized bed combustor, circulating bed	1-01-002-18 1-02-002-18 1-03-002-18	— ^g	E	3.9	E	18	E
Fluidized bed combustor, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	— ^g	E	15.2	D	18	D

^a Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. SCC = Source Classification Code.

^b Expressed as SO₂, including SO₂, SO₃, and gaseous sulfates. Factors in parentheses should be used to estimate gaseous SO_x emissions for subbituminous coal. In all cases, S is weight percent sulfur content of coal as fired. Emission factor would be calculated by multiplying the weight percent sulfur in the coal by the numerical value preceding S. For example, if fuel is 1.2% sulfur, then S equals 1.2. On average for bituminous coal, 95% of fuel sulfur is emitted as SO₂, and only about 0.7% of fuel sulfur is emitted as SO₃ and gaseous sulfate. An equally small percent of fuel sulfur is emitted as particulate sulfate (References 9, 13). Small quantities of sulfur are also retained in bottom ash. With subbituminous coal, about 10% more fuel sulfur is retained in the bottom ash and particulate because of the more alkaline nature of the coal ash. Conversion to gaseous sulfate appears about the same as for bituminous coal.

^c Expressed as NO₂. Generally, 95+ volume % of nitrogen oxides present in combustion exhaust will be in the form of NO, the rest NO₂ (Reference 11). To express factors as NO, multiply factors by 0.66. All factors represent emission at baseline operation (i. e., 60 to 110% load and no NO_x control measures).

Table 1.1-1 (cont.).

- ^d Nominal values achievable under normal operating conditions. Values 1 or 2 orders of magnitude higher can occur when combustion is not complete.
- ^e Emission factors for CO₂ emissions from coal combustion should be calculated using $\text{CO}_2/\text{ton coal} = 73.3C$, where C is the weight percent carbon content of the coal. For example, if coal is 83% carbon, then C equals 83.
- ^f Includes traveling grate, vibrating grate, and chain grate stokers.
- ^g Sulfur dioxide emission factors for fluidized bed combustion are a function of fuel sulfur content and calcium-to-sulfur ratio. For both bubbling bed and circulating bed design, use: $\text{lb SO}_2/\text{ton coal} = 39.6(S)(\text{Ca}/S)^{-1.9}$. In this equation, S is the weight percent sulfur in the fuel and Ca/S is the molar calcium-to-sulfur ratio in the bed. This equation may be used when the Ca/S is between 1.5 and 7. When no calcium-based sorbents are used and the bed material is inert with respect to sulfur capture, the emission factor for underfeed stokers should be used to estimate the FBC SO₂ emissions. In this case, the emission factor ratings are E for both bubbling and circulating units.

Table 1.1-2 (Metric Units). EMISSION FACTORS FOR SULFUR OXIDES (SO_x), NITROGEN OXIDES (NO_x), AND CARBON MONOXIDE (CO) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION^a

Firing Configuration	SCC	SO _x ^b		NO _x ^c		CO ^{d,e}	
		kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
Pulverized coal fired, dry bottom, wall fired	1-01-002-02/22	19S	A	10.85	A	0.25	A
	1-02-002-02/22	(17.5S)					
	1-03-002-06/22						
Pulverized coal fired, dry bottom, tangentially fired	1-01-002-12/26	19S	A	7.2	A	0.25	A
	1-02-002-12/26	(17.5S)					
	1-03-002-16/26						
Pulverized coal fired, wet bottom	1-01-002-01/21	19S	D	17	C	0.25	A
	1-02-002-01/21	(17.5S)					
	1-03-002-05/21						
Cyclone furnace	1-01-002-03/23	19S	D	16.9	C	0.25	A
	1-02-002-03/23	(17.5S)					
	1-03-002-03/23						
Spreader stoker	1-01-002-04/24	19S	B	6.85	A	2.5	A
	1-02-002-04/24	(17.5S)					
	1-03-002-09/24						
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24	19S	B	6.85	A	2.5	A
	1-02-002-04/24	(17.5S)					
	1-03-002-09/24						
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24	19S	A	6.85	A	2.5	A
	1-02-002-04/24	(17.5S)					
	1-03-002-09/24						
Overfeed stoker ^f	1-01-002-05/25	19S	B	3.75	A	3	B
	1-02-002-05/25	(17.5S)					
	1-03-002-07/25						

Table 1.1-2 (cont.).

Firing Configuration	SCC	SO _x ^b		NO _x ^c		CO ^{d,e}	
		kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
Overfeed stoker, with multiple cyclones ^f	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	19S (17.5S)	B	3.75	A	3	B
Underfeed stoker	1-02-002-06 1-03-002-08	15.5S	B	4.75	A	5.5	B
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	15.5S	B	4.75	A	5.5	B
Hand-fed units	1-03-002-14	15.5S	D	4.55	E	137.5	E
Fluidized bed combustor, circulating bed	1-01-002-18 1-02-002-18 1-03-002-18	— ^g	E	1.95	E	9	E
Fluidized bed combustor, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	— ^g	E	7.6	D	9	D

^a Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. SCC = Source Classification Code.

^b Expressed as SO₂, including SO₂, SO₃, and gaseous sulfates. Factors in parentheses should be used to estimate gaseous SO_x emissions for subbituminous coal. In all cases, S is weight percent sulfur content of coal as fired. Emission factor would be calculated by multiplying the weight percent sulfur in the coal by the numerical value preceding S. For example, if fuel is 1.2% sulfur, then S equals 1.2. On average for bituminous coal, 95% of fuel sulfur is emitted as SO₂, and only about 0.7% of fuel sulfur is emitted as SO₃ and gaseous sulfate. An equally small percent of fuel sulfur is emitted as particulate sulfate (References 9, 13). Small quantities of sulfur are also retained in bottom ash. With subbituminous coal, about 10% more fuel sulfur is retained in the bottom ash and particulate because of the more alkaline nature of the coal ash. Conversion to gaseous sulfate appears about the same as for bituminous coal.

^c Expressed as NO₂. Generally, 95+ volume % of nitrogen oxides present in combustion exhaust will be in the form of NO, the rest NO₂ (Reference 11). To express factors as NO, multiply factors by 0.66. All factors represent emission at baseline operation (i. e., 60 to 110% load and no NO_x control measures).

Table 1.1-2 (cont.).

- ^d Nominal values achievable under normal operating conditions. Values 1 or 2 orders of magnitude higher can occur when combustion is not complete.
- ^e Emission factors for CO₂ emissions from coal combustion should be calculated using $\text{CO}_2/\text{Mg coal} = 36.7C$, where C is the weight percent carbon content of the coal. For example, if coal is 83% carbon, then C equals 83.
- ^f Includes traveling grate, vibrating grate, and chain grate stokers.
- ^g Sulfur dioxide emission factors for fluidized bed combustion are a function of fuel sulfur content and calcium-to-sulfur ratio. For both bubbling bed and circulating bed design, use: $\text{kg SO}_2/\text{Mg coal} = 19.8(S)(\text{Ca}/S)^{-1.9}$. In this equation, S is the weight percent sulfur in the fuel and Ca/S is the molar calcium-to-sulfur ratio in the bed. This equation may be used when the Ca/S is between 1.5 and 7. When no calcium-based sorbents are used and the bed material is inert with respect to sulfur capture, the emission factor for underfeed stokers should be used to estimate the FBC SO₂ emissions. In this case, the emission factor ratings are E for both bubbling and circulating units.

Table 1.1-3 (English Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM) AND PM LESS THAN 10 MICROMETERS (PM-10) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION^a

Firing Configuration	SCC	Filterable PM ^b		PM-10	
		lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
Pulverized coal fired, dry bottom, wall fired	1-01-002-02/22 1-02-002-02/22 1-03-002-06/22	10A	A	2.3A	E
Pulverized coal fired, dry bottom, tangentially fired	1-01-002-12/26 1-02-002-12/26 1-03-002-16/26	10A	B	2.3A ^c	E
Pulverized coal fired, wet bottom	1-01-002-01/21 1-02-002-01/21 1-03-002-05/21	7A ^d	D	2.6A	E
Cyclone furnace	1-01-002-03/23 1-02-002-03/23 1-03-002-03/23	2A ^d	E	0.26A	E
Spreader stoker	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	66 ^e	B	13.2	E
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	17	B	12.4	E
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	12	A	7.8	E
Overfeed stoker ^f	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	16 ^g	C	6.0	E

Table 1.1-3 (cont.).

Firing Configuration	SCC	Filterable PM ^b		PM-10	
		lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
Overfeed stoker, with multiple cyclones ^f	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	9 ^h	C	5.0	E
Underfeed stoker	1-02-002-06 1-03-002-08	15 ^j	D	6.2	E
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	11 ^h	D	6.2 ^j	E
Hand-fed units	1-03-002-14	15	E	6.2 ^k	E
Fluidized bed combustor, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	— ^m	E	— ^m	E
Fluidized bed combustor, circulating bed	1-01-002-18 1-02-002-18 1-03-002-18	— ^m	E	— ^m	E

^a Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired.

SCC = Source Classification Code.

^b Based on EPA Method 5 (front half catch) as described in Reference 28. Where particulate is expressed in terms of coal ash content, A, factor is determined by multiplying weight % ash content of coal (as fired) by the numerical value preceding the A. For example, if coal with 8% ash is fired in a pulverized coal fired, dry bottom unit, the PM emission factor would be 10 x 8, or 80 lb/ton. The "condensable" matter collected in back half catch of EPA Method 5 averages <5% of front half, or "filterable", catch for pulverized coal and cyclone furnaces; 10% for spreader stokers; 15% for other stokers; and 50% for handfired units (References 6, 29, 30).

^c No data found; emission factor for pulverized coal-fired dry bottom boilers used.

^d Uncontrolled particulate emissions, when no fly ash reinjection is employed. When control device is installed, and collected fly ash is reinjected to boiler, particulate from boiler reaching control equipment can increase up to a factor of two.

^e Accounts for fly ash settling in an economizer, air heater, or breaching upstream of control device or stack. (Particulate directly at boiler outlet typically will be twice this level.) Factor should be applied even when fly ash is reinjected to boiler from air heater or economizer dust hoppers.

Table 1.1-3 (cont.).

^f Includes traveling grate, vibrating grate, and chain grate stokers.

^g Accounts for fly ash settling in breaching or stack base. Particulate loadings directly at boiler outlet typically can be 50% higher.

^h See Reference 34 for discussion of apparently low multiple cyclone control efficiencies, regarding uncontrolled emissions.

^j Accounts for fly ash settling in breaching downstream of boiler outlet.

^k No data found; emission factor for underfeed stoker used.

^m No data found; use emission factor for spreader stoker with multiple cyclones and no reinjection.

Table 1.1-4 (Metric Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM) AND PM LESS THAN 10 MICROMETERS (PM-10) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION^a

Firing Configuration	SCC	Filterable PM ^b		PM-10	
		kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
Pulverized coal fired, dry bottom, wall fired	1-01-002-02/22 1-02-002-02/22 1-03-002-06/22	5A	A	1.15A	E
Pulverized coal fired, dry bottom, tangentially fired	1-01-002-12/26 1-02-002-12/26 1-03-002-16/26	5A	B	1.15A ^c	E
Pulverized coal fired, wet bottom	1-01-002-01/21 1-02-002-01/21 1-03-002-05/21	3.5A ^d	D	1.3A	E
Cyclone furnace	1-01-002-03/23 1-02-002-03/23 1-03-002-03/23	1A ^d	E	0.13A	E
Spreader stoker	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	33 ^e	B	6.6	E
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	8.5	B	6.6	E
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	6	A	3.9	E
Overfeed stoker ^f	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	8 ^g	C	3.0	E

Table 1.1-4 (cont.).

Firing Configuration	SCC	Filterable PM ^b		PM-10	
		kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
Overfeed stoker, with multiple cyclones ^f	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	4.5 ^h	C	2.5	E
Underfeed stoker	1-02-002-06 1-03-002-08	7.5 ^j	D	3.1	E
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	5.5 ^h	D	3.1 ^j	E
Hand-fed units	1-03-002-14	7.5	E	3.1 ^k	E
Fluidized bed combustor, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	6	E	6.6 ^m	E
Fluidized bed combustor, circulating bed	1-01-002-18 1-02-002-18 1-03-002-18	8.5	E	6.6	E

^a Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired.

SCC = Source Classification Code.

^b Based on EPA Method 5 (front half catch) as described in Reference 28. Where particulate is expressed in terms of coal ash content, A, factor is determined by multiplying weight % ash content of coal (as fired) by the numerical value preceding the A. For example, if coal with 8% ash is fired in a pulverized coal fired, dry bottom unit, the PM emission factor would be 5 x 8, or 40 kg/Mg. The "condensable" matter collected in back half catch of EPA Method 5 averages <5% of front half, or "filterable", catch for pulverized coal and cyclone furnaces; 10% for spreader stokers; 15% for other stokers; and 50% for handfired units (References 6,29,30).

^c No data found; use assumed emission factor for pulverized coal-fired dry bottom boilers.

^d Uncontrolled particulate emissions, when no fly ash reinjection is employed. When control device is installed, and collected fly ash is reinjected to boiler, particulate from boiler reaching control equipment can increase up to a factor of two.

^e Accounts for fly ash settling in an economizer, air heater, or breaching upstream of control device or stack. (Particulate directly at boiler outlet typically will be twice this level.) Factor should be applied even when fly ash is reinjected to boiler from air heater or economizer dust hoppers.

Table 1.1-4 (cont.).

^f Includes traveling grate, vibrating grate, and chain grate stokers.

^g Accounts for fly ash settling in breaching or stack base. Particulate loadings directly at boiler outlet typically can be 50% higher.

^h See Reference 34 for discussion of apparently low multiple cyclone control efficiencies, regarding uncontrolled emissions.

^j Accounts for fly ash settling in breaching downstream of boiler outlet.

^k No data found; use emission factor for underfeed stoker.

^m No data found; use emission factor for spreader stoker.

Table 1.1-5 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR DRY BOTTOM BOILERS BURNING PULVERIZED BITUMINOUS COAL^a

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size					Cumulative Emission Factor ^c (kg/Mg [lb/ton] Coal, As Fired)				
	Uncontrolled	Controlled				Uncontrolled ^d	Controlled ^e			
		Multiple Cyclones	Scrubber	ESP	Baghouse		Multiple Cyclones ^f	Scrubber ^g	ESP ^g	Baghouse ^f
15	32	54	81	79	97	1.6A (3.2A)	0.54A (1.08A)	0.24A (0.48A)	0.032A (0.064A)	0.010A (0.02A)
10	23	29	71	67	92	1.15A (2.3A)	0.29A (0.58A)	0.21A (0.42A)	0.027A (0.054A)	0.009A (0.02A)
6	17	14	62	50	77	0.85A (1.7A)	0.14A (0.28A)	0.19A (0.38A)	0.020A (0.024A)	0.008A (0.02A)
2.5	6	3	51	29	53	0.3A (0.6A)	0.03A (0.06A)	0.15A (0.3A)	0.012A (0.024A)	0.005A (0.01A)
1.25	2	1	35	17	31	0.10A (0.2A)	0.01A (0.02A)	0.11A (0.22A)	0.007A (0.01A)	0.003A (0.006A)
1.00	2	1	31	14	25	0.10A (0.2A)	0.01A (0.02A)	0.09A (0.18A)	0.006A (0.01A)	0.003A (0.006A)
0.625	1	1	20	12	14	0.05A (0.10A)	0.01A (0.02A)	0.06A (0.12A)	0.005A (0.01A)	0.001A (0.002A)
TOTAL	100	100	100	100	100	5A (10A)	1A (2A)	0.3A (0.6A)	0.04A (0.08A)	0.01A (0.02A)

^a Reference 32. Applicable Source Classification Codes are 1-01-002-02, 1-02-002-02, 1-03-002-06, 1-01-002-12, 1-02-002-12, and 1-03-002-16. ESP = electrostatic precipitator.

^b Expressed as aerodynamic equivalent diameter.

^c A = coal ash weight percent, as fired. For example, if coal ash weight is 8.2%, then A = 8.2.

^d EMISSION FACTOR RATING = C.

^e Estimated control efficiency for multiple cyclones is 80%; for scrubber, 94%; for ESP, 99.2%; and for baghouse, 99.8%.

^f EMISSION FACTOR RATING = E.

^g EMISSION FACTOR RATING = D.

Table 1.1-6 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR WET BOTTOM BOILERS BURNING PULVERIZED BITUMINOUS COAL^a

EMISSION FACTOR RATING: E

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size			Cumulative Emission Factor ^c (kg/Mg [lb/ton] Coal, As Fired)		
	Uncontrolled	Controlled		Uncontrolled	Controlled ^d	
		Multiple Cyclones	ESP		Multiple Cyclones	ESP
15	40	99	83	1.4A (2.8A)	0.69A (1.38A)	0.023A (0.046A)
10	37	93	75	1.30A (2.6A)	0.65A (1.3A)	0.021A (0.042A)
6	33	84	63	1.16A (2.32A)	0.59A (1.18A)	0.018A (0.036A)
2.5	21	61	40	0.74A (1.48A)	0.43A (0.86A)	0.011A (0.022A)
1.25	6	31	17	0.21A (0.42A)	0.22A (0.44A)	0.005A (0.01A)
1.00	4	19	8	0.14A (0.28A)	0.13A (0.26A)	0.002A (0.004A)
0.625	2	— ^e	— ^e	0.07A (0.14A)	— ^e	— ^e
TOTAL	100	100	100	3.5A (7.0A)	0.7A (1.4A)	0.028A (0.056A)

^a Reference 32. Applicable Source Classification Codes are 1-01-002-01, 1-02-002-01, and 1-03-002-05. ESP = electrostatic precipitator.

^b Expressed as aerodynamic equivalent diameter.

^c A = coal ash weight %, as fired. For example, if coal ash weight equals 8.2%, then A = 8.2.

^d Estimated control efficiency for multiple cyclones is 94%; and for ESP, 99.2%.

^e Insufficient data.

Table 1.1-7 (Metric And English Units). CUMULATIVE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR CYCLONE FURNACES BURNING BITUMINOUS COAL^a

EMISSION FACTOR RATING: E

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size			Cumulative Emission Factor ^c (kg/Mg [lb/ton] Coal, As Fired)		
	Uncontrolled	Controlled		Uncontrolled	Controlled ^e	
		Multiple Cyclones	ESP		Multiple Cyclones	ESP
15	33	95	90	0.33A (0.66A)	0.057A (0.114A)	0.0064A (0.013A)
10	13	94	68	0.13A (0.26A)	0.056A (0.112A)	0.0054A (0.011A)
6	8	93	56	0.08A (0.16A)	0.056A (0.112A)	0.0045A (0.009A)
2.5	0	92	36	0	0.055A (0.11A)	0.0029A (0.006A)
1.25	0	85	22	0	0.051A (0.10A)	0.0018A (0.004A)
1.00	0	82	17	0	0.049A (0.10A)	0.0014A (0.003A)
0.625	0	— ^d	— ^d	0	— ^d	— ^d
TOTAL	100	100	100	1A (2A)	0.06A (0.12A)	0.008A (0.016A)

^a Reference 32. Applicable Source Classification Codes are 1-01-002-03, 1-02-002-03, and 1-03-002-03. ESP = electrostatic precipitator.

^b Expressed as aerodynamic equivalent diameter.

^c A = coal ash weight percent, as fired.

^d Insufficient data.

^e Estimated control efficiency for multiple cyclones is 94%; and for ESP, 99.2%.

Table 1.1-8 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR SPREADER STOKERS BURNING BITUMINOUS COAL^a

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size					Cumulative Emission Factor ^c (kg/Mg [lb/ton]) Coal, As Fired)				
	Uncontrolled	Controlled				Uncontrolled ^c	Controlled ^d			
		Multiple Cyclones ^c	Multiple Cyclones ^d	ESP	Baghouse		Multiple Cyclones ^{c,f}	Multiple Cyclones ^{d,e}	ESP ^{f,g}	Baghouse ^{c,g}
15	28	86	74	97	72	9.2 (18.5)	7.3 (14.6)	4.4 (8.8)	0.23 (0.46)	0.043 (0.086)
10	20	73	65	90	60	6.6 (13.2)	6.2 (12)	3.9 (7.8)	0.22 (0.44)	0.036 (0.072)
6	14	51	52	82	46	4.6 (9.2)	4.3 (8.6)	3.1 (6.2)	0.20 (0.40)	0.028 (0.056)
2.5	7	8	27	61	26	2.3 (4.6)	0.7 (1.4)	1.6 (3.2)	0.15 (0.30)	0.016 (0.032)
1.25	5	2	16	46	18	1.6 (3.3)	0.2 (0.4)	1.0 (2.0)	0.11 (0.22)	0.011 (0.022)
1.00	5	2	14	41	15	1.6 (3.3)	0.2 (0.4)	0.8 (1.6)	0.10 (0.20)	0.009 (0.018)
0.625	4	1	9	— ^h	7	1.3 (2.6)	0.1 (0.2)	0.5 (1.0)	— ^h	0.004 (0.008)
TOTAL	100	100	100	100	100	33 (66.0)	8.5 (17.0)	6.0 (12.0)	0.24 (0.48)	0.08 (0.12)

^a Reference 32. Applicable Source Classification Codes are 1-01-002-04, 1-02-002-04, 1-03-002-09. ESP = electrostatic precipitator.

^b Expressed as aerodynamic equivalent diameter.

^c With flyash reinjection.

^d Without flyash reinjection.

^e EMISSION FACTOR RATING = C.

^f EMISSION FACTOR RATING = E.

^g Estimated control efficiency for ESP is 99.22%; and for baghouse, 99.8%.

^h Insufficient data.

Table 1.1-9 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR OVERFEED STOKERS BURNING BITUMINOUS COAL^a

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size		Cumulative Emission Factor ^c (kg/Mg [lb/ton] Coal, As Fired)			
	Uncontrolled	Multiple Cyclones Controlled	Uncontrolled		Multiple Cyclones Controlled ^d	
			Factor	RATING	Factor	RATING
15	49	60	3.9 (7.8)	C	2.7 (5.4)	E
10	37	55	3.0 (6.0)	C	2.5 (5.0)	E
6	24	49	1.9 (3.8)	C	2.2 (4.4)	E
2.5	14	43	1.1 (2.2)	C	1.9 (3.8)	E
1.25	13	39	1.0 (2.0)	C	1.8 (3.6)	E
1.00	12	39	1.0 (2.0)	C	1.8 (3.6)	E
0.625	— ^c	16	— ^c	C	0.7 (1.4)	E
TOTAL	100	100	8.0 (16.0)	C	4.5 (9.0)	E

^a Reference 32. Applicable Source Classification Codes are 1-01-002-05, 1-02-002-05, and 1-03-002-07.

^b Expressed as aerodynamic equivalent diameter.

^c Insufficient data.

^d Estimated control efficiency for multiple cyclones is 80%.

Table 1.1-10 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR UNDERFEED STOKERS BURNING BITUMINOUS COAL^a

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size	Uncontrolled Cumulative Emission Factor ^c (kg/Mg [lb/ton] Coal, As Fired)	
		Factor	RATING
15	50	3.8 (7.6)	C
10	41	3.1 (6.2)	C
6	32	2.4 (4.8)	C
2.5	25	1.9 (3.8)	C
1.25	22	1.7 (3.4)	C
1.00	21	1.6 (3.2)	C
0.625	18	1.4 (2.7)	C
TOTAL	100	7.5 (15.0)	C

^a Reference 32. Applicable Source Classification Codes are 1-02-002-06 and 1-03-002-08.

^b Expressed as aerodynamic equivalent diameter.

^c May also be used for uncontrolled hand-fired units.

Table 1.1-11 (English Units). EMISSION FACTORS FOR METHANE (CH₄), NONMETHANE TOTAL ORGANIC COMPOUNDS (NMTOC), AND NITROUS OXIDE (N₂O) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION^a

Firing Configuration	SCC	CH ₄ ^b		NMTOC ^{b,c}		N ₂ O ^d	
		lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
Pulverized coal fired, dry bottom, wall fired	1-01-002-02/22 1-02-002-02/22 1-03-002-06/22	0.04	B	0.06	B	0.09	D
Pulverized coal fired, dry bottom, tangentially fired	1-01-002-12/26 1-02-002-12/26 1-03-002-16/26	0.04	B	0.06	B	0.03	D
Pulverized coal fired, wet bottom	1-01-002-01/21 1-02-002-01/21 1-03-002-05/21	0.05	B	0.04	B	0.09 ^e	E
Cyclone furnace	1-01-002-03/23 1-02-002-03/23 1-03-002-03/23	0.01	B	0.11	B	0.09 ^e	E
Spreader stoker	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	0.06	B	0.05	B	0.09 ^e	E
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	0.06	B	0.05	B	0.09 ^e	E
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	0.06	B	0.05	B	0.09 ^e	E

Table 1.1-11 (cont.).

Firing Configuration	SCC	CH ₄ ^b		NMTOC ^{b,c}		N ₂ O ^d	
		lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
Overfeed stoker ^f	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	0.06	B	0.05	B	0.09 ^e	E
Overfeed stoker, with multiple cyclones ^f	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	0.06	B	0.05	B	0.09 ^e	E
Underfeed stoker	1-02-002-06 1-03-002-08	0.8	B	1.3	B	0.09 ^e	E
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	0.8	B	1.3	B	0.09 ^e	E
Hand-fed units	1-03-002-14	5	E	10	E	0.09 ^e	E
Fluidized bed combustor, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	0.06	E	0.05	E	5.5 ^g	E
Fluidized bed combustor, circulating bed	1-01-002-18 1-02-002-18 1-03-002-18	0.06	E	0.05	E	5.5	E

^a Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. SCC = Source Classification Code.

^b Reference 35. Nominal values achievable under normal operating conditions; values 1 or 2 orders of magnitude higher can occur when combustion is not complete.

^c Nonmethane total organic compounds are expressed as C2 to C16 alkane equivalents (Reference 31). Because of limited data, the effects of firing configuration on NMTOC emission factors could not be distinguished. As a result, all data were averaged collectively to develop a single average emission factor for pulverized coal units, cyclones, spreaders, and overfeed stokers.

^d References 36-38.

^e No data found; emission factor for pulverized coal-fired dry bottom boilers used.

^f Includes traveling grate, vibrating grate, and chain grate stokers.

^g No data found; emission factor for circulating fluidized bed used.

Table 1.1-12 (Metric Units). EMISSION FACTORS FOR METHANE (CH₄), NONMETHANE TOTAL ORGANIC COMPOUNDS (NMTOC), AND NITROUS OXIDE (N₂O) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION^a

Firing Configuration	SCC	CH ₄ ^b		NMTOC ^{b,c}		N ₂ O ^d	
		kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
Pulverized coal fired, dry bottom, wall fired	1-01-002-02/22	0.02	B	0.04	B	0.045	D
	1-02-002-02/22						
	1-03-002-06/22						
Pulverized coal fired, dry bottom, tangentially fired	1-01-002-12/26	0.02	B	0.04	B	0.015	D
	1-02-002-12/26						
	1-03-002-16/26						
Pulverized coal fired, wet bottom	1-01-002-01/21	0.025	B	0.02	B	0.045 ^e	E
	1-02-002-01/21						
	1-03-002-05/21						
Cyclone furnace	1-01-002-03/23	0.005	B	0.055	B	0.045 ^e	E
	1-02-002-03/23						
	1-03-002-03/23						
Spreader stoker	1-01-002-04/24	0.03	B	0.025	B	0.045 ^e	E
	1-02-002-04/24						
	1-03-002-09/24						
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24	0.03	B	0.025	B	0.045 ^e	E
	1-02-002-04/24						
	1-03-002-09/24						
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24	0.03	B	0.025	B	0.045 ^e	E
	1-02-002-04/24						
	1-03-002-09/24						

Table 1.1-12 (cont.).

Firing Configuration	SCC	CH ₄ ^b		NMTOC ^{b,c}		N ₂ O ^d	
		kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
Overfeed stoker ^f	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	0.03	B	0.025	B	0.045 ^e	E
Overfeed stoker, with multiple cyclones ^f	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	0.03	B	0.025	B	0.045 ^e	E
Underfeed stoker	1-02-002-06 1-03-002-08	0.4	B	0.65	B	0.045 ^e	E
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	0.4	B	0.65	B	0.045 ^e	E
Hand-fed units	1-03-002-14	2.5	E	5	E	0.045 ^e	E
Fluidized bed combustor, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	0.03	E	0.025	E	2.75 ^g	E
Fluidized bed combustor, circulating bed	1-01-002-18 1-02-002-18 1-03-002-18	0.03	E	0.025	E	2.75	E

^a Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. SCC = Source Classification Code.

^b Reference 35. Nominal values achievable under normal operating conditions; values 1 or 2 orders of magnitude higher can occur when combustion is not complete.

^c Nonmethane total organic compounds are expressed as C2 to C16 alkane equivalents (Reference 31). Because of limited data, the effects of firing configuration on NMTOC emission factors could not be distinguished. As a result, all data were averaged collectively to develop a single average emission factor for pulverized coal units, cyclones, spreaders, and overfeed stokers.

^d References 36-38.

^e No data found; use emission factor for pulverized coal-fired dry bottom boilers.

^f Includes traveling grate, vibrating grate, and chain grate stokers.

^g No data found; use emission factor for circulating fluidized bed.

Table 1.1-13 (English Units). EMISSION FACTORS FOR TRACE ELEMENTS, POLYCYCLIC ORGANIC MATTER (POM), AND FORMALDEHYDE (HCOH) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION^a

EMISSION FACTOR RATING: E

Firing Configuration (SCC)	Emission Factor, lb/10 ¹² Btu									
	As	Be	Cd	Cr	Pb	Mn	Hg	Ni	POM	HCOH
Pulverized coal, configuration unknown (no SCC)	ND	ND	ND	1922	ND	ND	ND	ND	ND	112 ^b
Pulverized coal, wet bottom (1-01-002-01/21, 1-02-002-01/21, 1-03-002-05/21)	538	81	44-70	1020-1570	507 ^c	808-2980	16	840-1290	ND	ND
Pulverized coal, dry bottom (1-01-002-02/22, 1-02-002-06/22, 1-03-002-06/22)	684	81	44.4	1250-1570	507 ^c	228-2980	16	1030-1290	2.08	ND
Pulverized coal, dry bottom, tangential (1-01-002-12/26, 1-02-002-12/26, 1-03-002-16/26)	ND	ND	ND	ND	ND	ND	ND	ND	2.4	ND
Cyclone furnace (1-01-002-03/23, 1-02-002-03/23, 1-03-002-03/23)	115	<81	28	212-1502	507 ^c	228-1300	16	174-1290	ND	ND
Stoker, configuration unknown (no SCC)	ND	73	ND	19-300	ND	2170	16	775-1290	ND	ND
Spreader stoker (1-01-002-04/24, 1-02-002-04/24, 1-03-002-09/24)	264-542	ND	21-43	942-1570	507 ^c	ND	ND	ND	ND	221 ^d
Overfeed stoker, traveling grate (1-01-002-05/25, 1-02-002-05/25, 1-03-002-07/25)	542-1030	ND	43-82	ND	507 ^c	ND	ND	ND	ND	140 ^e

^a References 39-44. The emission factors in this table represent the ranges of factors reported in the literature. If only 1 data point was found, it is still reported in this table. SCC = Source Classification Code. ND = no data.

^b Based on 2 units; 456 MWe and 133 million Btu/hr.

^c Lead emission factors were taken directly from an EPA background document for support of the NAAQS.

^d Based on 1 unit; 59 million Btu/hr.

^e Based on 1 unit; 52 million Btu/hr.

Older traveling grate stokers are often uncontrolled. Indeed, particulate control has often been considered unnecessary because of anthracite's low smoking tendencies and the fact that a significant fraction of large size flyash from stokers is readily collected in flyash hoppers as well as in the breeching and base of the stack. Cyclone collectors have been employed on traveling grate stokers, and limited information suggests these devices may be up to 75 percent efficient on particulate. Flyash reinjection, frequently used in traveling grate stokers to enhance fuel use efficiency, tends to increase PM emissions per unit of fuel combusted. High-energy venturi scrubbers can generally achieve PM collection efficiencies of 90 percent or greater.

Emission factors and ratings for pollutants from anthracite coal combustion and anthracite culm combustion are given in Tables 1.2-1, 1.2-2, 1.2-3, 1.2-4, 1.2-5, 1.2-6, and 1.2-7. Cumulative size distribution data and size-specific emission factors and ratings for particulate emissions are summarized in Table 1.2-8. Uncontrolled and controlled size-specific emission factors are presented in Figure 1.2-1. Particle size distribution data for bituminous coal combustion may be used for uncontrolled emissions from pulverized anthracite-fired furnaces, and data for anthracite-fired traveling grate stokers may be used for hand-fired units (Figure 1.2-2).¹⁰⁻¹³

Table 1.2-1 (Metric And English Units). EMISSION FACTORS FOR SPECIATED METALS FROM ANTHRACITE COAL COMBUSTION IN STOKER FIRED BOILERS^a

EMISSION FACTOR RATING: E

Pollutant	Emission Factor Range		Average Emission Factor	
	kg/Mg	lb/ton	kg/Mg	lb/ton
Mercury	4.4 E-05 - 6.5 E-05	8.7 E-05 - 1.3 E-04	6.5 E-05	1.3 E-04
Arsenic	BDL - 1.2 E-04	BDL - 2.4 E-04	9.3 E-05	1.9 E-04
Antimony	BDL	BDL	BDL	BDL
Beryllium	1.5 E-05 - 2.7 E-04	3.0 E-05 - 5.4 E-04	1.5 E-04	3.1 E-04
Cadmium	2.3 E-05 - 5.5 E-03	4.5 E-05 - 1.1 E-04	3.6 E-05	7.1 E-05
Chromium	3.0 E-03 - 2.5 E-02	5.9 E-03 - 4.9 E-02	1.4 E-02	2.8 E-02
Manganese	4.9 E-04 - 2.7 E-03	9.8 E-04 - 5.3 E-03	1.8 E-03	3.6 E-03
Nickel	3.9 E-03 - 1.8 E-02	7.8 E-03 - 3.5 E-02	1.3 E-02	2.6 E-02
Selenium	2.4 E-04 - 1.1 E-03	4.7 E-04 - 2.1 E-03	6.3 E-04	1.3 E-03

^a Reference 9. Units are kg of pollutant/Mg of coal burned and lb of pollutant/ton of coal burned. Source Classification Codes are 1-01-001-02, 1-02-001-04, and 1-03-001-02. BDL = below detection limit.

Table 1.2-2 (Metric And English Units). EMISSION FACTORS FOR TOTAL ORGANIC COMPOUNDS (TOC) AND METHANE (CH₄) FROM ANTHRACITE COAL COMBUSTORS^a

Source Category	TOC Emission Factor			CH ₄ Emission Factor		
	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING
Stoker fired boilers ^b (SCC 1-01-001-02, 1-02-001-04, 1-03-001-02)	0.10	0.20	E	ND	ND	NA
Residential space heaters ^c (SCC A2104001000)	ND	ND	NA	4	8	E

^a Units are kg of pollutant/Mg of coal burned and lb of pollutant/ton of coal burned. SCC = Source Classification Code. ND = no data. NA = not applicable.

^b Reference 9.

^c Reference 14.

Table 1.2-3 (Metric Units). EMISSION FACTORS FOR SPECIATED ORGANIC COMPOUNDS FROM ANTHRACITE COAL COMBUSTORS^a

EMISSION FACTOR RATING: E

Pollutant	Stoker Fired Boilers ^b (SCC 1-01-001-02, 1-02-001-04, 1-03-001-02)	Residential Space Heaters ^c (No SCC)	
	Emission Factor	Emission Factor Range	Emission Factor
Biphenyl	1.25 E-02	ND	ND
Phenanthrene	3.4 E-03	4.6 E-02 - 2.1 E-02	1.6 E-01
Naphthalene	0.65 E-01	4.5 E-03 - 2.4 E-02	1.5 E-01
Acenaphthene	ND	7.0 E-03 - 3.4 E-01	3.5 E-01
Acenaphthalene	ND	7.0 E-03 - 2.0 E-02	2.5 E-01
Fluorene	ND	4.5 E-03 - 2.9 E-02	1.7 E-02
Anthracene	ND	4.5 E-03 - 2.3 E-02	1.6 E-02
Fluoranthrene	ND	4.8 E-02 - 1.7 E-01	1.1 E-01
Pyrene	ND	2.7 E-02 - 1.2 E-01	7.9 E-02
Benzo(a)anthracene	ND	7.0 E-03 - 1.0 E-01	2.8 E-01
Chrysene	ND	1.2 E-02 - 1.1 E-01	5.3 E-02
Benzo(k)fluoranthrene	ND	7.0 E-03 - 3.1 E-02	2.5 E-01
Benzo(e)pyrene	ND	2.3 E-03 - 7.3 E-03	4.2 E-03
Benzo(a)pyrene	ND	1.9 E-03 - 4.5 E-03	3.5 E-03
Perylene	ND	3.8 E-04 - 1.2 E-03	8.5 E-04
Indeno(123-cd) perylene	ND	2.3 E-03 - 7.0 E-03	2.4 E-01
Benzo(g,h,i,) perylene	ND	2.2 E-03 - 6.0 E-03	2.1 E-01
Anthanthrene	ND	9.5 E-05 - 5.5 E-04	3.5 E-03
Coronene	ND	5.5 E-04 - 4.0 E-03	1.2 E-02

^a Units are kg of pollutant/Mg of anthracite coal burned. SCC = Source Classification Code.

ND = no data.

^b Reference 9.

^c Reference 14.

Table 1.2-4 (English Units). EMISSION FACTORS FOR SPECIATED ORGANIC COMPOUNDS FROM ANTHRACITE COAL COMBUSTORS^a

EMISSION FACTOR RATING: E

Pollutant	Stoker Fired Boilers ^b (SCC 1-01-001-02, 1-02-001-04, 1-03-001-02)	Residential Space Heaters ^c (SCC A2104001000)	
	Emission Factor	Emission Factor Range	Emission Factor
Biphenyl	2.5 E-02	ND	ND
Phenanthrene	6.8 E-03	9.1 E-02 - 4.3 E-02	3.2 E-01
Naphthalene	1.3 E-01	9.0 E-03 - 4.8 E-02	3.0 E-01
Acenaphthene	ND	1.4 E-02 - 6.7 E-01	7.0 E-01
Acenaphthalene	ND	1.4 E-02 - 3.0 E-01	4.9 E-01
Fluorene	ND	9.0 E-03 - 5.8 E-02	3.4 E-02
Anthracene	ND	9.0 E-03 - 4.5 E-02	3.3 E-02
Fluoranthrene	ND	9.6 E-02 - 3.3 E-01	2.2 E-01
Pyrene	ND	5.4 E-02 - 2.4 E-01	1.6 E-01
Benzo(a)anthracene	ND	1.4 E-02 - 2.0 E-01	5.5 E-01
Chrysene	ND	2.3 E-02 - 2.2 E-01	1.1 E-01
Benzo(k)fluoranthrene	ND	1.4 E-02 - 6.3 E-02	5.0 E-01
Benzo(e)pyrene	ND	4.5 E-03 - 1.5 E-02	8.4 E-03
Benzo(a)pyrene	ND	3.8 E-03 - 9.0 E-03	7.0 E-03
Perylene	ND	7.6 E-04 - 2.3 E-03	1.7 E-03
Indeno(123-cd) perylene	ND	4.5 E-03 - 1.4 E-02	4.7 E-01
Benzo(g,h,i,) perylene	ND	4.3 E-03 - 1.2 E-02	4.2 E-01
Anthanthrene	ND	1.9 E-04 - 1.1 E-03	7.0 E-03
Coronene	ND	1.1 E-03 - 8.0 E-03	2.4 E-02

^a Units are lbs. of pollutant/ton of anthracite coal burned. SCC = Source Classification Code.
ND = no data.

^b Reference 9.

^c Reference 14.

Table 1.2-5 (Metric And English Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM) AND LEAD (Pb)
FROM ANTHRACITE COAL COMBUSTORS^a

Source Category	Filterable PM Emission Factor			Condensable PM Emission Factor			Pb Emission Factor		
	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING
Stoker fired boilers ^b (SCC 1-01-001-02, 1-02-001-04, 1-03-001-02)	0.4A ^c	0.8A	C	0.04A	0.08A	C	4.5 E-03	8.9 E-03	E
Hand fired units ^d (SCC 1-02-002-07, 1-03-001-03)	5	10	B	ND	ND	NA	ND	ND	NA

^a Units are kg of pollutant/Mg of coal burned and lb of pollutant/ton of coal burned. SCC = Source Classification Code. ND = no data.

NA = not applicable.

^b References 9-12.

^c A = ash content of fuel, weight percent.

^d Reference 16.

1.3 Fuel Oil Combustion

1.3.1 General^{1-2, 26}

Two major categories of fuel oil are burned by combustion sources: distillate oils and residual oils. These oils are further distinguished by grade numbers, with Nos. 1 and 2 being distillate oils; Nos. 5 and 6 being residual oils; and No. 4 either distillate oil or a mixture of distillate and residual oils. No. 6 fuel oil is sometimes referred to as Bunker C. Distillate oils are more volatile and less viscous than residual oils. They have negligible nitrogen and ash contents and usually contain less than 0.3 percent sulfur (by weight). Distillate oils are used mainly in domestic and small commercial applications. Being more viscous and less volatile than distillate oils, the heavier residual oils (Nos. 5 and 6) must be heated for ease of handling and to facilitate proper atomization. Because residual oils are produced from the residue remaining after the lighter fractions (gasoline, kerosene, and distillate oils) have been removed from the crude oil, they contain significant quantities of ash, nitrogen, and sulfur. Residual oils are used mainly in utility, industrial, and large commercial applications.

1.3.2 Emissions²⁷

Emissions from fuel oil combustion depend on the grade and composition of the fuel, the type and size of the boiler, the firing and loading practices used, and the level of equipment maintenance. Because the combustion characteristics of distillate and residual oils are different, their combustion can produce significantly different emissions. In general, the baseline emissions of criteria and noncriteria pollutants are those from uncontrolled combustion sources. Uncontrolled sources are those without add-on air pollution control (APC) equipment or other combustion modifications designed for emission control. Baseline emissions for sulfur dioxide (SO₂) and particulate matter (PM) can also be obtained from measurements taken upstream of APC equipment.

In this section, point source emissions of nitrogen oxides (NO_x), SO₂, PM, and carbon monoxide (CO) are being evaluated as criteria pollutants (those emissions for which National Primary and Secondary Ambient Air Quality Standards have been established. Particulate matter emissions are sometimes reported as total suspended particulate (TSP). More recent data generally quantify the portion of inhalable PM that is considered to be less than 10 micrometers in aerodynamic diameter (PM-10). In addition to the criteria pollutants, this section includes point source emissions of some noncriteria pollutants, nitrous oxide (N₂O), volatile organic compounds (VOCs), and hazardous air pollutants (HAPs), as well as data on particle size distribution to support PM-10 emission inventory efforts. Emissions of carbon dioxide (CO₂) are also being considered because of its possible participation in global climatic change and the corresponding interest in including this gas in emission inventories. Most of the carbon in fossil fuels is emitted as CO₂ during combustion. Minor amounts of carbon are emitted as CO, much of which ultimately oxidizes to CO₂ or as carbon in the ash. Finally, fugitive emissions associated with the use of oil at the combustion source are being included in this section.

Tables 1.3-1, 1.3-2, 1.3-3, and 1.3-4 present emission factors for uncontrolled emissions of criteria pollutants from fuel oil combustion. A general discussion of emissions of criteria and noncriteria pollutants from coal combustion is given in the following paragraphs. Tables 1.3-5, 1.3-6, 1.3-7, and 1.3-8 present cumulative size distribution data and size-specific emission factors for

Table 1.3-1 (Metric Units). CRITERIA POLLUTANT EMISSION FACTORS FOR UNCONTROLLED FUEL OIL COMBUSTION

Firing Configuration (SCC) ^a	SO ₂ ^b		SO ₃ ^c		NO _x ^d		CO ^{e,f}		Filterable PM ^{g,h}	
	kg/10 ³ L	EMISSION FACTOR RATING	kg/10 ³ L	EMISSION FACTOR RATING	kg/10 ³ L	EMISSION FACTOR RATING	kg/10 ³ L	EMISSION FACTOR RATING	kg/10 ³ L	EMISSION FACTOR RATING
Utility boilers										
No. 6 oil fired, normal firing (1-01-004-01)	19S	A	0.69S	C	8	A	0.6	A	1.12(S)+0.37	A
No. 6 oil fired, tangential firing (1-01-004-04)	19S	A	0.69S	C	5	A	0.6	A	1.12(S)+0.37	A
No. 5 oil fired, normal firing (1-01-004-05)	19S	A	0.69S	C	8	A	0.6	A	1.2	B
No. 5 oil fired, tangential firing (1-01-004-06)	19S	A	0.69S	C	5	A	0.6	A	1.2	B
No. 4 oil fired, normal firing (1-01-005-04)	18S	A	0.69S	C	8	A	0.6	A	0.84	B
No. 4 oil fired, tangential firing (1-01-005-05)	18S	A	0.69S	C	5	A	0.6	A	0.84	B
Industrial boilers										
No. 6 oil fired (1-02-004-01/02/03)	19S	A	0.24S	A	6.6	A	0.6	A	1.12(S)+0.37	A
No. 5 oil fired (1-02-004-04)	19S	A	0.24S	A	6.6	A	0.6	A	1.2	B
Distillate oil fired (1-02-005-01/02/03)	17S	A	0.24S	A	2.4	A	0.6	A	0.24	A
No. 4 oil fired (1-02-005-04)	18S	A	0.24S	A	2.4	A	0.6	A	0.84	B
Commercial/institutional/residential combustors										
No. 6 oil fired (1-03-004-01/02/03)	19S	A	0.24S	A	6.6	A	0.6	A	1.12(S)+0.37	A
No. 5 oil fired (1-03-004-04)	19S	A	0.24S	A	6.6	A	0.6	A	1.2	B
Distillate oil fired (1-03-005-01/02/03)	17S	A	0.24S	A	2.4	A	0.6	A	0.24	A
No. 4 oil fired (1-03-005-04)	18S	A	0.24S	A	2.4	A	0.6	A	0.84	B
Residential furnace (A2104004/A2104011)	17S	A	0.24S	A	2.2	A	0.6	A	0.3	A

Table 1.3-1 (cont.).

- ^a SCC = Source Classification Code.
- ^b References 1-6,23,42-46. S indicates that the weight % of sulfur in the oil should be multiplied by the value given. For example, if the fuel is 1.0% sulfur, then S = 1.0.
- ^c References 1-5,45-46,22.
- ^d References 3-4,10,15,24,42-46,48-49. Expressed as NO₂. Test results indicate that at least 95% by weight of NO_x is NO for all boiler types except residential furnaces, where about 75% is NO. For utility vertical fired boilers use 12.6 kg/10³ L at full load and normal (>15%) excess air. Nitrogen oxides emissions from residual oil combustion in industrial and commercial boilers are related to fuel nitrogen content, estimated by the following empirical relationship: kg NO₂ /10³ L = 2.465 + 12.526(N), where N is the weight percent of nitrogen in the oil. For example, if the fuel is 1.0% Nitrogen, then N equals 1.0.
- ^e References 3-5,8-10,23,42-46,48. CO emissions may increase by factors of 10 to 100 if the unit is improperly operated or not well maintained.
- ^f Emission factors for CO₂ from oil combustion should be calculated using kg CO₂/10³ L oil = 31.0 C (distillate) or 34.6 C (residual). C equals the weight percent carbon in the fuel. For example, if the fuel is 86% carbon, then C equals 86.
- ^g References 3-5,7,21,23-24,42-46,47,49. Filterable PM is that particulate collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values include the sum of that particulate collected on the PM-10 filter of an EPA Method 201 or 201A sampling train and condensable emissions as measured by EPA Method 202.
- ^h Particulate emission factors for residual oil combustion are, on average, a function of fuel oil grade and sulfur content: where S is the weight % of sulfur in oil. For example, if the fuel is 1.0% sulfur, then S = 1.0.

Table 1.3-2 (English Units). CRITERIA POLLUTANT EMISSION FACTORS FOR UNCONTROLLED FUEL OIL COMBUSTION

Firing Configuration (SCC) ^a	SO ₂ ^b		SO ₃ ^c		NO _x ^d		CO ^{e,f}		Filterable PM ^{g,h}	
	lb/10 ³ gal	EMISSION FACTOR RATING	lb/10 ³ gal	EMISSION FACTOR RATING	lb/10 ³ gal	EMISSION FACTOR RATING	lb/10 ³ gal	EMISSION FACTOR RATING	lb/10 ³ gal	EMISSION FACTOR RATING
Utility boilers										
No. 6 oil fired, normal firing (1-01-004-01)	157S	A	5.7S	C	67	A	5	A	9.19(S)+3.22	A
No. 6 oil fired, tangential firing (1-01-004-04)	157S	A	5.7S	C	42	A	5	A	9.19(S)+3.22	A
No. 5 oil fired, normal firing (1-01-004-05)	157S	A	5.7S	C	67	A	5	A	10	B
No. 5 oil fired, tangential firing (1-01-004-06)	157S	A	5.7S	C	42	A	5	A	10	B
No. 4 oil fired, normal firing (1-01-005-04)	150S	A	5.7S	C	67	A	5	A	7	B
No. 4 oil fired, tangential firing (1-01-005-05)	150S	A	5.7S	C	42	A	5	A	7	B
Industrial boilers										
No. 6 oil fired (1-02-004-01/02/03)	157S	A	2S	A	55	A	5	A	9.19(S)+3.22	A
No. 5 oil fired (1-02-004-04)	157S	A	2S	A	55	A	5	A	10	B
Distillate oil fired (1-02-005-01/02/03)	142S	A	2S	A	20	A	5	A	2	A
No. 4 oil fired (1-02-005-04)	150S	A	2S	A	20	A	5	A	7	B
Commercial/institutional/residential combustors										
No. 6 oil fired (1-03-004-01/02/03)	157S	A	2S	A	55	A	5	A	9.19(S)+3.22	A
No. 5 oil fired (1-03-004-04)	157S	A	2S	A	55	A	5	A	10	B
Distillate oil fired (1-03-005-01/02/03)	142S	A	2S	A	20	A	5	A	2	A
No. 4 oil fired (1-03-005-04)	150S	A	2S	A	20	A	5	A	7	B
Residential furnace (A2104004/A2104011)	142S	A	2S	A	18	A	5	A	3	A

Table 1.3-2 (cont.).

- ^a SCC = Source Classification Code.
- ^b References 1-6,23,42-46. S indicates that the weight % of sulfur in the oil should be multiplied by the value given. For example, if the fuel is 1.0% sulfur, then S equals 1.0.
- ^c References 1-5,45-46,22.
- ^d References 3-4,10,15,24,42-46,48-49. Expressed as NO₂. Test results indicate that at least 95% by weight of NO_x is NO for all boiler types except residential furnaces, where about 75% is NO. For utility vertical fired boilers use 105 lb/10³ gal at full load and normal (> 15%) excess air. Nitrogen oxides emissions from residual oil combustion in industrial and commercial boilers are related to fuel nitrogen content, estimated by the following empirical relationship: lb NO₂ /10³ gal = 20.54 + 104.39(N), where N is the weight percent of nitrogen in the oil. For example, if the fuel is 1.0% Nitrogen, then N equals 1.0.
- ^e References 3-5,8-10,23,42-46,48. CO emissions may increase by factors of 10 to 100 if the unit is improperly operated or not well maintained.
- ^f Emission factors for CO₂ from oil combustion should be calculated using lb CO₂/10³ gal oil = 259 C (distillate) or 288 C (residual). C equals the weight percent carbon in the fuel. For example, if the fuel is 86% carbon, then C equals 86.
- ^g References 3-5,7,21,23-24,42-46,47,49. Filterable PM is that particulate collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values include the sum of that particulate collected on the PM-10 filter of an EPA Method 201 or 201A sampling train and condensable emissions as measured by EPA Method 202.
- ^h Particulate emission factors for residual oil combustion are, on average, a function of fuel oil grade and sulfur content: where S is the weight % of sulfur in oil. For example, if the fuel is 1.0% sulfur, then S equals 1.0.

Table 1.3-3 (Metric Units). EMISSION FACTORS FOR TOTAL ORGANIC COMPOUNDS (TOC), METHANE, AND NONMETHANE TOC (NMTOC) FROM UNCONTROLLED FUEL OIL COMBUSTION

Firing Configuration (SCC) ^a	TOC ^b		Methane ^b		NMTOC ^b	
	kg/10 ³ L	EMISSION FACTOR RATING	kg/10 ³ L	EMISSION FACTOR RATING	kg/10 ³ L	EMISSION FACTOR RATING
Utility boilers						
No. 6 oil fired, normal firing (1-01-004-01)	0.125	A	0.034	A	0.091	A
No. 6 oil fired, tangential firing (1-01-004-04)	0.125	A	0.034	A	0.091	A
No. 5 oil fired, normal firing (1-01-004-05)	0.125	A	0.034	A	0.091	A
No. 5 oil fired, tangential firing (1-01-004-06)	0.125	A	0.034	A	0.091	A
No. 4 oil fired, normal firing (1-01-005-04)	0.125	A	0.034	A	0.091	A
No. 4 oil fired, tangential firing (1-01-005-05)	0.125	A	0.034	A	0.091	A
Industrial boilers						
No. 6 oil fired (1-02-004-01/02/03)	0.154	A	0.12	A	0.034	A
No. 5 oil fired (1-02-004-04)	0.154	A	0.12	A	0.034	A
Distillate oil fired (1-02-005-01/02/03)	0.030	A	0.006	A	0.024	A
No. 4 oil fired (1-02-005-04)	0.030	A	0.006	A	0.024	A
Commercial/institutional/ residential combustors						
No. 6 oil fired (1-03-004-01/02/03)	0.193	A	0.057	A	0.136	A
No. 5 oil fired (1-03-004-04)	0.193	A	0.057	A	0.136	A
Distillate oil fired (1-03-005-01/02/03)	0.067	A	0.026	A	0.041	A
No. 4 oil fired (1-03-005-04)	0.067	A	0.026	A	0.041	A
Residential furnace (No SCC)	0.299	A	0.214	A	0.085	A

^a SCC = Source Classification Code.

^b References 16-19. Volatile organic compound emissions can increase by several orders of magnitude if the boiler is improperly operated or is not well maintained.

Table 1.3-4 (English Units). EMISSION FACTORS FOR TOTAL ORGANIC COMPOUNDS (TOC), METHANE, AND NONMETHANE TOC (NMTOC) FROM UNCONTROLLED FUEL OIL COMBUSTION

Firing Configuration (SCC) ^a	TOC ^b		Methane ^b		NMTOC ^b	
	lb/10 ³ gal	EMISSION FACTOR RATING	lb/10 ³ gal	EMISSION FACTOR RATING	lb/10 ³ gal	EMISSION FACTOR RATING
Utility boilers						
No. 6 oil fired, normal firing (1-01-004-01)	1.04	A	0.28	A	0.76	A
No. 6 oil fired, tangential firing (1-01-004-04)	1.04	A	0.28	A	0.76	A
No. 5 oil fired, normal firing (1-01-004-05)	1.04	A	0.28	A	0.76	A
No. 5 oil fired, tangential firing (1-01-004-06)	1.04	A	0.28	A	0.76	A
No. 4 oil fired, normal firing (1-01-005-04)	1.04	A	0.28	A	0.76	A
No. 4 oil fired, tangential firing (1-01-005-05)	1.04	A	0.28	A	0.76	A
Industrial boilers						
No. 6 oil fired (1-02-004-01/02/03)	1.28	A	1.0	A	0.28	A
No. 5 oil fired (1-02-004-04)	1.28	A	1.0	A	0.28	A
Distillate oil fired (1-02-005-01/02/03)	0.252	A	0.052	A	0.2	A
No. 4 oil fired (1-02-005-04)	0.252	A	0.052	A	0.2	A
Commercial/institutional/residential combustors						
No. 6 oil fired (1-03-004-01/02/03)	1.605	A	0.475	A	1.13	A
No. 5 oil fired (1-03-004-04)	1.605	A	0.475	A	1.13	A
Distillate oil fired (1-03-005-01/02/03)	0.556	A	0.216	A	0.34	A
No. 4 oil fired (1-03-005-04)	0.556	A	0.216	A	0.34	A
Residential furnace (No SCC)	2.493	A	1.78	A	0.713	A

^a SCC = Source Classification Code.

^b References 16-19. Volatile organic compound emissions can increase by several orders of magnitude if the boiler is improperly operated or is not well maintained.

Table 1.3-5 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR UTILITY BOILERS FIRING RESIDUAL OIL^a

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size			Cumulative Emission Factor [$\text{kg}/10^3 \text{ L}$ ($\text{lb}/10^3 \text{ gal}$)]					
	Uncontrolled	Controlled		Uncontrolled ^c		ESP Controlled ^d		Scrubber Controlled ^e	
		ESP	Scrubber	Factor	RATING	Factor	RATING	Factor	RATING
15	80	75	100	0.80A (6.7A)	C	0.0060A (0.05A)	E	0.06A (0.50A)	D
10	71	63	100	0.71A (5.9A)	C	0.005A (0.042A)	E	0.06A (0.050A)	D
6	58	52	100	0.58A (4.8A)	C	0.0042A (0.035A)	E	0.06A (0.50A)	D
2.5	52	41	97	0.52A (4.3A)	C	0.0033A (0.028A)	E	0.058A (0.48A)	D
1.25	43	31	91	0.43A (3.6A)	C	0.0025A (0.021A)	E	0.055A (0.46A)	D
1.00	39	28	84	0.39A (3.3A)	C	0.0022A (0.018A)	E	0.050A (0.42A)	D
0.625	20	20	64	0.20A (1.74)	C	0.0008A (0.007A)	E	0.038A (0.32A)	D
TOTAL	100	100	100	1A (8.3A)	C	0.008A (0.067A)	E	0.06A (0.50A)	D

^a Reference 29. Source Classification Codes 1-01-004-01/04/05/06 and 1-01-005-04/05. ESP = electrostatic precipitator.

^b Expressed as aerodynamic equivalent diameter.

^c Particulate emission factors for residual oil combustion without emission controls are, on average, a function of fuel oil grade and sulfur content where S is the weight % of sulfur in the oil. For example, if the fuel is 1.0% sulfur, then S equals 1.0.

No. 6 oil: $A = 1.12(S) + 0.37 \text{ kg}/10^3 \text{ L}$,

No. 5 oil: $A = 1.2 \text{ kg}/10^3 \text{ L}$

No. 4 oil: $A = 0.84 \text{ kg}/10^3 \text{ L}$

^d Estimated control efficiency for ESP is 99.2%.

^e Estimated control efficiency for scrubber is 94%.

Table 1.3-6 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR INDUSTRIAL BOILERS FIRING RESIDUAL OIL^a

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size		Cumulative Emission Factor ^c [Kg/10 ³ l (lb/10 ³ gal)]			
	Uncontrolled	Multiple Cyclone Controlled	Uncontrolled		Multiple Cyclone Controlled ^e	
			Factor	RATING	Factor	RATING
15	91	100	0.91A (7.59A)	D	0.20A (1.67A)	E
10	86	95	0.86A (7.17A)	D	0.19A (1.58A)	E
6	77	72	0.77A (6.42A)	D	0.14A (1.17A)	E
2.5	56	22	0.56A (4.67A)	D	0.04A (0.33A)	E
1.25	39	21	0.39A (3.25A)	D	0.04A (0.33A)	E
1.00	36	21	0.36A (3.00A)	D	0.04A (0.33A)	E
0.625	30	— ^d	0.30A (2.50A)	D	— ^d	NA
TOTAL	100	100	1A (8.34A)	D	0.2A (1.67A)	E

^a Reference 29. Source Classification Codes 1-02-004-01/02/03/04 and 1-02-005-04. NA = not applicable.

^b Expressed as aerodynamic equivalent diameter.

^c Particulate emission factors for residual oil combustion without emission controls are, on average, a function of fuel oil grade and sulfur content where S is the weight % of sulfur in the oil. For example, if the fuel is 1.0% sulfur, then S equals 1.0.

No. 6 oil: $A = 1.12(S) + 0.38 \text{ kg}/10^3 \text{ L}$,

No. 5 oil: $A = 1.2 \text{ kg}/10^3 \text{ L}$

No. 4 oil: $A = 0.84 \text{ kg}/10^3 \text{ L}$

^d Insufficient data.

^e Estimated control efficiency for multiple cyclone is 80%.

Table 1.3-7 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR UNCONTROLLED INDUSTRIAL BOILERS FIRING DISTILLATE OIL^a

EMISSION FACTOR RATING: E

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size	Cumulative Emission Factor [kg/10 ³ L (lb/10 ³ gal)]
	Uncontrolled	Uncontrolled
15	68	0.16 (1.33)
10	50	0.12 (1.00)
6	30	0.07 (0.58)
2.5	12	0.03 (0.25)
1.25	9	0.02 (0.17)
1.00	8	0.02 (0.17)
0.625	2	0.005 (0.04)
TOTAL	100	0.24 (2.00)

^a Reference 29. Source Classification Codes 1-02-005-01/02/03.

^b Expressed as aerodynamic equivalent diameter.

Table 1.3-8 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR UNCONTROLLED COMMERCIAL BOILERS BURNING RESIDUAL AND DISTILLATE OIL^a

EMISSION FACTOR RATING: D

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size		Cumulative Emission Factor ^c [$\text{kg}/10^3 \text{ L}$ ($\text{lb}/10^3 \text{ gal}$)]	
	Uncontrolled, Residual Oil	Uncontrolled, Distillate Oil	Uncontrolled, Residual Oil	Uncontrolled, Distillate Oil
15	78	60	0.78A (6.50A)	0.14 (1.17)
10	62	55	0.62A (5.17A)	0.13 (1.08)
6	44	49	0.44A (3.67A)	0.12 (1.00)
2.5	23	42	0.23A (1.92A)	0.10 (0.83)
1.25	16	38	0.16A (1.33A)	0.09 (0.75)
1.00	14	37	0.14A (1.17A)	0.09 (0.75)
0.625	13	35	0.13A (1.08A)	0.08 (0.67)
TOTAL	100	100	1A (8.34A)	0.24 (2.00)

^a Reference 29. Source Classification Codes: 1-03-004-01/02/03/04 and 1-03-005-01/02/03/04.

^b Expressed as aerodynamic equivalent diameter.

^c Particulate emission factors for residual oil combustion without emission controls are, on average, a function of fuel oil grade and sulfur content where S is the weight % of sulfur in the oil. For example, if the fuel is 1.0% sulfur, then S equals 1.0.

No. 6 oil: $A = 1.12(S) + 0.37 \text{ kg}/10^3 \text{ L}$,

No. 5 oil: $A = 1.2 \text{ kg}/10^3 \text{ L}$

No. 4 oil: $A = 0.84 \text{ kg}/10^3 \text{ L}$

No. 2 oil: $A = 0.24 \text{ kg}/10^3 \text{ L}$

particulate emissions from fuel oil combustion. Uncontrolled and controlled size-specific emission factors are presented in Figure 1.3-1, Figure 1.3-2, Figure 1.3-3, and Figure 1.3-4. Distillate and residual oil categories are given separately, because their combustion produces significantly different particulate, SO_2 , and NO_x emissions.

1.3.2.1 Particulate Matter Emissions^{3-7,12-13,21,23-24}

Particulate matter emissions depend predominantly on the grade of fuel fired. Combustion of lighter distillate oils results in significantly lower PM formation than does combustion of heavier residual oils. Among residual oils, firing of Nos. 4 or 5 oils usually produces less PM than does the firing of heavier No. 6 oil.

In general, PM emissions depend on the completeness of combustion as well as on the oil ash content. The PM emitted by distillate oil-fired boilers is primarily carbonaceous particles resulting from incomplete combustion of oil and is not correlated to the ash or sulfur content of the oil. However, PM emissions from residual oil burning is related to the oil sulfur content. This is because low sulfur No. 6 oil, either refined from naturally low sulfur crude oil or desulfurized by one of

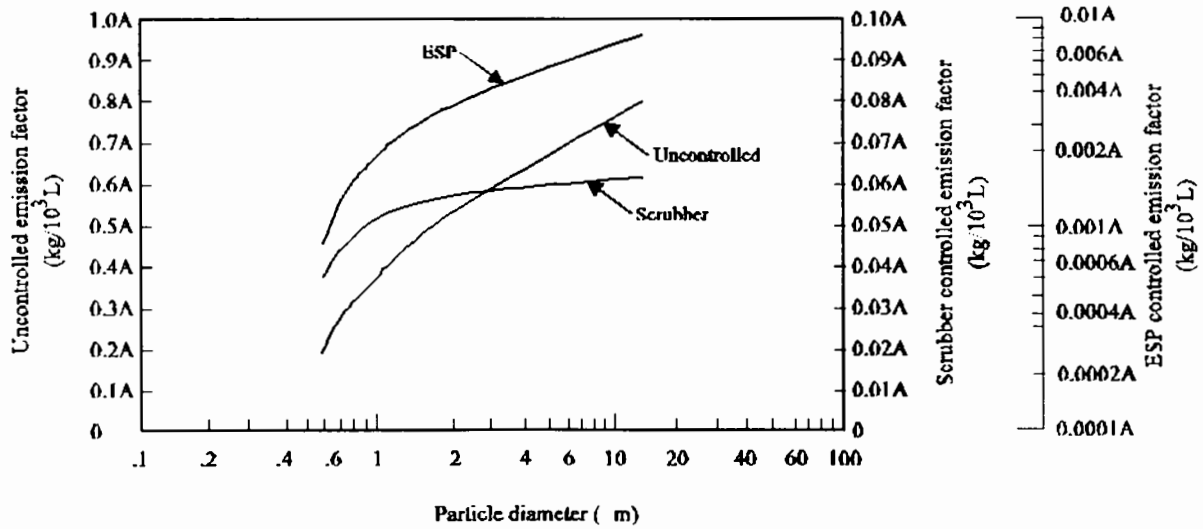


Figure 1.3-1. Cumulative size-specific emission factors for utility boilers firing residual oil.

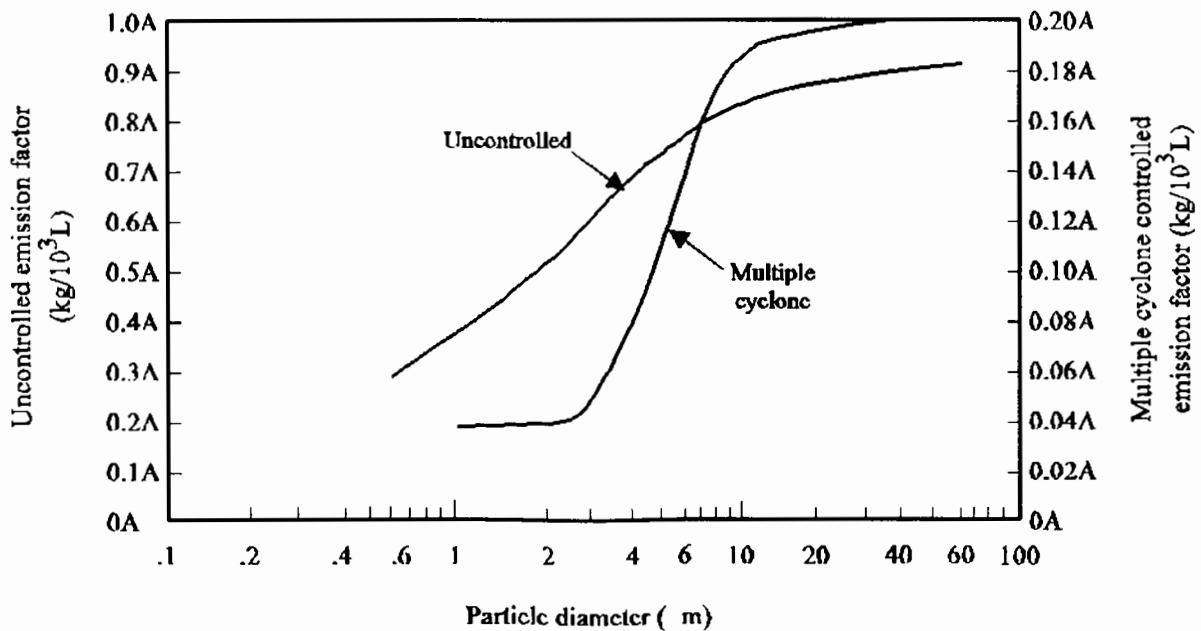


Figure 1.3-2. Cumulative size-specific emission factors for industrial boilers firing residual oil.

combustion (SC), reduced air preheat (RAP), low NO_x burners (LNBs), or some combination thereof may result in NO_x reductions of 5 to 60 percent. Load reduction (LR) can likewise decrease NO_x production. Nitrogen oxides emissions may be reduced from 0.5 to 1 percent for each percentage reduction in load from full load operation. It should be noted that most of these variables, with the exception of excess air, influence the NO_x emissions only of large oil fired boilers. Low excess air-firing is possible in many small boilers, but the resulting NO_x reductions are less significant.

Recent N₂O emissions data indicate that direct N₂O emissions from oil combustion units are considerably below the measurements made prior to 1988. Nevertheless, the N₂O formation and reaction mechanisms are still not well understood or well characterized. Additional sampling and research is needed to fully characterize N₂O emissions and to understand the N₂O formation mechanism. Emissions can vary widely from unit to unit, or even from the same unit at different operating conditions. It has been shown in some cases that N₂O increases with decreasing boiler temperature. For this update, average emission factors based on reported test data have been developed for conventional oil combustion systems. These factors are presented in Table 1.3-9.

Table 1.3-9 (Metric And English Units). EMISSION FACTORS FOR NITROUS OXIDE (N₂O), POLYCYCLIC ORGANIC MATTER (POM), AND FORMALDEHYDE (HCOH) FROM FUEL OIL COMBUSTION

EMISSION FACTOR RATING: E

Firing Configuration (SCC) ^a	Emission Factor, kg/10 ³ L (lb/10 ³ gal)		
	N ₂ O ^b	POM ^c	HCOH ^c
Utility/industrial/commercial boilers			
No. 6 oil fired (1-01-004-01, 1-02-004-01, 1-03-004-01)	0.013 (0.11)	0.00013-0.00015 (0.0011-0.0013)	0.0029-0.0073 (0.024-0.061)
Distillate oil fired (1-01-005-01, 1-02-005-01, 1-03-005-01)	0.013 (0.11)	0.00040 (0.0033)	0.0042-0.0073 (0.035-0.061)
Residential furnaces (No SCC)	0.006 (0.05)	ND	ND

^a SCC = Source Classification Code. ND = no data.

^b References 28-29.

^c References 16-19.

^d Particulate and gaseous POM.

^e Particulate POM only.

The new source performance standards (NSPS) for PM, SO₂, and NO_x emissions from residual oil combustion in fossil fuel-fired boilers are shown in Table 1.3-10.

1.3.2.4 Carbon Monoxide Emissions¹⁶⁻¹⁹ -

The rate of CO emissions from combustion sources depends on the oxidation efficiency of the fuel. By controlling the combustion process carefully, CO emissions can be minimized. Thus if a unit is operated improperly or not well maintained, the resulting concentrations of CO (as well as organic compounds) may increase by several orders of magnitude. Smaller boilers, heaters, and furnaces tend to emit more of these pollutants than larger combustors. This is because smaller units

Table 1.3-10 (Metric And English Units). NEW SOURCE PERFORMANCE STANDARDS FOR FOSSIL FUEL FIRED BOILERS

Standard/ Boiler Types/ Applicability Criteria	Boiler Size MW (Million Btu/hr)	Fuel Or Boiler Type	PM ng/J (lb/MMBtu) [% reduction]	SO ₂ ng/J (lb/MMBtu) [% reduction]	NO _x ng/J (lb/MMBtu) [% reduction]
Subpart D	> 73 (> 250)	Gas	43 (0.10)	NA ^d	86 (0.20)
Industrial-Utility		Oil	43 (0.10)	340 (0.80)	129 (0.30)
Commence construction after 8/17/71		Bit./Subbit. Coal	43 (0.10)	520 (1.20)	300 (0.70)
Subpart Da	> 73 (> 250)	Gas	13 (0.03) [NA]	340 (0.80) [90] ^a	86 (0.20) [25]
Utility		Oil	13 (0.03) [70]	340 (0.80) [90] ^a	130 (0.30) [30]
Commence construction after 9/18/78		Bit./Subbit. Coal	13 (0.03) [99]	520 (1.20) [90] ^a	260/210 ^c (0.60/0.50) [65/65]
Subpart Db	> 29 (> 100)	Gas	NA ^d	NA ^d	43 ^f (0.10)
Industrial-Commercial Institution		Distillate Oil	43 (0.10)	340 ⁿ (0.80) [90]	43 ^f (0.10)
Commence construction after 6/19/84^m		Residual Oil	(Same as for distillate oil)	(Same as for distillate oil)	130 ^g (0.30)
		Pulverized Bit./Subbit. Coal	22 ^e (0.05)	520 ^e (1.20) [90]	300 (0.70)
		Spreader Stoker & FBC	22 ^e (0.05)	520 ^e (1.20) [90]	260 (0.60)
		Mass-Feed Stoker	22 ^e (0.05)	520 ^e (1.20) [90]	210 (0.50)

Table 1.3-10 (cont.).

Standard/ Boiler Types/ Applicability Criteria	Boiler Size MW (Million Btu/hr)	Fuel Or Boiler Type	PM ng/J (lb/MMBtu) [% reduction]	SO ₂ ng/J (lb/MMBtu) [% reduction]	NO _x ng/J (lb/MMBtu) [% reduction]
Subpart Dc	2.9 - 29 (10 - 100)	Gas	— ^h	—	—
Small Industrial Commercial- Institutional		Oil	— ^{h,j}	215 (0.50)	—
Commence construction after 6/9/89		Bit./Subbit. Coal	22 ^{j,k} (0.05)	520 ^k (1.20) [90]	—

^a Zero percent reduction when emissions are less than 86 ng/J (0.20 lb/MMBtu). FBC = fluidized bed combustion. NA = not applicable.

^b 70 percent reduction when emissions are less than 260 ng/J (0.60 lb/MMBtu).

^c The first number applies to bituminous coal and the second to subbituminous coal.

^d Standard applies when gas is fired in combination with coal; see 40 CFR 60, Subpart Db.

^e Standard is adjusted for fuel combinations and capacity factor limits; see 40 CFR 60, Subpart Db.

^f For furnace heat release rates greater than 730,000 J/s-m³ (70,000 Btu/hr-ft³), the standard is 86 ng/J (0.20 lb/MMBtu).

^g For furnace heat release rates greater than 730,000 J/s-m³ (70,000 Btu/hr-ft³), the standard is 170 ng/J (0.40 lb/MMBtu).

^h Standard applies when gas or oil is fired in combination with coal; see 40 CFR 60, Subpart Dc.

^j 20 percent capacity limit applies for heat input capacities of 8.7 Mwt (30 MMBtu/hr) or greater.

^k Standard is adjusted for fuel combinations and capacity factor limits; see 40 CFR 60, Subpart Dc.

^m Additional requirements apply to facilities which commenced construction, modification, or reconstruction after 6/19/84 but on or before 6/19/86 (see 40 Code of Federal Regulations Part 60, Subpart Db).

ⁿ 215 ng/J (0.50 lb/million Btu) limit (but no percent reduction requirement) applies if facilities combust only very low sulfur oil (<0.5 wt. % sulfur).

usually have a higher ratio of heat transfer surface area to flame volume leading to reduced flame temperature and combustion intensity and, therefore, lower combustion efficiency than larger combustors.

The presence of CO in the exhaust gases of combustion systems results principally from incomplete fuel combustion. Several conditions can lead to incomplete combustion, including:

- insufficient oxygen (O₂) availability;
- poor fuel/air mixing;
- cold wall flame quenching;
- reduced combustion temperature;

- decreased combustion gas residence time; and
- load reduction (i. e., reduced combustion intensity).

Since various combustion modifications for NO_x reduction can produce one or more of the above conditions, the possibility of increased CO emissions is a concern for environmental, energy efficiency, and operational reasons.

1.3.2.5 Organic Compound Emissions^{16-19,30-35,64}

Small amounts of organic compounds are emitted from combustion. As with CO emissions, the rate at which organic compounds are emitted depends, to some extent, on the combustion efficiency of the boiler. Therefore, any combustion modification which reduces the combustion efficiency will most likely increase the concentrations of organic compounds in the flue gases.

Total organic compounds (TOCs) include VOCs, semi-volatile organic compounds, and condensible organic compounds. Emissions of VOCs are primarily characterized by the criteria pollutant class of unburned vapor phase hydrocarbons. Unburned hydrocarbon emissions can include essentially all vapor phase organic compounds emitted from a combustion source. These are primarily emissions of aliphatic, oxygenated, and low molecular weight aromatic compounds which exist in the vapor phase at flue gas temperatures. These emissions include all alkanes, alkenes, aldehydes, carboxylic acids, and substituted benzenes (e. g., benzene, toluene, xylene, and ethyl benzene).

The remaining organic emissions are composed largely of compounds emitted from combustion sources in a condensed phase. These compounds can almost exclusively be classed into a group known as polycyclic organic matter (POM), and a subset of compounds called polynuclear aromatic hydrocarbons (PNA or PAH). There are also PAH-nitrogen analogs. Information available in the literature on POM compounds generally pertains to these PAH groups.

Formaldehyde is formed and emitted during combustion of hydrocarbon-based fuels including coal and oil. Formaldehyde is present in the vapor phase of the flue gas. Formaldehyde is subject to oxidation and decomposition at the high temperatures encountered during combustion. Thus, larger units with efficient combustion (resulting from closely regulated air-fuel ratios, uniformly high combustion chamber temperatures, and relatively long gas retention times) have lower formaldehyde emission rates than do smaller, less efficient combustion units. Average emission factors for POM and formaldehyde from fuel oil combustors are presented in Table 1.3-9, together with N₂O emissions data.

1.3.2.6 Trace Element Emissions^{16-19,36-40}

Trace elements are also emitted from the combustion of oil. For this update of AP-42, trace metals included in the list of 189 hazardous air pollutants under Title III of the 1990 Clean Air Act Amendments are considered. The quantity of trace metals emitted depends on combustion temperature, fuel feed mechanism, and the composition of the fuel. The temperature determines the degree of volatilization of specific compounds contained in the fuel. The fuel feed mechanism affects the separation of emissions into bottom ash and fly ash.

The quantity of any given metal emitted, in general, depends on:

- the physical and chemical properties of the element itself;
- its concentration in the fuel;

Table 1.4-1 (Metric And English Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM)
FROM NATURAL GAS COMBUSTION^a

Combustor Type (Size, 10 ⁶ Btu/hr Heat Input) (SCC) ^b	Filterable PM ^c			Condensable PM ^d		
	kg/10 ⁶ m ³	lb/10 ⁶ ft ³	RATING	kg/10 ⁶ m ³	lb/10 ⁶ ft ³	RATING
Utility/large industrial boilers (> 100) (1-01-006-01, 1-01-006-04)	16 - 80	1 - 5	B	ND	ND	NA
Small industrial boilers (10 - 100) (1-02-006-02)	99	6.2	B	120	7.5	D
Commercial boilers (0.3 - < 10) (1-03-006-03)	72	4.5	C	120	7.5	C
Residential furnaces (< 0.3) (No SCC)	2.8	0.18	C	180	11	D

^a References 9-14. All factors represent uncontrolled emissions. Units are kg of pollutant/10⁶ cubic meters natural gas fired and lb of pollutant/10⁶ cubic feet natural gas fired. Based on an average natural gas higher heating value of 8270 kcal/m³ (1000 Btu/scf). 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. ND = no data. NA = not applicable.

^b SCC = Source Classification Code.

^c Filterable PM is that particulate matter collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

^d Condensable PM is that particulate matter collected using EPA Method 202, (or equivalent). Total PM is the sum of the filterable PM and condensable PM. All PM emissions can be assumed to be less than 10 micrometers in aerodynamic equivalent diameter (PM-10).

Table 1.4-2 (Metric And English Units). EMISSION FACTORS FOR SULFUR DIOXIDE (SO₂), NITROGEN OXIDES (NO_x), AND CARBON MONOXIDE (CO) FROM NATURAL GAS COMBUSTION^a

Combustor Type (Size, 10 ⁶ Btu/hr Heat Input) (SCC) ^b	SO ₂ ^c			NO _x ^d			CO ^e		
	kg/10 ⁶ m ³	lb/10 ⁶ ft ³	RATING	kg/10 ⁶ m ³	lb/10 ⁶ ft ³	RATING	kg/10 ⁶ m ³	lb/10 ⁶ ft ³	RATING
Utility/Large Industrial Boilers (> 100) (1-01-006-01, 1-01-006-04)									
Uncontrolled	9.6	0.6	A	8800	550 ^f	A	640	40	A
Controlled - Low NO _x burners	9.6	0.6	A	1300	81 ^f	D	ND	ND	NA
Controlled - Flue gas recirculation	9.6	0.6	A	850	53 ^f	D	ND	ND	NA
Small Industrial Boilers (10 - 100) (1-02-006-02)									
Uncontrolled	9.6	0.6	A	2240	140	A	560	35	A
Controlled - Low NO _x burners	9.6	0.6	A	1300	81 ^f	D	980	61	D
Controlled - Flue gas recirculation	9.6	0.6	A	480	30	C	590	37	C
Commercial Boilers (0.3 - <10) (1-03-006-03)									
Uncontrolled	9.6	0.6	A	1600	100	B	330	21	C
Controlled - Low NO _x burners	9.6	0.6	A	270	17	C	236	15	C
Controlled - Flue gas recirculation	9.6	0.6	A	580	36	D	ND	ND	NA
Residential Furnaces (<0.3) (No SCC)									
Uncontrolled	9.6	0.6	A	1500	94	B	640	40	B

^a Units are kg of pollutant/10⁶ cubic meters natural gas fired and lb of pollutant/10⁶ cubic feet natural gas fired. Based on an average natural gas fired higher heating value of 8270 kcal/m³ (1000 Btu/scf). 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. ND = no data. NA = not applicable.

^b SCC = Source Classification Code.

^c Reference 7. Based on average sulfur content of natural gas, 4600 g/10⁶ Nm³ (2000 gr/10⁶ scf).

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 hogged 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 is from 65 to 95 percent. The most widely used wet scrubbers for wood-fired boilers are venturi scrubbers. With gas-side pressure drops exceeding 4 kPa (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.

Emissions of nitrogen oxides (NO_x) from wood-fired boilers are lower than those from coal-fired boilers due to the lower nitrogen content of wood and the lower combustion temperatures which characterize wood-fired boilers. 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 non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) to waste wood-fired boilers has either been accomplished (SNCR) or is being contemplated (SCR). Both systems are post-combustion 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, 1.6-5, 1.6-6, and 1.6-7.²¹⁻²² Emission factors are for uncontrolled combustors unless otherwise indicated. Cumulative particle size distribution data and associated emission factors are presented in Tables 1.6-8 and 1.6-9. 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 2,500 kcal/kg (4,500 Btu/lb) higher heating values.

Table 1.6-1 (Metric And English Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM), PARTICULATE MATTER LESS THAN 10 MICROMETERS (PM-10), AND LEAD FROM WOOD WASTE COMBUSTION^a

Source Category (SCC) ^b	PM ^c			PM-10 ^d			Lead ^e		
	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING
Bark-fired boilers (1-01-009-01, 1-02-009-01, 1-02-009-04, 1-03-009-01)									
Uncontrolled	23.5	47	B	8.4	16.8	D	1.4 E-03	2.9 E-03	D
Mechanical collector with flyash reinjection	7	14	B	5.5	11.0	D	ND ^f	ND	
without flyash reinjection	4.5	9.0	B	1.62	3.24	D			
Wet scrubber	1.44	2.88	D	1.25	2.50	D	ND	ND	
Wood/bark-fired boilers (1-01-009-02, 1-02-009-02, 1-02-009-05, 1-03-009-02)									
Uncontrolled	3.6	7.2	C	3.24	6.48	E	ND	ND	
Mechanical collector with flyash reinjection	3.0	6.0	C	2.73	5.46	E	1.6 E-04 ^g	3.2 E-04 ^g	D
without flyash reinjection	2.7	5.4	C	0.86	1.72	E	1.6 E-04 ^g	3.2 E-04 ^g	
Wet scrubber	0.24	0.48	D	0.216	0.432	E	1.8 E-04	3.5 E-04	D
Electrostatic precipitator	0.02	0.04	D	ND	ND		8.0 E-05	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	4.4	8.8	C	ND	ND		ND	ND	
Mechanical collector without flyash reinjection	2.1	4.2	C	1.3 ^h	2.6 ^h	D	1.5 E-04	3.1 E-04	D
Electrostatic precipitator	0.08	0.17	D	ND	ND		5.5 E-03	1.1 E-03	D

Table 1.6-1 (cont.).

- ^a Units are kg of pollutant/Mg of wood waste burned and lb of pollutant/ton of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2500 kcal/kg (4500 Btu/lb) higher heating value.
- ^b SCC = Source Classification Code.
- ^c References 11-15.
- ^d References 13,16.
- ^e References 11,13-15,17.
- ^f ND = no data.
- ^g Due to lead's relative volatility, it is assumed that flyash reinjection does not have a significant effect on lead emissions following mechanical collectors.
- ^h Based on one test in which 61 percent of emitted PM was less than 10 micrometer in size.

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

Source Category (SCC) ^b	NO _x ^c			SO _x ^d			CO ^e		
	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING
Fuel cell/Dutch oven boiler (no SCC)	0.19 (0.0017 - 0.75)	0.38 (0.0033 - 1.5)	C	0.037 (0.005 - 0.1)	0.075 (0.01 - 0.2)	B	3.3 (0.33 - 11)	6.6 (0.65 - 21)	C
Stoker boilers (no SCC)	0.75 (0.33 - 1.8)	1.5 (0.66 - 3.6)	C	0.037 (0.005 - 0.1)	0.075 (0.01 - 0.2)	B	6.8 (0.95 - 40)	13.6 (1.9 - 80)	C
FBC boilers (no SCC)	1.0	2.0	D	0.037 (0.005 - 0.1)	0.075 (0.01 - 0.2)	B	0.7 (0.24 - 1.2)	1.4 (0.47 - 2.4)	D

^a Units are kg of pollutant/Mg of wood waste burned and lb of pollutant/ton of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2,500 kcal/kg (4,500 Btu/lb) higher heating value. FBC = fluidized bed combustion.

^b SCC = Source Classification Code.

^c References 12-14,18-20. NO_x formation is primarily a function of wood nitrogen content. Higher values in the range (parentheses) should be used for wood nitrogen contents above a typical value of 0.08 weight percent, as fired.

^d Reference 23. Lower limit of the range (in parentheses) should be used for wood and higher values for bark.

^e References 11-15,18,24-26. Higher values in the range (in parentheses) should be used if combustion conditions are less than adequate, such as unusually wet wood or high air-to-fuel ratios.

Table 1.7-1 (Metric Units). EMISSION FACTORS FOR SULFUR OXIDES (SO_x),
NITROGEN OXIDES (NO_x), AND CARBON MONOXIDE (CO)
FROM UNCONTROLLED LIGNITE COMBUSTION^a

Firing Configuration (SCC) ^b	SO _x ^{c,f}		NO _x ^d		CO ^e	
	Emission Factor	RATING	Emission Factor	RATING	Emission Factor	RATING
Pulverized coal, dry bottom, tangential (SCC 1-01-003-02)	15S	C	3.7	C	0.13	C
Pulverized coal, dry bottom, wall fired (SCC 1-01-003-01)	15S	C	5.6	C		
Cyclone (SCC 1-01-003-03)	15S	C	6.3	C		
Spreader stoker (SCC 1-01-003-06)	15S	C	2.9	C		
Traveling Grate (overfeed) stoker (SCC 1-01-003-04)	15S	C	ND			
Atmospheric fluidized bed	5S	D	1.8	C	0.08	C

^a Units are kg of pollutant/Mg of fuel burned. ND = no data.

^b SCC = Source Classification Code.

^c Reference 2.

^d References 2-3,7-8,15-16.

^e References 7,16.

^f S = Weight % sulfur content of lignite, wet basis. For example, if the sulfur content equals 3.4%, then S = 3.4. For high sodium ash (Na₂O > 8%), use 11S. For low sodium ash (Na₂O < 2%), use 17S. If ash sodium content is unknown, use 15S.

Table 1.7-2 (English Units). EMISSION FACTORS FOR SULFUR OXIDES (SO_x),
NITROGEN OXIDES (NO_x), AND CARBON MONOXIDE (CO)
FROM UNCONTROLLED LIGNITE COMBUSTION^a

Firing Configuration (SCC) ^b	SO _x ^{c,f}		NO _x ^d		CO ^e	
	Emission Factor	RATING	Emission Factor	RATING	Emission Factor	RATING
Pulverized coal, dry bottom, tangential (SCC 1-01-003-02)	30S	C	7.3	C	0.25	C
Pulverized coal, dry bottom, wall fired (SCC 1-01-003-01)	30S	C	11.1	C		
Cyclone (SCC 1-01-003-03)	30S	C	12.5	C		
Spreader stoker (SCC 1-01-003-06)	30S	C	5.8	C		
Traveling grate (overfeed) stoker (SCC 1-01-003-04)	30S	C	ND			
Atmospheric fluidized bed	10S	D	3.6	C	0.15	C

^a Units are lb of pollutant/ton of fuel burned.

^b SCC = Source Classification Code.

^c Reference 2.

^d References 2-3,7-8,15-16.

^e References 7,16.

^f S = Weight % sulfur content of lignite, wet basis. For example, if the sulfur content equals 3.4%, then S = 3.4. For high sodium ash (Na₂O > 8%), use 22S. For low sodium ash (Na₂O < 2%), use 34S. If ash sodium content is unknown, use 30S.

Table 1.7-3 (Metric And English Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM) AND NITROUS OXIDE (N₂O) FROM LIGNITE COMBUSTION^a

Firing Configuration (SCC)	PM ^b		N ₂ O ^c	
	Emission Factor	RATING	Emission Factor	RATING
Pulverized coal, dry bottom, tangential (SCC 1-01-003-02)	3.3A (6.5A)	E		
Pulverized coal, dry bottom, wall fired (SCC 1-01-003-01)	2.6A (5.1A)	E		
Cyclone (SCC 1-01-003-03)	3.4A (6.7A)	C		
Spreader stoker (SCC 1-01-003-06)	4.0A (8.0A)	E		
Other stoker (SCC 1-01-003-04)	1.7A (3.4A)	E		
Atmospheric fluidized bed			1.2 (2.5)	E

^a Units are kg of pollutant/Mg of fuel burned and lb of pollutant/ton of fuel burned.

SCC = Source Classification Code.

^b References 5-6,12,14. A = weight % ash content of lignite, wet basis. For example, if the ash content is 5%, then A = 5.

^c Reference 18.

Table 1.7-4 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR BOILERS FIRING PULVERIZED LIGNITE^a

EMISSION FACTOR RATING: E

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size		Cumulative Emission Factor ^c	
	Uncontrolled	Multiple Cyclone Controlled	Uncontrolled	Multiple Cyclone Controlled ^d
15	51	77	1.7A (3.4A)	0.51A (1.0A)
10	35	67	1.2A (2.3A)	0.44A (0.88A)
6	26	57	0.86A (1.7A)	0.38A (0.75A)
2.5	10	27	0.33A (0.66A)	0.18A (0.36A)
1.25	7	16	0.23A (0.47A)	0.11A (0.21A)
1.00	6	14	0.20A (0.40A)	0.093A (0.19A)
0.625	3	8	0.10A (0.19A)	0.053A (0.11A)
TOTAL			3.3A (6.6A)	0.66A (1.3A)

^a Reference 13. Based on tangential-fired units. For wall-fired units, multiply emission factors in the table by 0.79.

^b Expressed as aerodynamic equivalent diameter.

^c Units are kg of pollutant/Mg of fuel burned and lb of pollutant/ton of fuel burned. A = weight % ash content of coal, wet basis.

^d Estimated control efficiency for multiple cyclone is 80%.

Table 1.7-5 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS
FOR LIGNITE-FIRED SPREADER STOKERS^a
(SCC 1-01-003-06)

EMISSION FACTOR RATING: E

Particle Size ^b (μm)	Cumulative Mass % \leq Stated Size		Cumulative Emission Factor ^c	
	Uncontrolled	Multiple Cyclone Controlled	Uncontrolled	Multiple Cyclone Controlled ^d
15	28	55	1.1A (2.2A)	0.44A (0.88A)
10	20	41	0.80A (1.6A)	0.33A (0.66A)
6	14	31	0.56A (1.1A)	0.25A (0.50A)
2.5	7	26	0.28A (0.56A)	0.21A (0.42A)
1.25	5	23	0.20A (0.40A)	0.18A (0.37A)
1.00	5	22	0.20A (0.40A)	0.18A (0.35A)
0.625	4	— ^e	0.16A (0.33A)	— ^e
TOTAL			4.0A (8.0A)	0.80A (1.6A)

^a Reference 13.

^b Expressed as aerodynamic equivalent diameter.

^c Units are kg of pollutant/Mg of fuel burned and lb of pollutant/ton of fuel burned. A = weight % ash content of lignite, wet basis. For example, if the lignite is 5% ash, then A equal 5.

^d Estimated control efficiency for multiple cyclone is 80%.

^e Insufficient data.

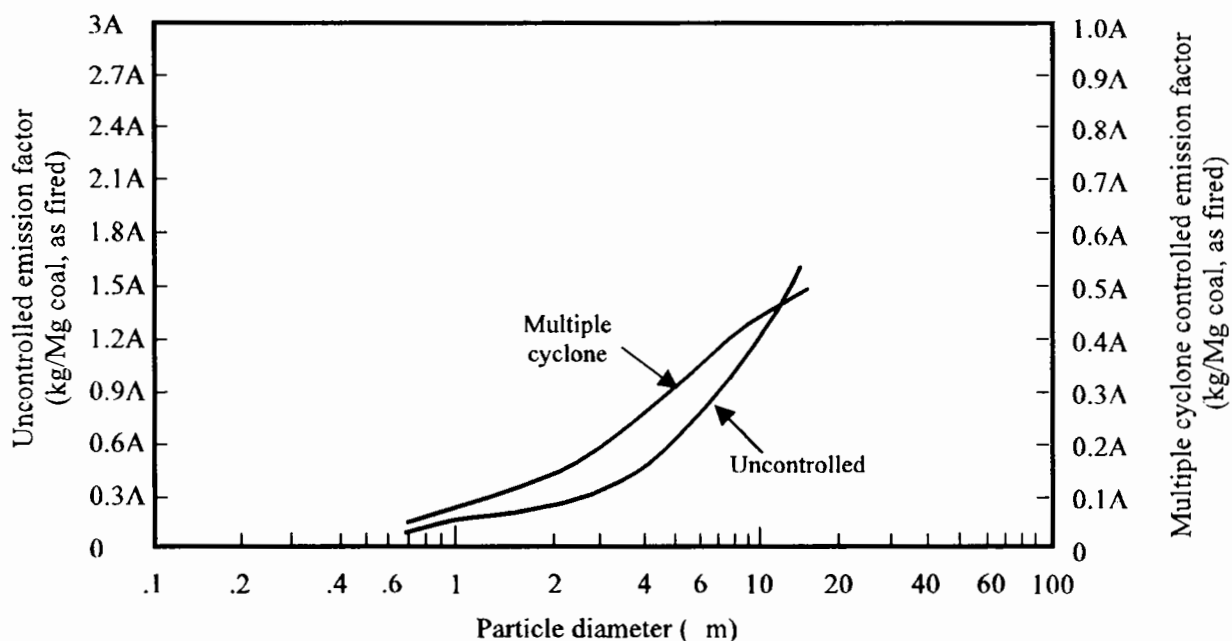


Figure 1.7-1. Cumulative size-specific emission factors for boilers firing pulverized lignite.

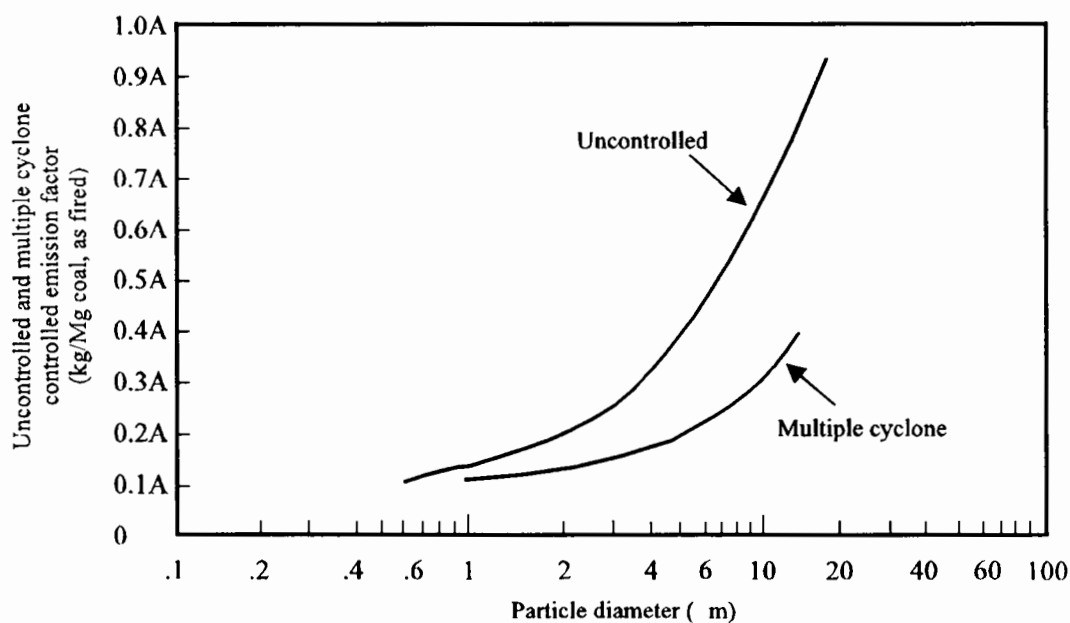


Figure 1.7-2. Cumulative size-specific emission factors for lignite-fired spreader stokers.

Table 1.11-3 (Metric And English Units). EMISSION FACTORS FOR TOTAL ORGANIC COMPOUNDS (TOC), HYDROGEN CHLORIDE (HCl), AND CARBON DIOXIDE (CO₂) FROM WASTE OIL COMBUSTORS^a

Source Category (SCC) ^b	TOC			HCl			CO ₂		
	kg/m ³	lb/1000 gal	RATING	kg/m ³	lb/1000 gal	RATING	kg/m ³	lb/1000 gal	RATING
Small boilers ^c (1-03-013-02)	0.1	1.0	D	7.9Cl ^d	66Cl	C	2,400	20,000	C
Space heaters ^e Vaporizing burner (1-05-001-14, 1-05-002-14)	0.1	1.0	D	ND	ND		2,700	23,000	D
Atomizing burner (1-05-001-13, 1-05-002-13)	0.1	1.0	D	ND	ND		2,900	24,000	D

^a Units are kg of pollutant/cubic meter of waste oil burned and lb of pollutant/1000 gallons of waste oil burned. ND = no data.

^b SCC = Source Classification Code.

^c References 2,4,6-7,9.

^d Cl = weight percent chlorine in fuel. Multiply numeric value by Cl to obtain emission factor.

^e References 4,6-7,9.

Table 1.11-4 (Metric And English Units). EMISSION FACTORS FOR SPECIATED METALS
FROM WASTE OIL COMBUSTORS^a

EMISSION FACTOR RATING: D

Pollutant	Small Boilers ^b (SCC 1-03-013-02)		Space Heaters: Vaporizing Burner ^c (SCC 1-05-001-14, 1-05-002-14)		Space Heaters: Atomizing Burner ^c (SCC 1-05-001-13, 1-05-002-13)	
	kg/m ³	lb/1000 gal	kg/m ³	lb/1000 gal	kg/m ³	lb/1000 gal
Antimony	ND	ND	4.1 E-05	3.4 E-04	5.4 E-04	4.5 E-03
Arsenic	1.3 E-02	1.1 E-01	3.0 E-04	2.5 E-03	7.2 E-03	6.0 E-02
Beryllium	ND	ND	ND	ND	2.1 E-04	1.8 E-03
Cadmium	1.1 E-03	9.3 E-03	1.8 E-05	1.5 E-04	1.4 E-03	1.2 E-02
Chromium	2.4 E-03	2.0 E-02	2.3 E-02	1.9 E-01	2.2 E-02	1.8 E-01
Cobalt	2.5 E-05	2.1 E-04	6.8 E-04	5.7 E-03	6.2 E-04	5.2 E-03
Manganese	8.2 E-03	6.8 E-02	2.6 E-04	2.2 E-03	6.0 E-03	5.0 E-02
Nickel	1.3 E-03	1.1 E-02	6.0 E-03	5.0 E-02	1.9 E-02	1.6 E-01
Selenium	ND	ND	ND	ND	ND	ND
Phosphorous	ND	ND	4.3 E-03	3.6 E-02	ND	ND

^a Pollutants in this table represent metal species measured for waste oil combustors. Other metal species may also have been emitted but were either not measured or were present at concentrations below analytical detection limits. Units are kg of pollutant/cubic meter of waste oil burned and lb of pollutant/1000 gallons of waste oil burned. SCC = Source Classification Code. ND = no data.

^b Reference 6.

^c References 6-7.

Table 3.1-1 (Metric Units). EMISSION FACTORS FOR LARGE UNCONTROLLED GAS TURBINES^a

Pollutant	EMISSION FACTOR RATING ^b	Natural Gas (SCC 2-01-002-01)		Fuel Oil (Distillate) (SCC 2-01-001-01)	
		g/kW-hr ^c (power output)	ng/J (fuel input)	g/kW-hr ^c (power output)	ng/J (fuel input)
NO _x	C	2.15	190	3.41	300
CO	D	0.52	46	0.233	20.6
CO ₂ ^d	B	546	48,160	799	70,520
TOC (as methane)	D	0.117	10.32	0.083	7.31
SO _x (as SO ₂) ^e	B	4.57S	404S	4.92S	434.3S
PM-10					
Solids	E	0.094	8.30	0.185	16.3
Condensables	E	0.11	9.72	0.113	9.89
Sizing %					
<0.05 μm	D	15%	15%	16%	16%
<0.10 μm	D	40%	40%	48%	48%
<0.15 μm	D	63%	63%	72%	72%
<0.20 μm	D	78%	78%	85%	85%
<0.25 μm	D	89%	89%	93%	93%
< 1 μm	D	100%	100%	100%	100%

^a References 1-8. SCC = Source Classification Code. PM-10 = particulate matter less than or equal to 10 micrometers (μm) aerodynamic diameter, and sizing % is expressed in μm.

^b Ratings reflect limited data and/or a lack of documentation of test results, may not apply to specific facilities or populations, and should be used with care.

^c Calculated from ng/J assuming an average heat rate of 11,318 kJ/kW-hr.

^d Based on 100% conversion of the fuel carbon to CO₂. CO₂ [ng/J] = 3.67*C/E, where C = carbon content of the fuel by weight (0.75), and E = energy content of fuel, 55.6 kJ/g. The uncontrolled CO₂ emission factors are also applicable to controlled gas turbines.

^e All sulfur in the fuel is assumed to be converted to SO₂. S = % sulfur in fuel.

Table 3.1-2 (English Units). EMISSION FACTORS FOR LARGE UNCONTROLLED GAS TURBINES^a

Pollutant	EMISSION FACTOR RATING ^b	Natural Gas (SCC 2-01-002-01)		Fuel Oil (Distillate) (SCC 2-01-001-01)	
		lb/hp-hr ^c (power output)	lb/MMBtu (fuel input)	lb/hp-hr ^c (power output)	lb/MMBtu (fuel input)
NO _x	C	3.53 E-03	0.44	5.60 E-03	0.698
CO	D	8.60 E-04	0.11	3.84 E-04	0.048
CO ₂ ^d	B	0.897	112	1.31	164
TOC (as methane)	D	1.92 E-04	0.024	1.37 E-04	0.017
SO _x (as SO ₂) ^e	B	7.52 E-03S	0.94S	8.09 E-03S	1.01S
PM-10					
Solids	E	1.54 E-04	0.0193	3.04 E-04	0.038
Condensables	E	1.81 E-04	0.0226	1.85 E-04	0.023
Sizing %					
<0.05 μm	D	15%	15%	16%	16%
<0.10 μm	D	40%	40%	48%	48%
<0.15 μm	D	63%	63%	72%	72%
<0.20 μm	D	78%	78%	85%	85%
<0.25 μm	D	89%	89%	93%	93%
<1 μm	D	100%	100%	100%	100%

^a References 1-8. SCC = Source Classification Code. PM-10 = particulate matter less than or equal to 10 μm aerodynamic diameter, and sizing % is expressed in μm. Condensables are also PM-10 and all PM from oil and gas fired turbines is less than 1 μm in size and therefore are considered PM-10.

^b Ratings reflect limited data and/or a lack of documentation of test results, may not apply to specific facilities or populations, and should be used with care.

^c Calculated from lb/MMBtu assuming an average heat rate of 8,000 Btu/hp-hr.

^d Based on 100% conversion of the fuel carbon to CO₂. CO₂ [lb/MMBtu] = 3.67*C/E, where C = carbon content of fuel by weight (0.75), and E = energy content of fuel, (0.0239 MMBtu/lb). The uncontrolled CO₂ emission factors are also applicable to controlled gas turbines.

^e All sulfur in the fuel is assumed to be converted to SO₂. S = % sulfur in fuel. When sulfur content is not available, 0.6 lb/10⁶ ft³ (0.0006 lb/MMBtu) can be used; however, the equation is more accurate.

Table 3.1-3 (Metric Units). EMISSION FACTORS FOR LARGE GAS-FIRED
CONTROLLED GAS TURBINES^a

EMISSION FACTOR RATING: C

Pollutant	Water Injection (0.8 water/fuel ratio)		Steam Injection (1.2 water/fuel ratio)		Selective Catalytic Reduction (with water injection)
	g/kW-hr (power output)	ng/J (fuel input)	g/kW-hr (power output)	ng/J (fuel input)	ng/J (fuel input)
NO _x	0.66	61	0.59	52	3.78 ^b
CO	1.3	120	0.71	69	3.61
TOC (as methane)	ND	ND	ND	ND	6.02
NH ₃	ND	ND	ND	ND	2.80
NMHC	ND	ND	ND	ND	1.38
Formaldehyde ^c	ND	ND	ND	ND	1.16

^a References 3,10-15. Source Classification Code 2-01-002-01. All data are averages of a limited number of tests and may not be typical of those reductions that can be achieved at a specific location. NMHC = nonmethane hydrocarbons. ND = no data.

^b An SCR catalyst reduces NO_x by an average of 78%.

^c Hazardous air pollutant listed in the *Clean Air Act*.

Table 3.1-4 (English Units). EMISSION FACTORS FOR LARGE GAS-FIRED
CONTROLLED GAS TURBINES^a

EMISSION FACTOR RATING: C

Pollutant	Water Injection (0.8 water/fuel ratio)		Steam Injection (1.2 water/fuel ratio)		Selective Catalytic Reduction (with water injection)
	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/MMBtu (fuel input)
NO _x	1.10 E-03	0.14	9.70 E-04	0.12	0.03 ^b
CO	2.07 E-03	0.28	1.17 E-03	0.16	0.0084
TOC (as methane)	ND	ND	ND	ND	0.014
NH ₃	ND	ND	ND	ND	0.0065
NMHC	ND	ND	ND	ND	0.0032
Formaldehyde ^c	ND	ND	ND	ND	0.0027

^a References 3,10-15. Source Classification Code 2-01-002-01. All data are averages of a limited number of tests and may not be typical of those reductions that can be achieved at a specific location. NMHC = nonmethane hydrocarbons. ND = no data.

^b An SCR catalyst reduces NO_x by an average of 78%.

^c Hazardous air pollutant listed in the *Clean Air Act*.

Table 3.2-1 (Metric Units). CRITERIA EMISSION FACTORS FOR UNCONTROLLED NATURAL GAS PRIME MOVERS^a

EMISSION FACTOR RATING: A (except as noted)

Pollutant	Gas Turbines (SCC 2-02-002-01)		2-Cycle Lean Burn (SCC 2-02-002-52)		4-Cycle Lean Burn (SCC 2-02-002-53)		4-Cycle Rich Burn (SCC 2-02-002-54)	
	g/kW-hr (power output)	ng/J (fuel input)	g/kW-hr (power output)	ng/J (fuel input)	g/kW-hr (power output)	ng/J (fuel input)	g/kW-hr (power output)	ng/J (fuel input)
NO _x	1.70	145	14.79	1,165	16.1	1,376	13.46	989
CO	1.11	71	2.04	165	2.15	181	11.55	687
CO ₂ ^b	543	47,424	543	47,424	543	47,424	543	47,424
TOC	0.24	22.8	8.14	645	6.57	516	1.66	116
TNMOC	0.013	0.86	0.58	47.3	0.97	77.4	0.19	12.9
CH ₄	0.228	21.9	7.56	615	5.50	473	1.48	103

^a References 1-5. Factors are based on entire population. Factors for individual engines from specific manufacturers may vary.

SCC = Source Classification Code. TNMOC = total nonmethane organic compounds.

^b EMISSION FACTOR RATING: B. Based on 100% conversion of the fuel carbon to CO₂. CO₂ [ng/J] = 3.67*C/E, where C = carbon content of fuel by weight (0.75), and E = energy content of fuel, 55.6 kJ/g. The uncontrolled CO₂ emission factors are also applicable to natural gas prime movers controlled by combustion modifications, NSCR, and SCR.

Table 3.2-2 (English Units). CRITERIA EMISSION FACTORS FOR UNCONTROLLED NATURAL GAS PRIME MOVERS^a

EMISSION FACTOR RATING: A (except as noted)

Pollutant	Gas Turbines (SCC 2-02-002-01)		2-Cycle Lean Burn (SCC 2-02-002-52)		4-Cycle Lean Burn (SCC 2-02-002-54)		4-Cycle Rich Burn (SCC 2-02-002-53)	
	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/hp-hr (power output)	lb/MMBtu (fuel input)
NO _x	2.87 E-03	0.34	0.024	2.7	0.026	3.2	0.022	2.3
CO	1.83 E-03	0.17	3.31 E-03	0.38	3.53 E-03	0.42	0.019	1.6
CO ₂ ^b	0.89	110	0.89	110	0.89	110	0.89	110
TOC	3.97 E-04	0.053	0.013	1.5	0.011	1.2	2.65 E-03	0.27
TNMOC	2.20 E-05	0.002	9.48 E-04	0.11	1.59 E-03	0.18	3.09 E-04	0.03
CH ₄	3.75 E-04	0.051	0.012	1.4	9.04 E-03	1.1	2.43 E-03	0.24

^a References 1-5. Factors are based on entire population. Factors for individual engines from specific manufacturers may vary.

SCC = Source Classification Code. TNMOC = total nonmethane organic compounds.

^b EMISSION FACTOR RATING: B. Based on 100% conversion of the fuel carbon to CO₂. CO₂ [lb/MMBtu] = 3.67*C/E, where C = carbon content of fuel by weight (0.75), and E = energy content of fuel, 0.0239 MMBtu/lb. The uncontrolled CO₂ emission factors are also applicable to natural gas prime movers controlled by combustion modifications, NSCR, and SCR.

Table 3.2-5 (Metric And English Units). EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS:
NSCR ON 4-CYCLE RICH BURN ENGINE^a
(SCC 2-02-002-53)

EMISSION FACTOR RATING: E

Pollutant	Inlet				Outlet			
	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu
NO _x	10	0.017	770	1.8	3.4	5.51 E-03	250	0.58
CO	16	0.026	1208	2.8	14	0.022	1000	2.4
TOC	0.44	7.28 E-04	33.97	0.079	0.27	4.41 E-04	20	0.047
NH ₃	0.07	1.10 E-04	5.16	0.012	1.10	1.81 E-03	82	0.19
C7 - C16	0.026	4.19 E-05	1.81	0.0042	0.0055	9.04 E-06	0.39	0.0009
C16+	0.029	3.75 E-05	1.72	0.004	0.0008	1.32 E-06	0.043	0.0001
PM solids (front half)	0.004	6.61 E-06	0.301	0.0007	0.004	6.61 E-06	0.30	0.0007
Benzene ^b	ND	ND	0.31	7.1 E-04	ND	ND	0.047	1.1 E-04
Toluene ^b	ND	ND	0.099	2.3 E-04	ND	ND	<0.0099	<2.3 E-05
Xylenes ^b	ND	ND	<0.025	<5.9 E-05	ND	ND	<0.017	<4.0 E-05
Propylene	ND	ND	<0.069	<1.6 E-04	ND	ND	<0.069	<1.6 E-04
Naphthalene ^b	ND	ND	<0.021	<4.9 E-05	ND	ND	<0.021	<4.9 E-05
Formaldehyde ^b	ND	ND	<0.69	<1.6 E-03	ND	ND	<0.003	<7.2 E-06
Acetaldehyde ^b	ND	ND	<0.026	<6.1 E-05	ND	ND	<0.0021	<4.8 E-06
Acrolein ^b	ND	ND	<0.016	<3.7 E-05	ND	ND	<0.0041	<9.6 E-06

^a References 4,7. Ratings reflect very limited data and may not apply to specific facilities. ND = no data.

^b Hazardous air pollutant listed in the *Clean Air Act*.

Table 3.2-6 (Metric And English Units). CONTROLLED EMISSION FACTORS FOR NATURAL GAS PRIME MOVERS:
SCR ON 4-CYCLE LEAN BURN ENGINE^a

EMISSION FACTOR RATING: E

Pollutant	Inlet				Outlet			
	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu
NO _x	26	0.042	2,800	6.4	4.8	7.94 E-03	510	1.2
CO	1.6	2.65 E-03	160	0.38	1.5	2.43 E-03	160	0.37
NH ₃	ND	ND	ND	ND	0.36	5.95 E-04	39	0.091
C7 - C16	0.009	1.54 E-05	0.99	0.0023	0.0042	6.83 E-06	0.56	0.0013
C16+	0.017	2.87 E-05	1.9	0.0044	0.0032	5.29 E-06	0.34	0.0008

^a Reference 8. Ratings reflect very limited data and may not apply to specific facilities. CO₂ emissions are not affected by control.
ND = no data.

Table 3.4-1 (Metric Units). GASEOUS EMISSION FACTORS FOR LARGE UNCONTROLLED STATIONARY DIESEL AND ALL STATIONARY DUAL-FUEL ENGINES^a

Pollutant	Diesel Fuel (SCC 2-02-004-01)			Dual Fuel ^b (SCC 2-02-004-02)		
	g/kW-hr (power output)	ng/J (fuel input)	EMISSION FACTOR RATING	g/kW-hr (power output)	ng/J (fuel input)	EMISSION FACTOR RATING
NO _x	14	1,322	C	12.3	1,331	D
CO	3.2	349	C	3.1	340	D
SO _x ^c	4.92S ₁	434S ₁	B	0.25S ₁ + 4.34S ₂	21.7S ₁ + 384S ₂	B
CO ₂ ^d	703	70,942	B	469	47,424	B
TOC (as CH ₄)	0.43	38	C	3.2	352	D
Methane	0.04	4	E ^e	2.4	240	E ^f
Nonmethane	0.44	45	E ^e	0.8	80	E ^f

^a Based on uncontrolled levels for each fuel, from References 4-6. When necessary, the average heating value of diesel was assumed to be 44,900 J/g with a density of 851 g/liter. The power output and fuel input values were averaged independently from each other, because of the use of actual brake-specific fuel consumption (BSFC) values for each data point and of the use of data possibly sufficient to calculate only 1 of the 2 emission factors (e. g., enough information to calculate ng/J, but not g/kW-hr). Factors are based on averages across all manufacturers and duty cycles. The actual emissions from a particular engine or manufacturer could vary considerably from these levels. SCC = Source Classification Code.

^b Dual fuel assumes 95% natural gas and 5% diesel fuel.

^c Assumes that all sulfur in the fuel is converted to SO₂. S₁ = % sulfur in fuel oil; S₂ = % sulfur in natural gas.

^d Assumes 100% conversion of carbon in fuel to CO₂ with 87 weight % carbon in diesel, 70 weight % carbon in natural gas, dual-fuel mixture of 5% diesel with 95% natural gas, average BSFC of 9,901,600 J/kW-hr, diesel heating value of 44,900 J/g, and natural gas heating value of 47,200 J/g.

^e Based on data from 1 engine.

^f Assumes that nonmethane organic compounds are 25% of TOC emissions from dual-fuel engines. Molecular weight of nonmethane gas stream is assumed to be that of methane.

Table 3.4-2 (English Units). GASEOUS EMISSION FACTORS FOR LARGE UNCONTROLLED STATIONARY DIESEL AND ALL STATIONARY DUAL-FUEL ENGINES^a

Pollutant	Diesel Fuel (SCC 2-02-004-01)			Dual Fuel ^b (SCC 2-02-004-02)		
	lb/hp-hr (power output)	lb/MMBtu (fuel input)	EMISSION FACTOR RATING	lb/hp-hr (power output)	lb/MMBtu (fuel input)	EMISSION FACTOR RATING
NO _x	0.024	3.1	C	0.020	3.1	D
CO	5.29 E-03	0.81	C	5.07 E-03	0.79	D
SO _x ^c	8.09 E-03S ₁	1.01S ₁	B	4.06 E-04S ₁ + 9.57 E-03S ₂	0.05S ₁ + 0.895S ₂	B
CO ₂ ^d	1.16	165	B	0.772	110	B
TOC (as CH ₄)	7.05 E-04	0.09	C	5.29 E-03	0.8	D
Methane	e	e	E ^e	3.97 E-03	0.6	E ^f
Nonmethane	e	e	E ^e	1.32 E-03	0.2	E ^f

^a Based on uncontrolled levels for each fuel, from References 4-6. When necessary, the average heating value of diesel was assumed to be 19,300 Btu/lb with a density of 7.1 lb/gallon. The power output and fuel input values were averaged independently from each other, because of the use of actual brake-specific fuel consumption (BSFC) values for each data point and of the use of data possibly sufficient to calculate only 1 of the 2 emission factors (e. g., enough information to calculate lb/MMBtu, but not lb/hp-hr). Factors are based on averages across all manufacturers and duty cycles. The actual emissions from a particular engine or manufacturer could vary considerably from these levels. SCC = Source Classification Code.

^b Dual fuel assumes 95% natural gas and 5% diesel fuel.

^c Assumes that all sulfur in the fuel is converted to SO₂. S₁ = % sulfur in fuel oil; S₂ = % sulfur in natural gas.

^d Assumes 100% conversion of carbon in fuel to CO₂ with 87 weight % carbon in diesel, 70 weight % carbon in natural gas, dual-fuel mixture of 5% diesel with 95% natural gas, average BSFC of 7,000 Btu/hp-hr, diesel heating value of 19,300 Btu/lb, and natural gas heating value of 1050 Btu/scf.

^e Based on data from 1 engine, TOC is by weight 9% methane and 91% nonmethane.

^f Assumes that nonmethane organic compounds are 25% of TOC emissions from dual-fuel engines. Molecular weight of nonmethane gas stream is assumed to be that of methane.

5.3 Natural Gas Processing

5.3.1 General¹

Natural gas from high-pressure wells is usually passed through field separators at the well to remove hydrocarbon condensate and water. Natural gasoline, butane, and propane are usually present in the gas, and gas processing plants are required for the recovery of these liquefiable constituents (see Figure 5.3-1). Natural gas is considered "sour" if hydrogen sulfide (H_2S) is present in amounts greater than 5.7 milligrams per normal cubic meters (mg/Nm^3) (0.25 grains per 100 standard cubic feet [$\text{gr}/100 \text{ scf}$]). The H_2S must be removed (called "sweetening" the gas) before the gas can be utilized. If H_2S is present, the gas is usually sweetened by absorption of the H_2S in an amine solution. Amine processes are used for over 95 percent of all gas sweetening in the United States. Other methods, such as carbonate processes, solid bed absorbents, and physical absorption, are employed in the other sweetening plants. Emission data for sweetening processes other than amine types are very meager, but a material balance on sulfur will give accurate estimates for sulfur dioxide (SO_2).

The major emission sources in the natural gas processing industry are compressor engines, acid gas wastes, fugitive emissions from leaking process equipment and if present, glycol dehydrator vent streams. Compressor engine emissions are discussed in Section 3.3.2. Fugitive leak emissions are detailed in *Protocol For Equipment Leak Emission Estimates*, EPA-453/R-95-017, November 1995. Regeneration of the glycol solutions used for dehydrating natural gas can release significant quantities of benzene, toluene, ethylbenzene, and xylene, as well as a wide range of less toxic organics. These emissions can be estimated by a thermodynamic software model (*GRI-GLYCalcTM*) available from the Gas Research Institute. Only the SO_2 emissions from gas sweetening operations are discussed here.

5.3.2 Process Description²⁻³

Many chemical processes are available for sweetening natural gas. At present, the amine process (also known as the Girdler process), is the most widely used method for H_2S removal. The process is summarized in reaction 1 and illustrated in Figure 5.3-2.



where:

R = mono, di, or tri-ethanol
N = nitrogen
H = hydrogen
S = sulfur

The recovered hydrogen sulfide gas stream may be: (1) vented, (2) flared in waste gas flares or modern smokeless flares, (3) incinerated, or (4) utilized for the production of elemental sulfur or sulfuric acid. If the recovered H_2S gas stream is not to be utilized as a feedstock for commercial applications, the gas is usually passed to a tail gas incinerator in which the H_2S is oxidized to SO_2 and is then passed to the atmosphere out a stack. For more details, the reader should consult Reference 8.

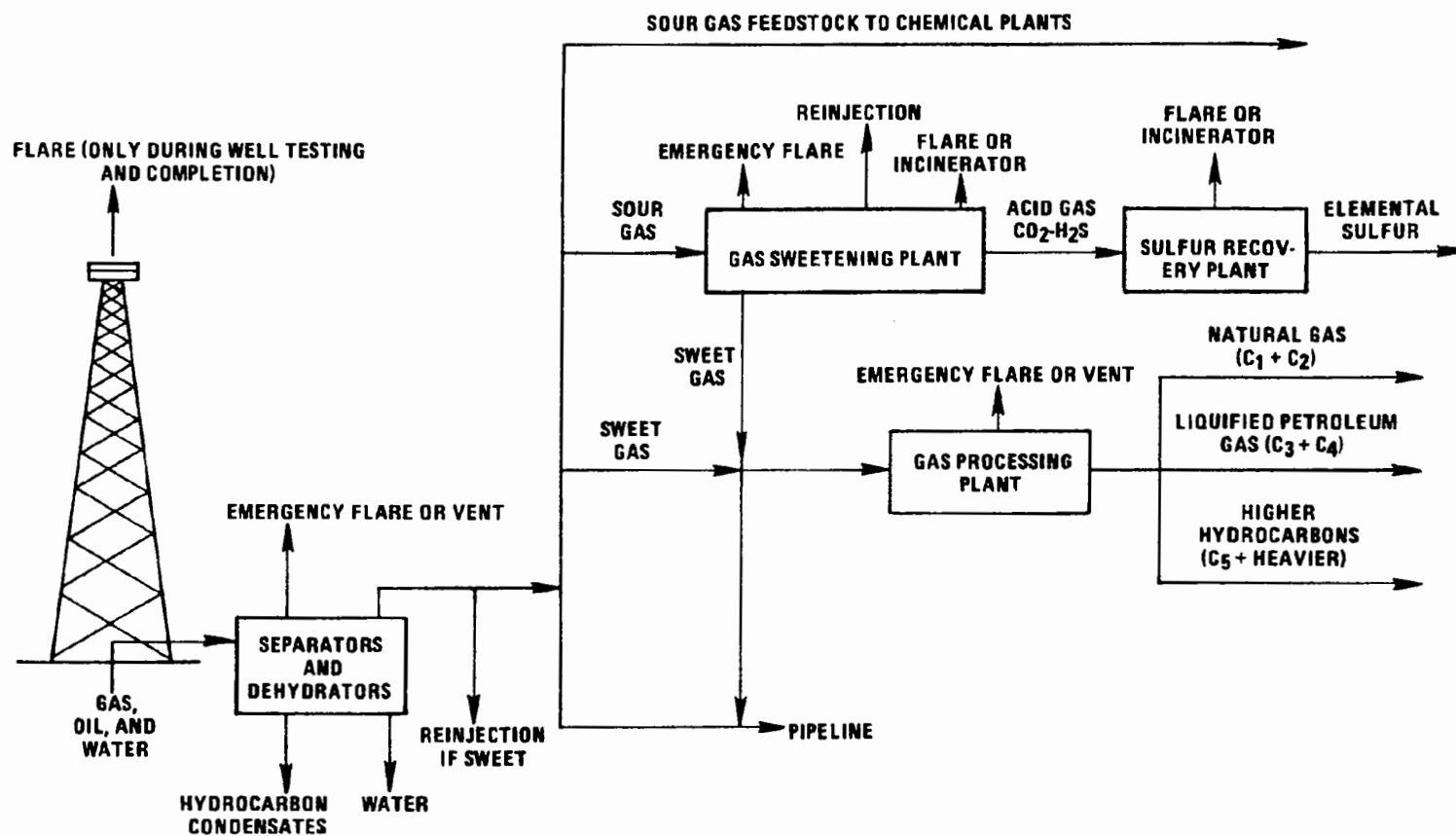


Figure 5.3-1. General flow diagram of the natural gas industry.

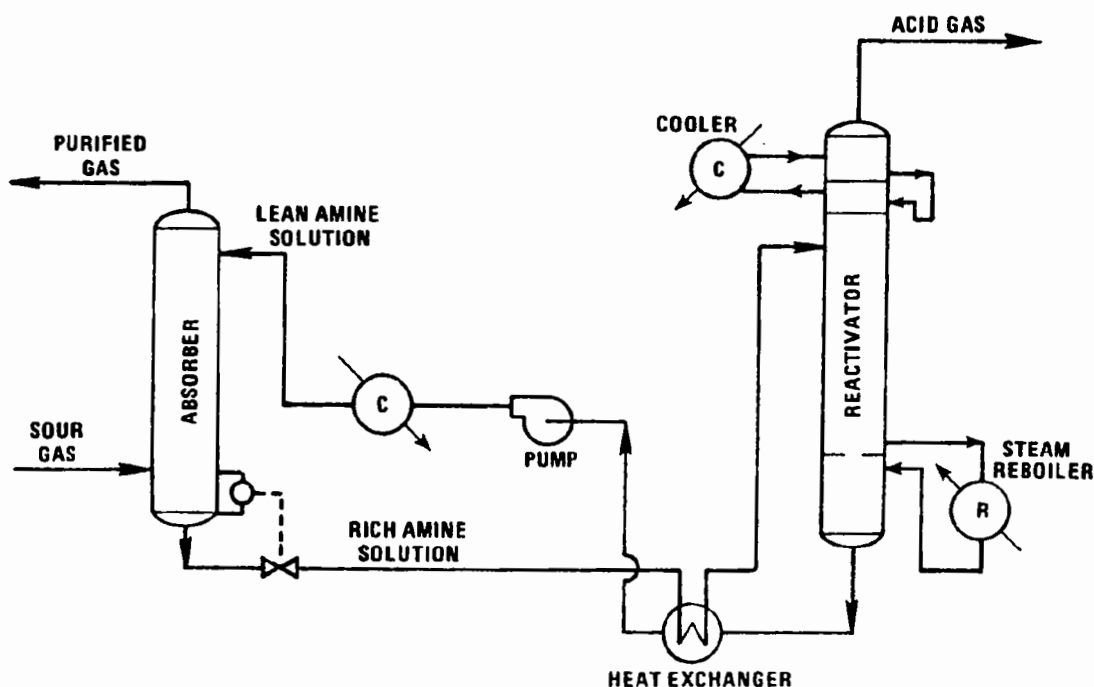


Figure 5.3-2. Flow diagram of the amine process for gas sweetening.

5.3.3 Emissions⁴⁻⁵

Emissions will result from gas sweetening plants only if the acid waste gas from the amine process is flared or incinerated. Most often, the acid waste gas is used as a feedstock in nearby sulfur recovery or sulfuric acid plants. See Sections 8.13 "Sulfur Recovery", or 8.10, "Sulfuric Acid", respectively, for these associated processes.

When flaring or incineration is practiced, the major pollutant of concern is SO_2 . Most plants employ elevated smokeless flares or tail gas incinerators for complete combustion of all waste gas constituents, including virtually 100 percent conversion of H_2S to SO_2 . Little particulate, smoke, or hydrocarbons result from these devices, and because gas temperatures do not usually exceed 650°C (1200°F), significant quantities of nitrogen oxides are not formed. Emission factors for gas sweetening plants with smokeless flares or incinerators are presented in Table 5.3-1. Factors are expressed in units of kilograms per 1000 cubic meters ($\text{kg}/10^3 \text{ m}^3$) and pounds per million standard cubic feet ($\text{lb}/10^6 \text{ scf}$).

Some plants still use older, less-efficient waste gas flares. Because these flares usually burn at temperatures lower than necessary for complete combustion, larger emissions of hydrocarbons and particulate, as well as H_2S , can occur. No data are available to estimate the magnitude of these emissions from waste gas flares.

Table 5.3.1 (Metric And English Units). EMISSION FACTORS FOR
GAS SWEETENING PLANTS^a

EMISSION FACTOR RATING: SULFUR OXIDES: A
ALL OTHERS: C

Process ^b	Particulate	Sulfur Oxides ^c (SO ₂)	Carbon Monoxide	Hydrocarbons	Nitrogen Oxides
Amine					
kg/10 ³ m ³ gas processed	Neg	26.98 S ^d	Neg	— ^e	Neg
lb/10 ⁶ scf gas processed	Neg	1685 S ^d	Neg	— ^e	Neg

^a Factors are presented only for smokeless flares and tail gas incinerators on the amine gas sweetening process with no sulfur recovery or sulfuric acid production present. Too little information exists to characterize emissions from older, less-efficient waste gas flares on the amine process or from other, less common gas sweetening processes. Factors for various internal combustion engines used in a gas processing plant are given in Section 3.3, "Gasoline and Diesel Industrial Engines". Factors for sulfuric acid plants and sulfur recovery plants are given in Section 8.10, "Sulfuric Acid", and Section 8.13, "Sulfur Recovery", respectively.

Neg = negligible.

^b References 2,4-7. Factors are for emissions after smokeless flares (with fuel gas and steam injection) or tail gas incinerators.

^c Assumes that 100% of the H₂S in the acid gas stream is converted to SO₂ during flaring or incineration and that the sweetening process removes 100% of the H₂S in the feedstock.

^d S is the H₂S content of the sour gas entering the gas sweetening plant, in mole or volume percent. For example, if the H₂S content is 2%, the emission factor would be 26.98 times 2, or 54.0 kg/1000 m³ (3370 lb/10⁶ scf) of sour gas processed. If the H₂S mole % is unknown, average values from Table 5.3-2 may be substituted. Note: If H₂S contents are reported in ppm or grains (gr) per 100 scf, use the following factors to convert to mole %:

10,000 ppm H₂S = 1 mole % H₂S

627 gr H₂S/100 scf = 1 mole % H₂S

The m³ or scf are to be measured at 60°F and 760 mm Hg for this application

(1 lb-mol = 379.5 scf).

^e Flare or incinerator stack gases are expected to have negligible hydrocarbon emissions. To estimate fugitive hydrocarbon emissions from leaking compressor seals, valves, and flanges, see "*Protocol For Equipment Leak Emission Estimates*", EPA-453/R-95-017, November 1995 (or updates).

**Table 5.3-2. AVERAGE HYDROGEN SULFIDE CONCENTRATIONS
IN NATURAL GAS BY AIR QUALITY CONTROL REGION^a**

State	AQCR Name	AQCR Number	Average H ₂ S, mole %
Alabama	Mobile-Pensacola-Panama City-Southern Mississippi (FL, MS)	5	3.30
Arizona	Four Corners (CO, NM, UT)	14	0.71
Arkansas	Monroe-El Dorado (LA)	19	0.15
	Shreveport-Texarkana-Tyler (LA, OK, TX)	22	0.55
California	Metropolitan Los Angeles	24	2.09
	San Joaquin Valley	31	0.89
	South Central Coast	32	3.66
	Southeast Desert	33	1.0
Colorado	Four Corners (AZ, NM, UT)	14	0.71
	Metropolitan Denver	36	0.1
	Pawnee	37	0.49
	San Isabel	38	0.3
	Yampa	40	0.31
Florida	Mobile-Pensacola-Panama City-Southern Mississippi (AL, MS)	5	3.30
Kansas	Northwest Kansas	97	0.005
	Southwest Kansas	100	0.02
Louisiana	Monroe-El Dorado (AR)	19	0.15
	Shreveport-Texarkana-Tyler (AR, OK, TX)	22	0.55
Michigan	Upper Michigan	126	0.5
Mississippi	Mississippi Delta	134	0.68
	Mobile-Pensacola-Panama City-Southern Mississippi (AL, FL)	5	3.30
Montana	Great Falls	141	3.93
	Miles City	143	0.4
New Mexico	Four Corners (AZ, CO, UT)	14	0.71
	Pecos-Permian Basin	155	0.83
North Dakota	North Dakota	172	1.74 ^b

Table 5.3-2 (cont.).

State	AQCR Name	AQCR Number	Average H ₂ S, mole %
Oklahoma	Northwestern Oklahoma	187	1.1
	Shreveport-Texarkana-Tyler (AR, LA, TX)	22	0.55
	Southeastern Oklahoma	188	0.3
Texas	Abilene-Wichita Falls	210	0.055
	Amarillo-Lubbock	211	0.26
	Austin-Waco	212	0.57
	Corpus Christi-Victoria	214	0.59
	Metropolitan Dallas-Fort Worth	215	2.54
	Metropolitan San Antonio	217	1.41
	Midland-Odessa-San Angelo	218	0.63
	Shreveport-Texarkana-Tyler (AR, LA, OK)	22	0.55
	Four Corners (AZ, CO, NM)	14	0.71
Utah			
Wyoming	Casper	241	1.262
	Wyoming (except Park, Bighorn, and Washakie Counties)	243	2.34 ^c

^a Reference 9. AQCR = Air Quality Control Region.

^b Sour gas only reported for Burke, Williams, and McKenzie Counties, ND.

^c Park, Bighorn, and Washakie Counties, WY, report gas with an average H₂S content of 23 mole %.

References For Section 5.3

1. D. K. Katz, *et al.*, *Handbook Of Natural Gas Engineering*, McGraw-Hill Book Company, New York, 1959.
2. R. R. Maddox, *Gas And Liquid Sweetening*, 2nd Ed. Campbell Petroleum Series, Norman, OK, 1974.
3. R. E. Kirk and D. F. Othmer (eds.), *Encyclopedia Of Chemical Technology*. Vol. 7, Interscience Encyclopedia, Inc., New York, NY, 1951.
4. *Sulfur Compound Emissions Of The Petroleum Production Industry*, EPA-650/2-75-030. U. S. Environmental Protection Agency, Cincinnati, OH, 1974.
5. Unpublished stack test data for gas sweetening plants, Ecology Audits, Inc., Dallas, TX, 1974.

6. *Control Techniques For Hydrocarbon And Organic Solvent Emissions From Stationary Sources*, AP-68, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1970.
7. *Control Techniques For Nitrogen Oxides From Stationary Sources*, AP-67, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1970.
8. B. J. Mullins, *et al.*, *Atmospheric Emissions Survey Of The Sour Gas Processing Industry*, EPA-450/3-75-076, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1975.
9. *Federal Air Quality Control Regions*, AP-102, U. S. Environmental Protection Agency, Research Triangle Park, NC, January 1972.

7. LIQUID STORAGE TANKS

This chapter presents models for estimating air emissions from organic liquid storage tanks. It also contains detailed descriptions of typical varieties of such tanks, including horizontal, vertical, and underground fixed roof tanks, and internal, external, and domed external floating roof tanks.

The emission estimation equations presented herein have been developed by the American Petroleum Institute (API), which retains the legal rights to these equations. API has granted EPA 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. Hence, the material presented is available for public use, but it cannot be sold without written permission from both the American Petroleum Institute and the U. S. Environmental Protection Agency.

The major pollutant of concern is volatile organic compounds. There also may be speciated organic compounds that may be toxic or hazardous.

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.

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.

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. 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

($^{\circ}\text{C} = [^{\circ}\text{R} - 492]/1.8$). 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, $^{\circ}\text{R}$

T_{AX} = daily maximum ambient temperature, $^{\circ}\text{R}$

T_{AN} = daily minimum ambient temperature, $^{\circ}\text{R}$

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, $^{\circ}\text{R}$

T_{AA} = daily average ambient temperature, $^{\circ}\text{R}$, 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, $^{\circ}\text{R}$; 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 7.1-14.

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

= 0.34 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 in an effort to reduce deck seam losses. However, emission factors are not currently available in AP-42 that represent the emission reduction 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, 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.

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

where:

Z_{V_i} = 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.

7.1.5 Sample Calculations¹⁹

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 :

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

$$R = \text{ideal gas constant} = 10.731 \frac{\text{psia}\cdot\text{ft}^3}{\text{lb-mole}\cdot^\circ\text{R}}$$

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 product, 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

$$= \sum_{i=1}^{n_f} (N_{F_i} K_{F_i}) = [(N_{F_1} K_{F_1}) + (N_{F_2} K_{F_2}) + \dots + N_{F_{n_f}} K_{F_{n_f}}]$$

where:

N_{F_i} = number of fittings of a particular type, dimensionless. N_{F_i} is determined for the specific tank or estimated from Tables 7.1-12, 7.1-13, or 7.1-14

K_{F_i} = deck fitting loss factor for a particular type of fitting, lb-mole/yr. K_{F_i} 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 bbl/1,000 ft² 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 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_{F_i} and N_{F_i} 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,

$$K_{F_{\text{access hatch}}} = K_{Fa} + K_{Fb}(K_v v)^m$$

$$= 36 + 5.9 [(0.7)(10.2)]^{1.2}$$

$$K_{F_{\text{access hatch}}} = 98.4 \text{ lb-mole/yr}$$

$$N_{F_{\text{access hatch}}} = 1$$

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,

$$K_{F_{\text{vacuum breaker}}} = K_{Fa} + K_{Fb} (K_v v)^m$$

$$K_{F_{\text{vacuum breaker}}} = 7.8 + 0.01 [(0.7)(10.2)]^4$$

$$K_{F_{\text{vacuum breaker}}} = 33.8 \text{ lb-mole/yr}$$

$$N_{F_{\text{vacuum breaker}}} = 1$$

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:

$$F_F = \sum_{i=1}^3 (K_{Fi})(N_{Fi})$$

$$= (98.4)(1) + (33.8)(1) + (2.3)(1)$$

$$= 134.5 \text{ lb-mole/yr}$$

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;

$$T_{AA} = (522.2 + 505.6)/2 = 513.9^\circ\text{R}$$

$$T_B = 513.9^\circ\text{R} + 6(0.17) - 1 = 513.92^\circ\text{R}$$

$$\begin{aligned} T_{LA} &= 0.44(513.9) + 0.56(513.92) + 0.0079(0.17)(1,165) \\ &= 515.5^\circ\text{R} = 55.8^\circ\text{F} = 56^\circ\text{F} \end{aligned}$$

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_{benzene} = 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:

$$Q = 100,000 \text{ gal} \times 10 \text{ turnovers/yr (given)}$$

$$= 1,000,000 \text{ gal} \times 2.381 \text{ bbl/100 gal} = 23,810 \text{ bbl/yr}$$

$$C = 0.0015 \text{ bbl}/10^3 \text{ ft}^2 \text{ (from Table 7.1-10)}$$

$$W_L = 1/[\sum (\text{wt fraction in liquid})/(\text{liquid component density from Table 7.1-3})]$$

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)

$$W_L = 1/[(0.75/7.4) + (0.15/7.3) + (0.10/6.5)]$$

$$= 1/(0.101 + 0.0205 + 0.0154)$$

$$= 1/0.1369$$

$$= 7.3 \text{ lb/gal}$$

$$D = 20 \text{ ft (given)}$$

$$L_{WD} = 0.943 \text{ QCW}_L/D$$

$$= [0.943(23,810)(0.0015)(7.3)/20]$$

$$= 12 \text{ lb of VOC/yr from withdrawal losses}$$

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.

$$L_T = L_{WD} + L_R + L_F + L_D \quad (3-1)$$

$$L_{WD} = \frac{(0.943) QCW_L}{D} \left[1 + \left(\frac{N_C F_C}{D} \right) \right] \quad (3-4)$$

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

$$L_F = F_F P^* M_V K_C \quad (3-5)$$

$$L_D = K_D S_D D^2 P^* M_V K_C \quad (3-6)$$

where:

$$L_T = \text{total loss, lb/yr}$$

$$L_{WD} = \text{withdrawal loss, lb/yr}$$

$$L_R = \text{rim seal loss, lb/yr}$$

$$L_F = \text{deck fitting loss, lb/yr}$$

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

= 0.34 for nonwelded decks

= 0 for welded decks

$$S_D = \text{deck seam length factor, ft/ft}^2$$

$$= L_{\text{seam}}/A_{\text{deck}}$$

and:

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

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

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:

$$K_C = 1.0 \text{ for volatile organic liquids}$$

$$N_C = 1 \text{ (from Table 7.1-11)}$$

$$F_C = 1.0 \text{ (assumed)}$$

$$K_{Ra} = 0.3 \text{ (from Table 7.1-8)}$$

$$K_{Rb} = 0.6 \text{ (from Table 7.1-8)}$$

$$v = 0 \text{ for internal floating roof tanks}$$

$$M_V = 62 \text{ lb/lb-mole (from Table 7.1-2)}$$

$$W_L = 4.9 \text{ lb/gal (from Table 7.1-2)}$$

$$C = 0.0015 \text{ bbl/1,000 ft}^2 \text{ (from Table 7.1-10)}$$

$$K_D = 0 \text{ for welded decks so } S_D \text{ is not needed}$$

$$F_F = \sum (K_{Fi} N_{Fi})$$

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,

$$T_{AA} = (530.97 + 508.87)/2 = 519.92^\circ\text{R}$$

$$T_B = 519.92 + 6(0.17) - 1 = 519.94^\circ\text{R}$$

$$T_{LA} = 0.44 (519.92) + 0.56 (519.94) + 0.0079(0.17)(1,373)$$

$$T_{LA} = 228.76 + 291.17 + 1.84$$

$$T_{LA} = 521.77^\circ\text{R or } 62^\circ\text{F}$$

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:

$$Q = (1,000,000 \text{ gal})(50 \text{ turnovers/yr})$$

$$= (50,000,000 \text{ gal})(2.381 \text{ bbl/100 gal}) = 1,190,500 \text{ bbl/yr}$$

$$C = 0.0015 \text{ bbl/1,000 ft}^2$$

$$W_L = 4.9 \text{ lb/gal}$$

$$D = 70 \text{ ft}$$

$$N_C = 1$$

$$F_C = 1$$

$$L_{WD} = [(0.943)(1,190,500)(0.0015)(4.9)]/70[1 + (1)(1)/70] = 120 \text{ lb/yr VOC for withdrawal losses}$$

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:

$$K_{Ra} = 0.3 \text{ lb-mole/ft}^2\text{-yr}$$

$$D = 70 \text{ ft}$$

$$P^* = 0.166$$

$$M_V = 62 \text{ lb/lb-mole}$$

$$K_C = 1.0$$

$$L_R = (0.3)(0.166)(70)(62)(1.0) = 216 \text{ lb/yr VOC from rim seals}$$

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 leg, 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:

$$\begin{aligned} L_T &= L_{WD} + L_R + L_F + L_D \\ &= 120 + 216 + 3,715 + 0 = 4,051 \text{ lb/yr of VOC emitted from the tank} \end{aligned}$$

12. Calculate amount of each component emitted from the tank. The individual component losses are equal to:

$$L_{T_i} = (Z_{V_i})(L_R + L_F + L_D) + (Z_{V_i})(L_{WD})$$

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 x 4,051 lb/yr	= Emissions, lb/yr
Air toxics		
Benzene	0.77	31.2
Toluene	0.66	26.7
Ethylbenzene	0.04	1.62
O-xylene	0.05	2.03
Nontoxics		
Isomers of pentane	26.78	1,085
N-butane	22.95	930
Iso-butane	9.83	398
N-pentane	8.56	347
Isomers of hexane	4.78	194
3-methyl pentane	2.34	94.8
Hexane	1.84	74.5
Others	21.40	867
Total	100	4,051

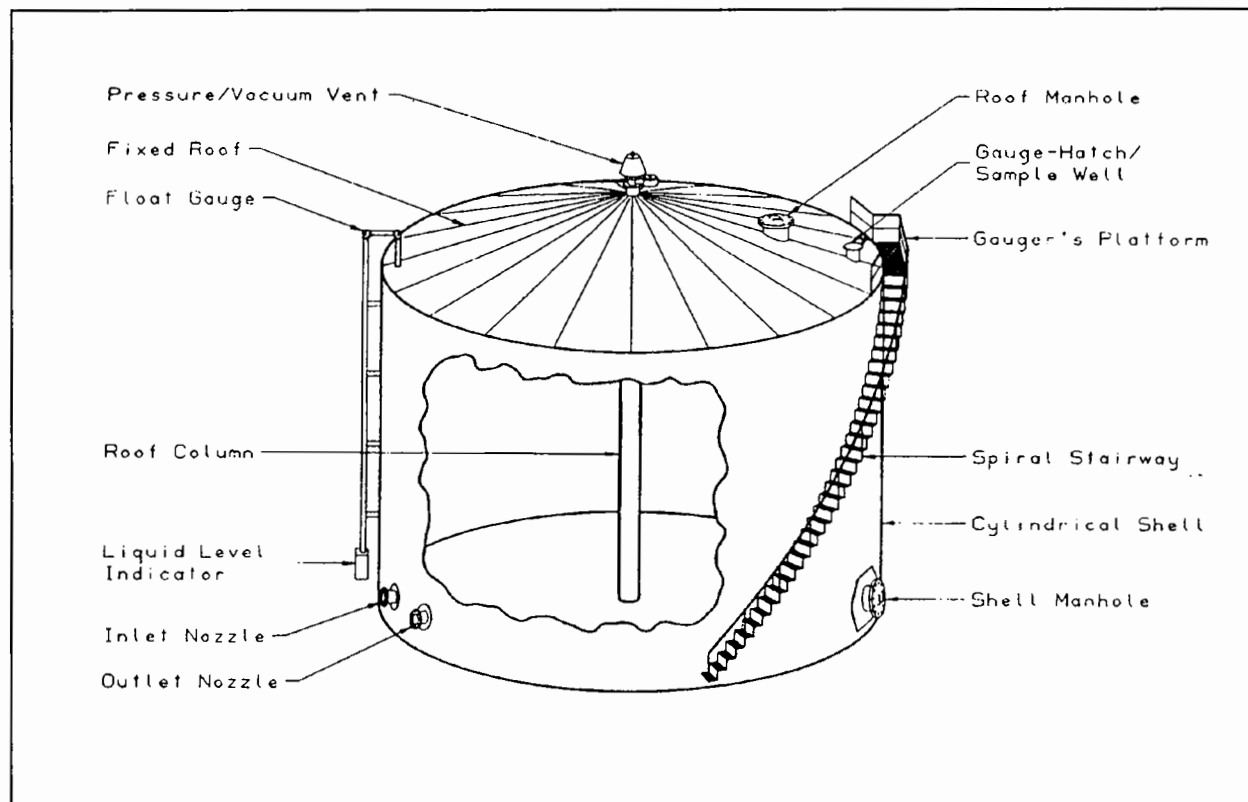


Figure 7.1-1. Typical fixed-roof tank.¹

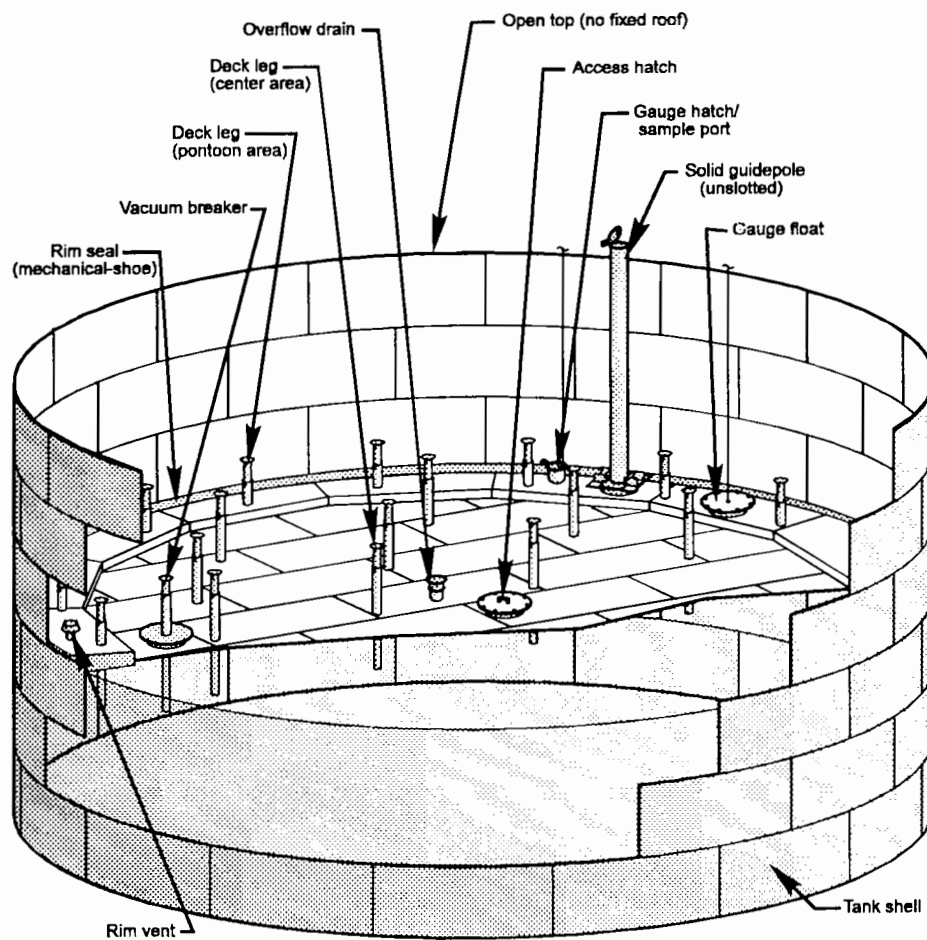


Figure 7.1-2. External floating roof tank (pontoon type).²¹

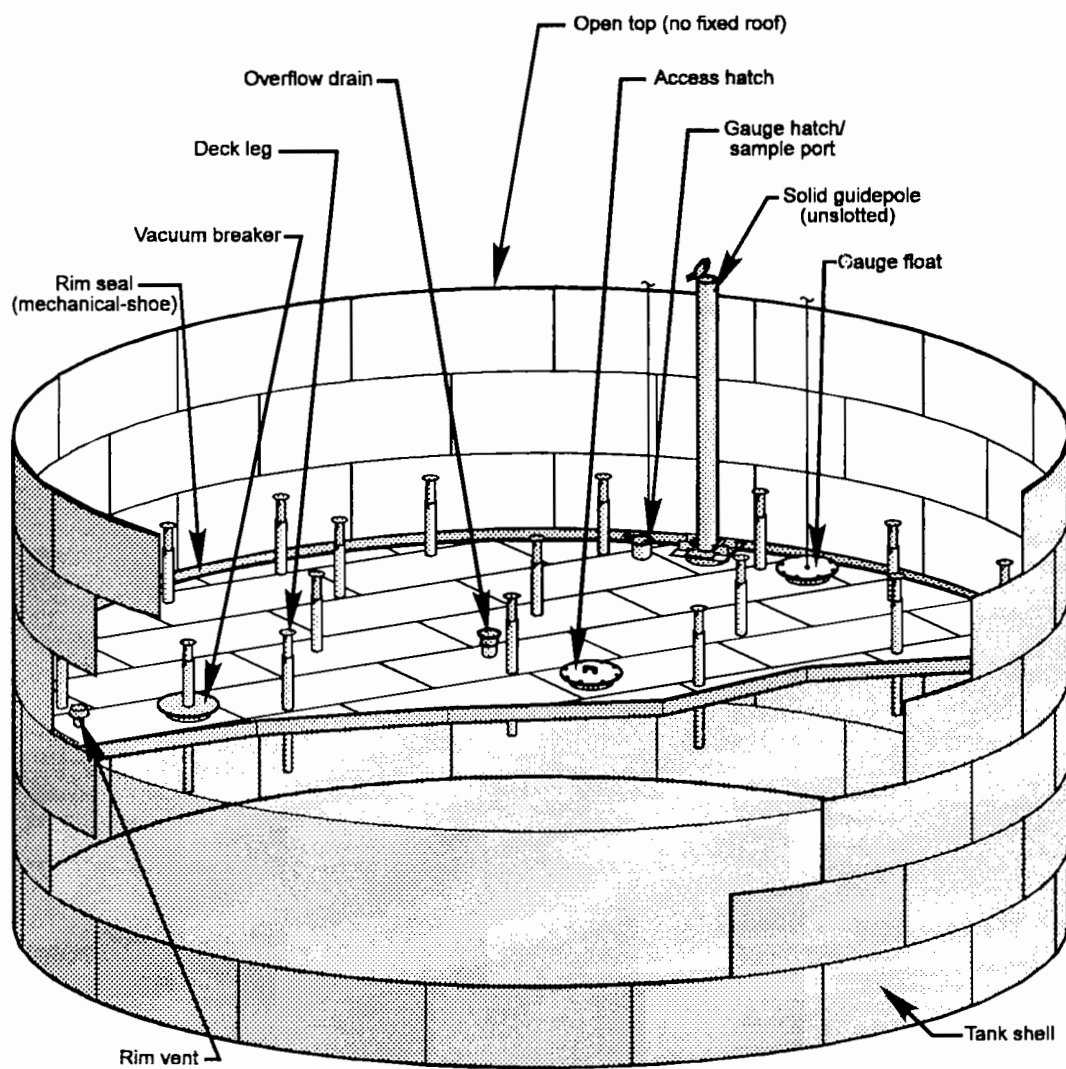


Figure 7.1-3. External floating roof tank (double-deck type).²¹

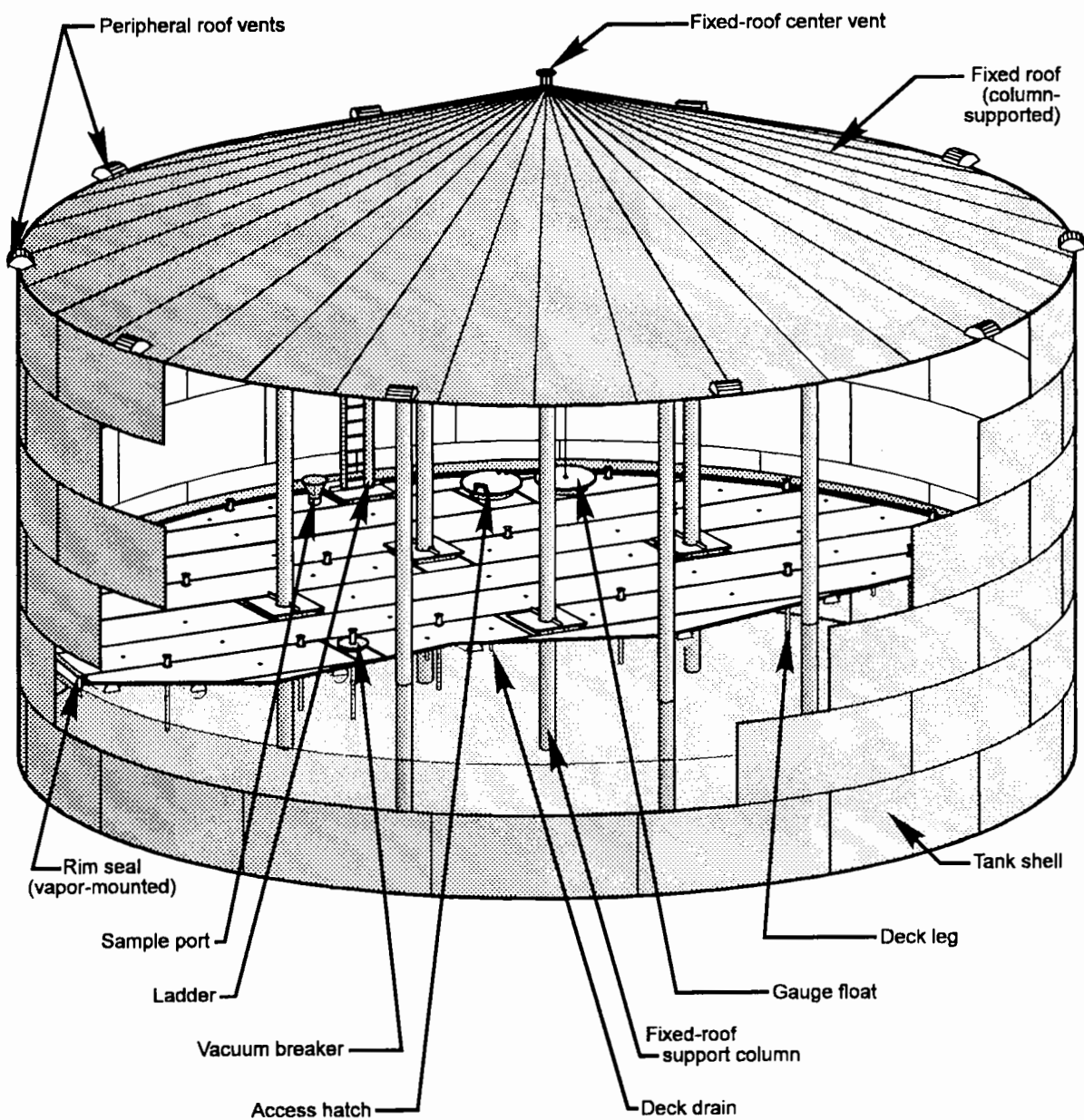


Figure 7.1-4. Internal floating roof tank.²¹

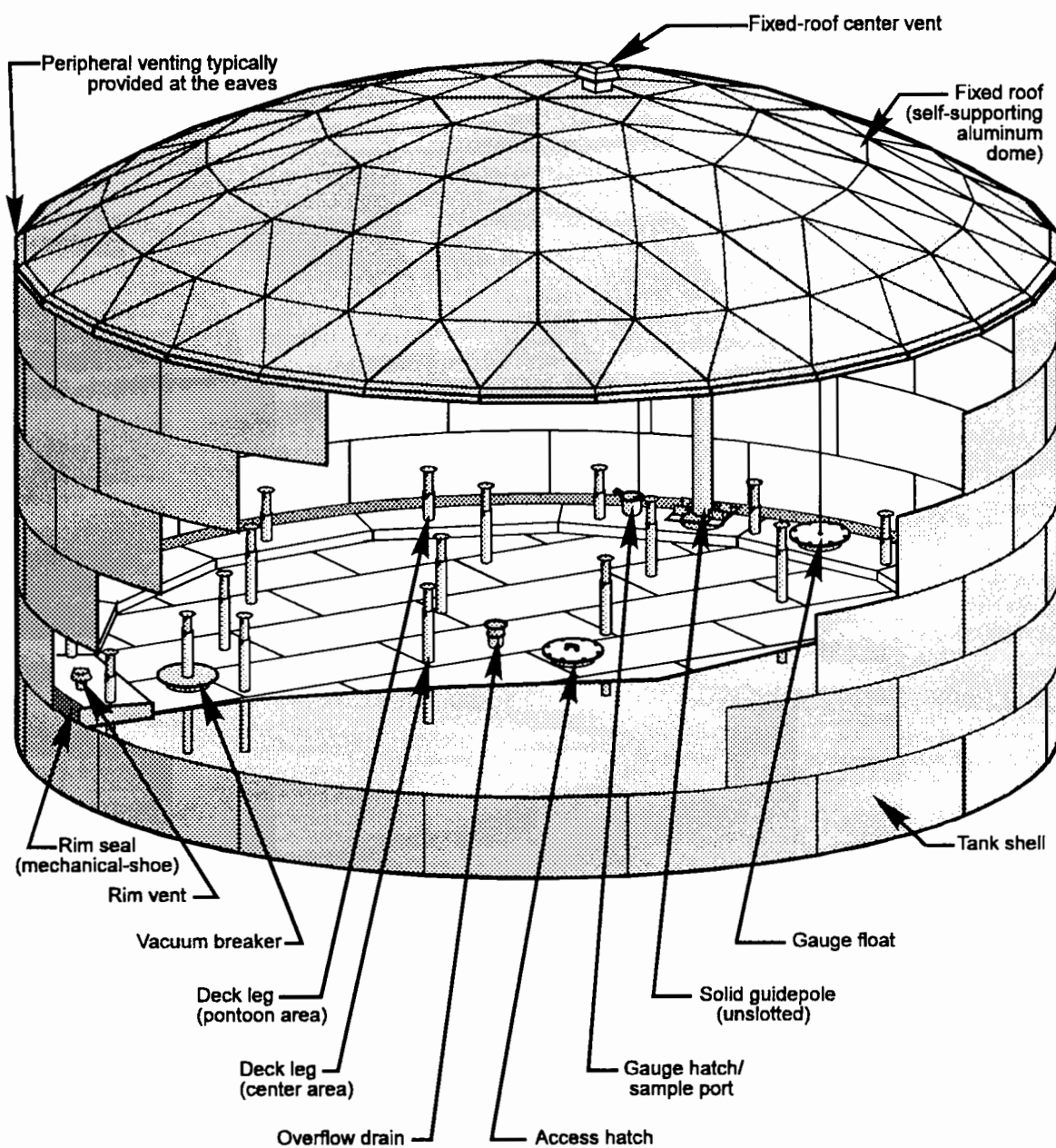


Figure 7.1-5. Domed external floating roof tank.²¹

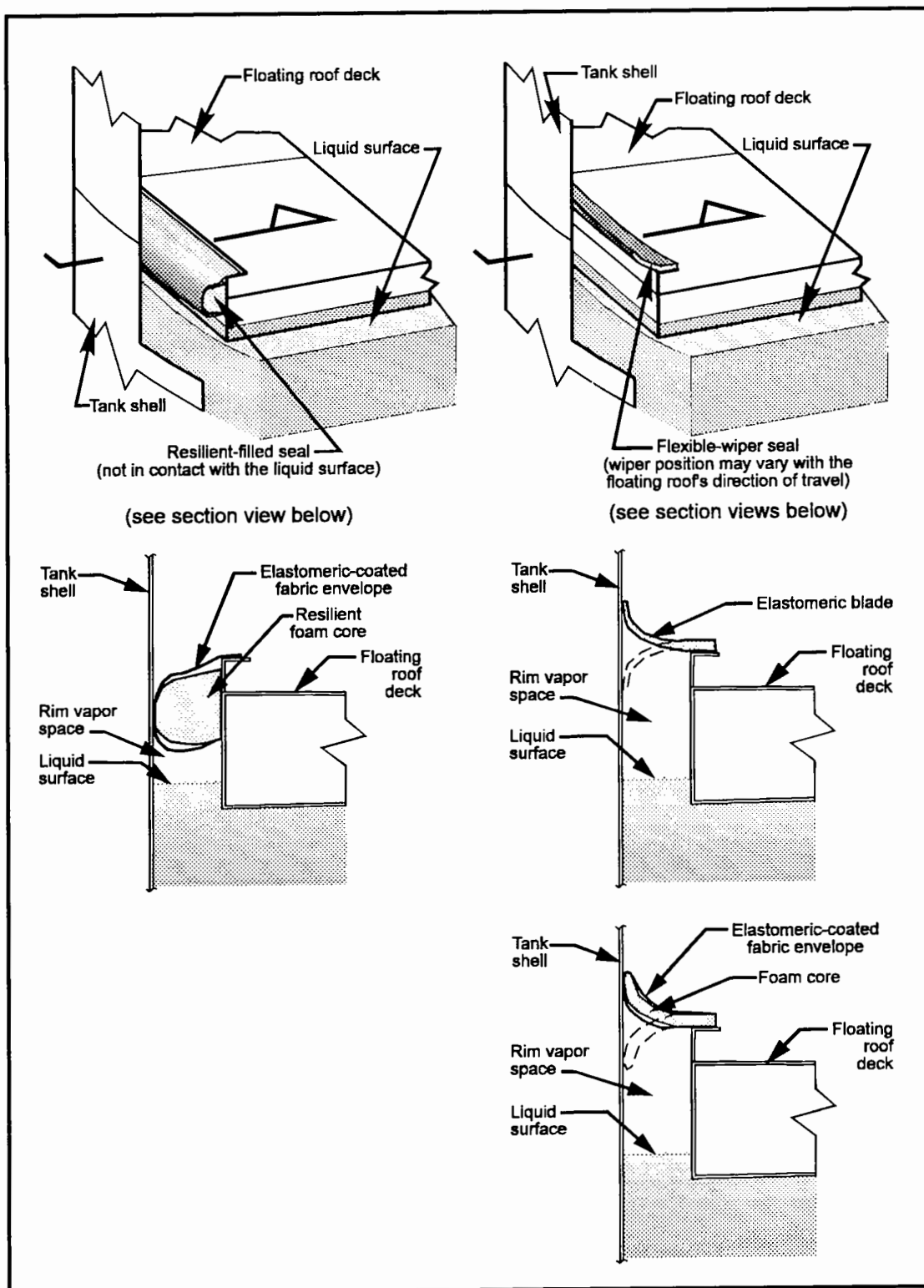


Figure 7.1-6. Vapor-mounted primary seals.²¹

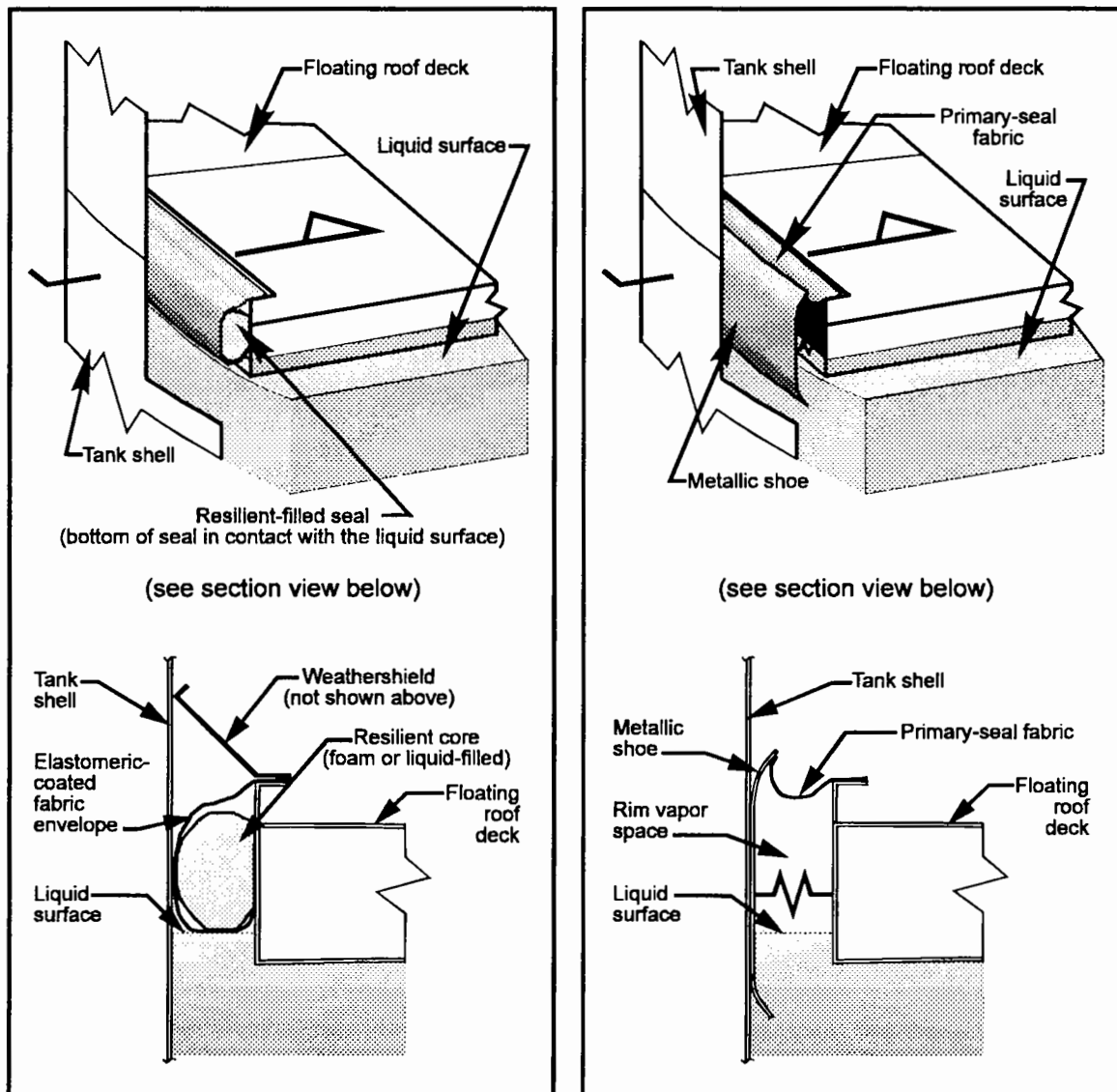


Figure 7.1-7. Liquid-mounted and mechanical shoe primary seals.²¹

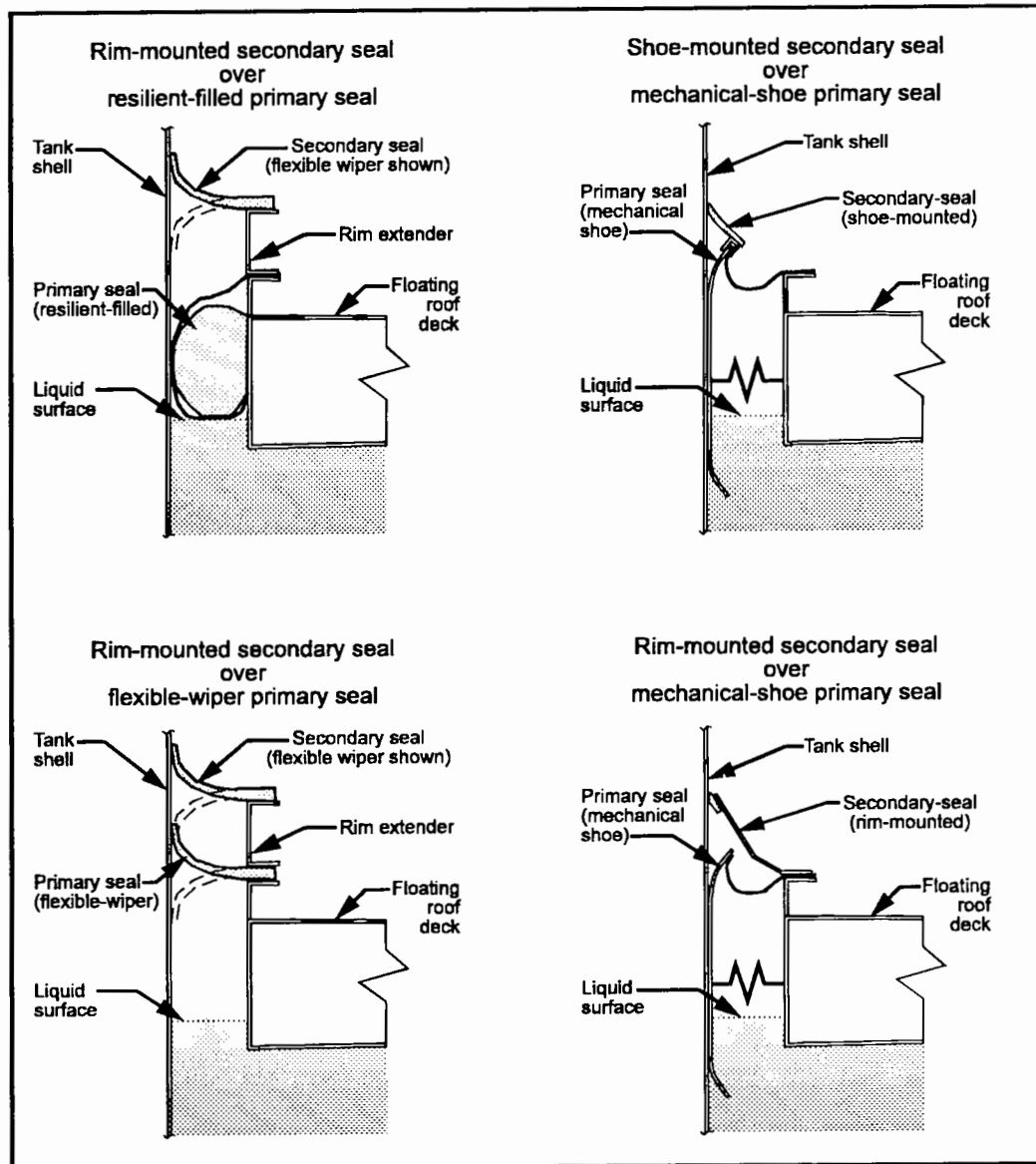


Figure 7.1-8. Secondary rim seals.²¹

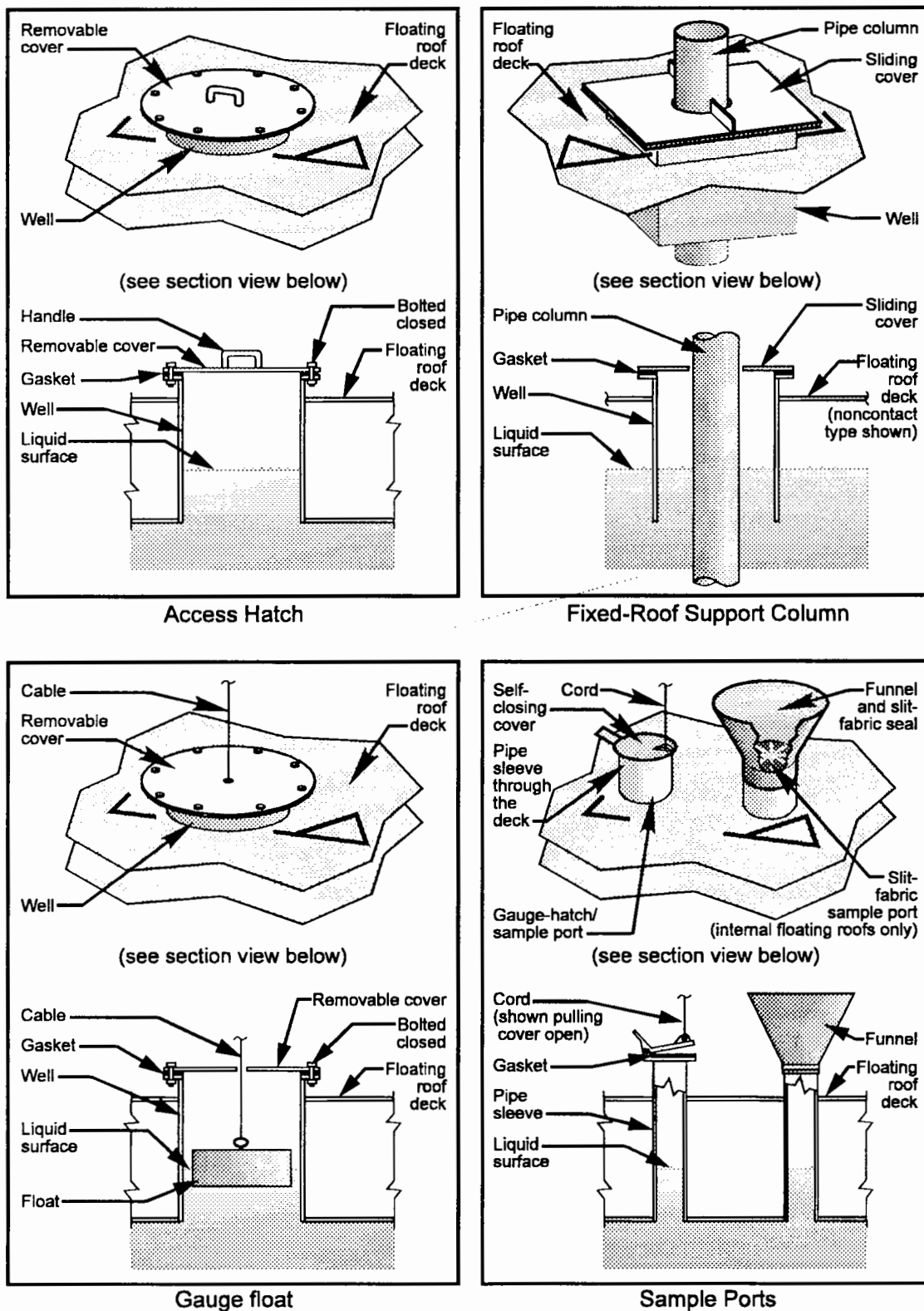


Figure 7.1-9. Deck fittings for floating roof tanks.²¹

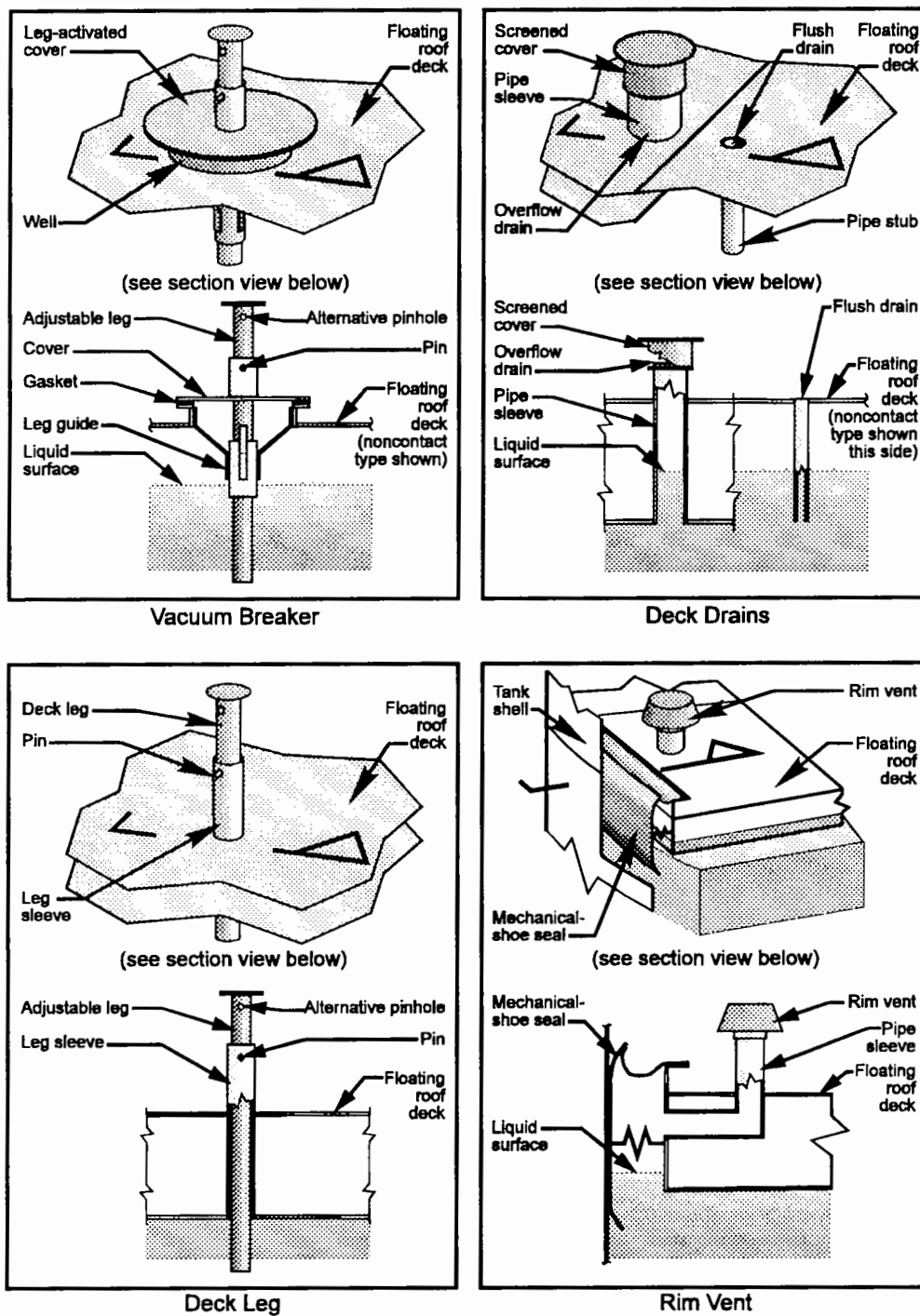
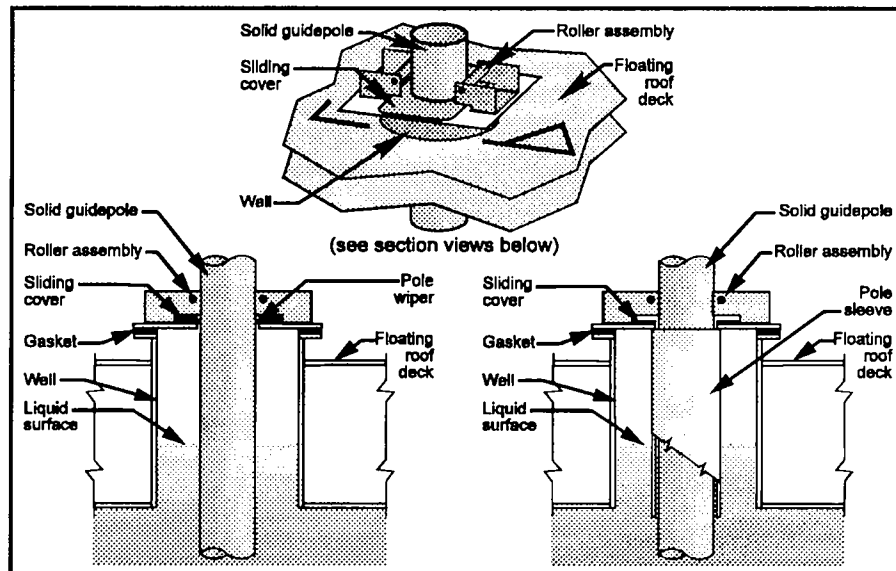
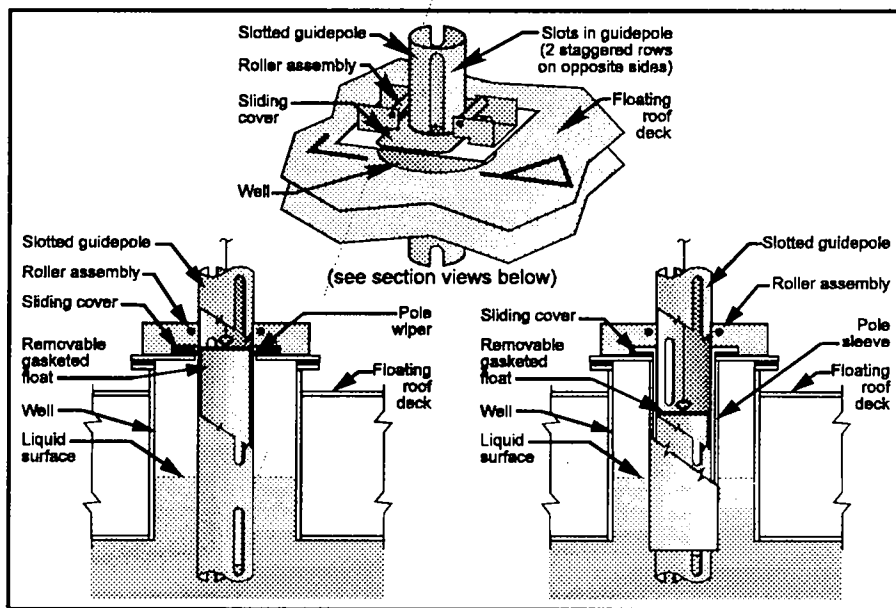


Figure 7.1-10. Deck fittings for floating roof tanks.²¹



Unslotted (solid) Guidepole



Slotted (perforated) Guidepole

Figure 7.1-11. Slotted and unslotted guidepoles.²¹

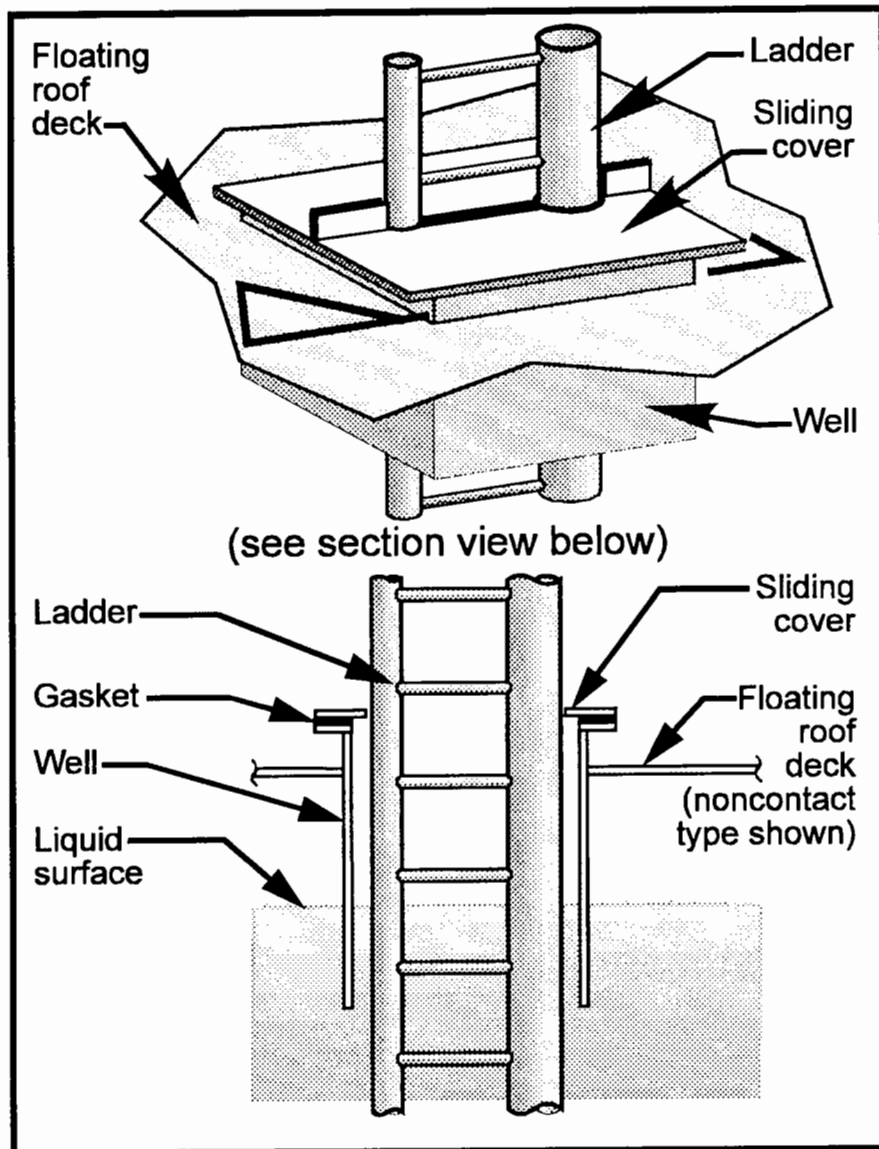


Figure 7.1-12. Ladder well.²¹

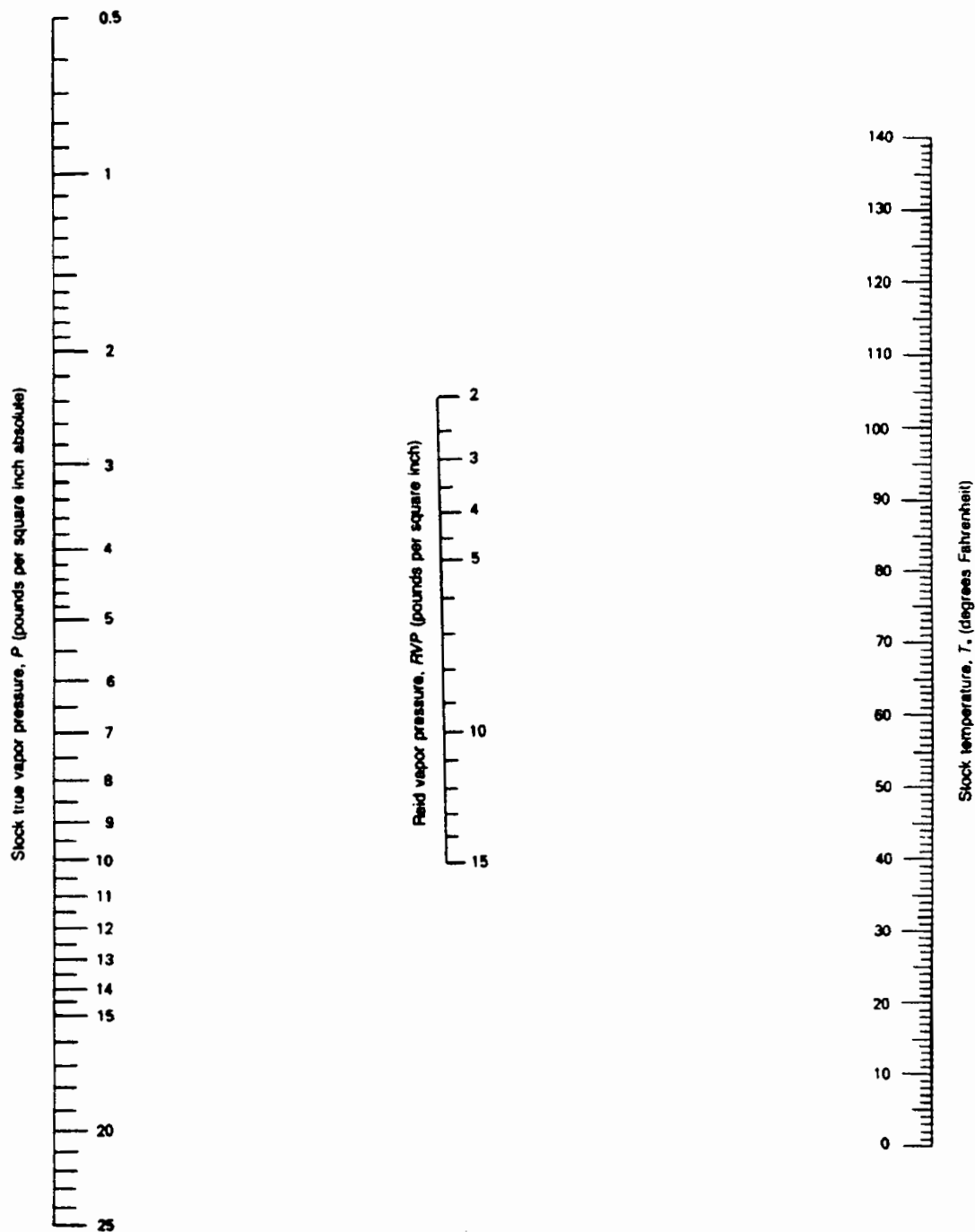


Figure 7.1-13a. True vapor pressure of crude oils with a Reid vapor pressure of 2 to 15 pounds per square inch.⁴

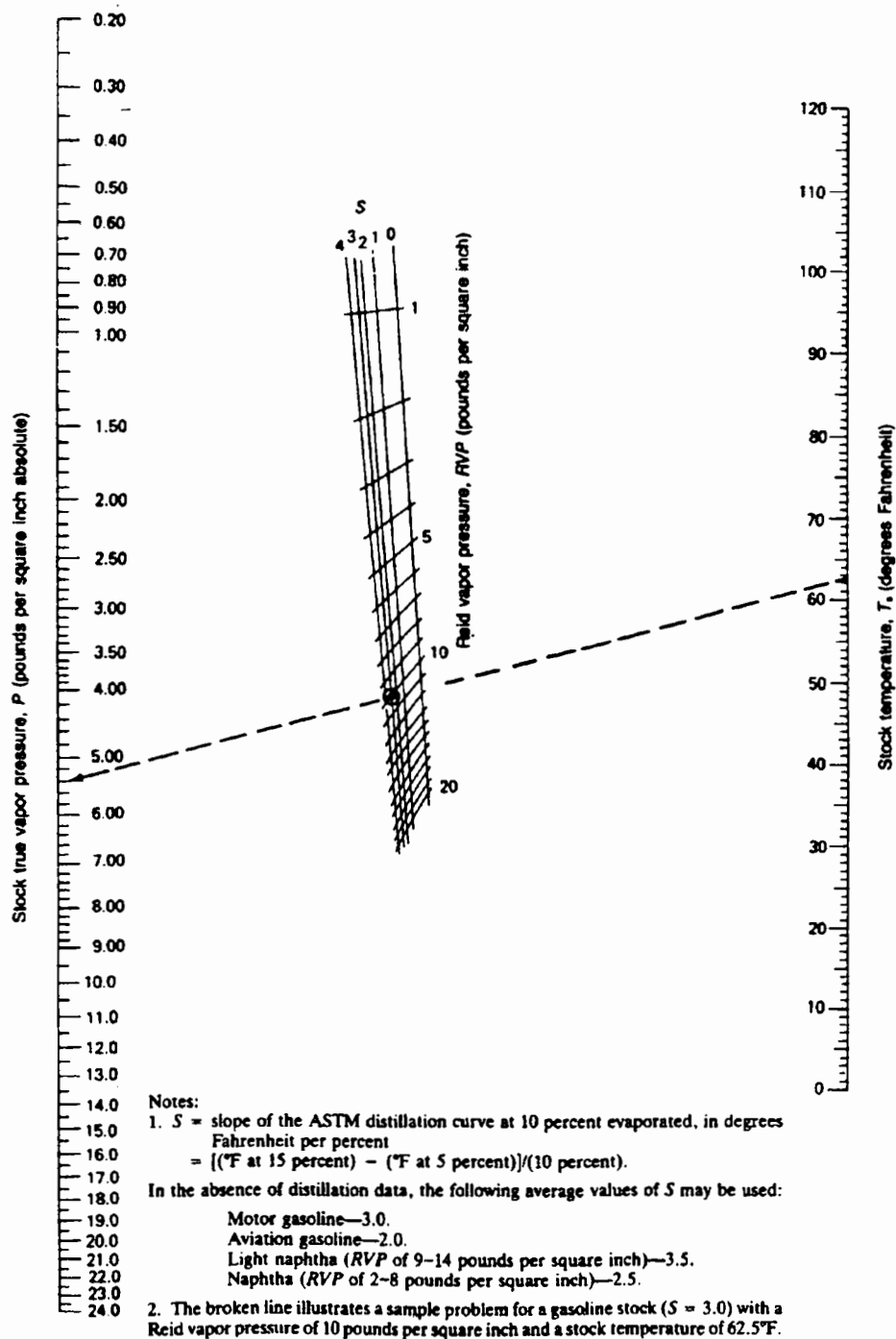


Figure 7.1-14a. True vapor pressure of refined petroleum stocks with a Reid vapor pressure of 1 to 20 pounds per square inch.⁴

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

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 7.1-14a 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 7.1-13b. Equation for true vapor pressure of crude oils with a Reid vapor pressure of 2 to 15 pounds per square inch.⁴

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

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 7.1-13a 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 7.1-14b. Equation for true vapor pressure of refined petroleum stocks with a Reid vapor pressure of 1 to 20 pounds per square inch.⁴

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

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

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 (°F/vol %)

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

$$A = 12.82 - 0.9672 \ln (RVP)$$

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

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

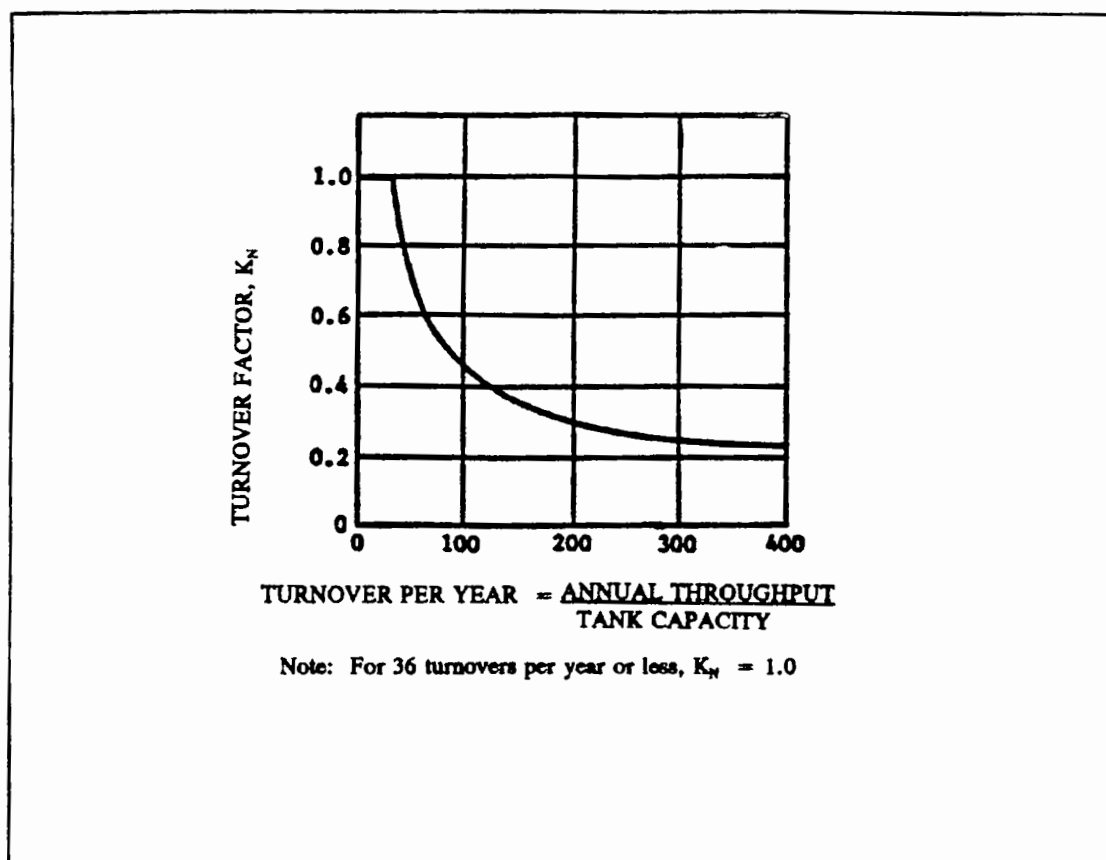
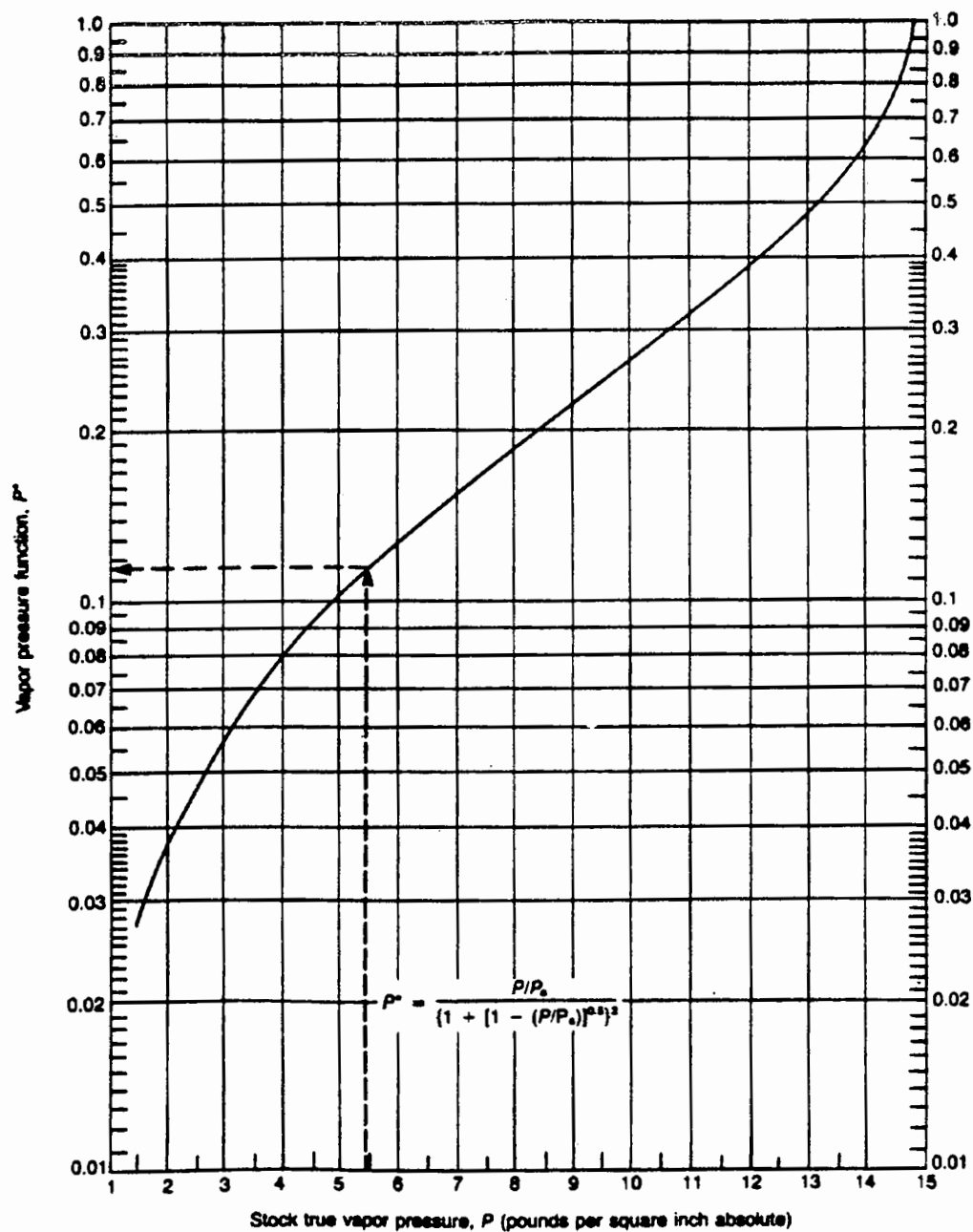


Figure 7.1-18. Turnover factor (K_N) for fixed roof tanks.⁸



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

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_D	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_{scam}	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	90°F	100°F
Gasoline RVP 13	62	4.9	5.6	4.7	5.7	6.9	8.3	9.9	11.7	13.8
Gasoline RVP 10	66	5.1	5.6	3.4	4.2	5.2	6.2	7.4	8.8	10.5
Gasoline RVP 7	68	5.2	5.6	2.3	2.9	3.5	4.3	5.2	6.2	7.4
Crude oil RVP 5	50	4.5	7.1	1.8	2.3	2.8	3.4	4.0	4.8	5.7
Jet naphtha (JP-4)	80	5.4	6.4	0.8	1.0	1.3	1.6	1.9	2.4	2.7
Jet kerosene	130	6.1	7.0	0.0041	0.0060	0.0085	0.011	0.015	0.021	0.029
Distillate fuel oil No. 2	130	6.1	7.1	0.0031	0.0045	0.0074	0.0090	0.012	0.016	0.022
Residual oil No. 6	190	6.4	7.9	0.00002	0.00003	0.00004	0.00006	0.00009	0.00013	0.00019

^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
<i>iso</i> -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
<i>tert</i> -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
<i>n</i> -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
<i>cis</i> -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
<i>trans</i> -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- <i>iso</i> -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_3F	137.38	75.4	12.480	7.032	8.804	10.900	13.40	16.31	19.69	23.60
<i>n</i> -Heptane	$\text{CH}_3(\text{CH}_2)_5\text{CH}_3$	100.20	209.2	5.727	0.290	0.406	0.541	0.735	0.967	1.238	1.586
<i>n</i> -Hexane	$\text{CH}_3(\text{CH}_2)_4\text{CH}_3$	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	$(\text{CH}_3)_3\text{CCH}_2\text{CH}(\text{CH}_3)_2$	114.22	210.6	5.794	0.213	0.387	0.580	0.812	1.093	1.392	1.740
Isopentane	$(\text{CH}_3)_2\text{CHCH}_2\text{CH}_3$	72.15	82.1	5.199	5.878	7.889	10.005	12.530	15.334	18.370	21.657
Isoprene	$(\text{CH}_2):\text{C}(\text{CH}_3)\text{CH}:\text{CH}_2$	68.11	93.5	5.707	4.757	6.130	7.677	9.668	11.699	14.503	17.113
Isopropyl alcohol	$(\text{CH}_3)_2\text{CHOH}$	60.09	180.1	6.573	0.213	0.329	0.483	0.677	0.928	1.296	1.779
Methacrylonitrile	$\text{CH}_2:\text{CH}(\text{CH}_3)\text{CN}$	67.09	194.5	6.738	0.483	0.657	0.870	1.160	1.470	1.934	2.456
Methyl acetate	$\text{CH}_3\text{OOCCH}_3$	74.08	134.8	7.831	1.489	2.011	2.746	3.693	4.699	5.762	6.961
Methyl acrylate	$\text{CH}_3\text{OOCCH}:\text{CH}_2$	86.09	176.9	7.996	0.599	0.773	1.025	1.354	1.798	2.398	3.055
Methyl alcohol	CH_3OH	32.04	148.4	6.630	0.735	1.006	1.412	1.953	2.610	3.461	4.525
Methylcyclohexane	$\text{CH}_3\text{-C}_6\text{H}_{11}$	98.18	213.7	6.441	0.309	0.425	0.541	0.735	0.986	1.315	1.721
Methylcyclopentane	$\text{CH}_3\text{C}_5\text{H}_9$	84.16	161.3	6.274	0.909	1.160	1.644	2.224	2.862	3.616	4.544
Methylene chloride	CH_2Cl_2	84.94	104.2	11.122	3.094	4.254	5.434	6.787	8.702	10.329	13.342
Methyl ethyl ketone	$\text{CH}_3\text{COC}_2\text{H}_5$	72.10	175.3	6.747	0.715	0.928	1.199	1.489	2.069	2.668	3.345
Methyl methacrylate	$\text{CH}_3\text{OOC}(\text{CH}_3):\text{CH}_2$	100.11	212.0	7.909	0.116	0.213	0.348	0.541	0.773	1.064	1.373
Methyl propyl ether	$\text{CH}_3\text{OC}_3\text{H}_7$	74.12	102.1	6.166	3.674	4.738	6.091	7.058	9.417	11.602	13.729
Nitromethane	CH_3NO_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	$\text{CH}_3(\text{CH}_2)_3\text{CH}_3$	72.15	96.9	5.253	4.293	5.454	6.828	8.433	10.445	12.959	15.474
<i>n</i> -Propylamine	$\text{C}_3\text{H}_7\text{NH}_2$	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_3CCl_3	133.42	165.2	11.216	0.909	1.218	1.586	2.030	2.610	3.307	4.199
Trichloroethylene	$\text{CHCl}:\text{CCl}_2$	131.40	188.6	12.272	0.503	0.677	0.889	1.180	1.508	2.030	2.610
Toluene	$\text{CH}_3\text{-C}_6\text{H}_5$	92.13	231.1	7.261	0.174	0.213	0.309	0.425	0.580	0.773	1.006
Vinyl acetate	$\text{CH}_2:\text{CHOOCCH}_3$	86.09	162.5	7.817	0.735	0.986	1.296	1.721	2.262	3.113	4.022
Vinylidene chloride	$\text{CH}_2:\text{CCl}_2$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	57.0	60.9	68.1	77.0	83.6	89.8	91.5	91.2	86.9	77.5	67.0	59.8	75.9
	T_{AN}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	$^{\circ}\text{F}$	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}	°F	34.1	36.8	47.6	60.7	70.8	79.1	82.7	81.1	74.8	62.9	49.8	38.4	59.9
	T _{AN}	°F	19.2	20.7	29.4	39.4	48.5	57.1	61.3	60.1	53.3	42.1	33.3	24.3	40.7
	I	Btu/ft ² -d	424	625	943	1317	1602	1762	1689	1510	1209	895	505	347	1069
Providence, RI	T _{AX}	°F	36.4	37.7	45.5	57.5	67.6	76.6	81.7	80.3	73.1	63.2	51.9	40.5	59.3
	T _{AN}	°F	20.0	20.9	29.2	38.3	47.6	57.0	63.3	61.9	53.8	43.1	34.8	24.1	41.2
	I	Btu/ft ² -d	506	739	1032	1374	1655	1776	1695	1499	1209	907	538	419	1112
Columbia, SC	T _{AX}	°F	56.2	59.5	67.1	77.0	83.8	89.2	91.9	91.0	85.5	76.5	67.1	58.8	75.3
	T _{AN}	°F	33.2	34.6	41.9	50.5	59.1	66.1	70.1	69.4	63.9	50.3	40.6	34.7	51.2
	I	Btu/ft ² -d	762	1021	1355	1747	1895	1947	1842	1703	1439	1211	921	722	1380
Sioux Falls, SD	T _{AX}	°F	22.9	29.3	40.1	58.1	70.5	80.3	86.2	83.9	73.5	62.1	43.7	29.3	56.7
	T _{AN}	°F	1.9	8.9	20.6	34.6	45.7	56.3	61.8	59.7	48.5	36.7	22.3	10.1	33.9
	I	Btu/ft ² -d	533	802	1152	1543	1894	2100	2150	1845	1410	1005	608	441	1290
Memphis, TN	T _{AX}	°F	48.3	53.0	61.4	72.9	81.0	88.4	91.5	90.3	84.3	74.5	61.4	52.3	71.6
	T _{AN}	°F	30.9	34.1	41.9	52.2	60.9	68.9	72.6	70.8	64.1	51.3	41.1	34.3	51.9
	I	Btu/ft ² -d	683	945	1278	1639	1885	2045	1972	1824	1471	1205	817	629	1366
Amarillo, TX	T _{AX}	°F	49.1	53.1	60.8	71.0	79.1	88.2	91.4	89.6	82.4	72.7	58.7	51.8	70.7
	T _{AN}	°F	21.7	26.1	32.0	42.0	51.9	61.5	66.2	64.5	56.9	45.5	32.1	24.8	43.8
	I	Btu/ft ² -d	960	1244	1631	2019	2212	2393	2281	2103	1761	1404	1033	872	1659
Corpus Christi, TX	T _{AX}	°F	66.5	69.9	76.1	82.1	86.7	91.2	94.2	94.1	90.1	83.9	75.1	69.3	81.6
	T _{AN}	°F	46.1	48.7	55.7	63.9	69.5	74.1	75.6	75.8	72.8	64.1	54.9	48.8	62.5
	I	Btu/ft ² -d	898	1147	1430	1642	1866	2094	2186	1991	1687	1416	1043	845	1521
Dallas, TX	T _{AX}	°F	54.0	59.1	67.2	76.8	84.4	93.2	97.8	97.3	89.7	79.5	66.2	58.1	76.9
	T _{AN}	°F	33.9	37.8	44.9	55.0	62.9	70.8	74.7	73.7	67.5	56.3	44.9	37.4	55.0
	I	Btu/ft ² -d	822	1071	1422	1627	1889	2135	2122	1950	1587	1276	936	780	1468
Houston, TX	T _{AX}	°F	61.9	65.7	72.1	79.0	85.1	90.9	93.6	93.1	88.7	81.9	71.6	65.2	79.1
	T _{AN}	°F	40.8	43.2	49.8	58.3	64.7	70.2	72.5	72.1	68.1	57.5	48.6	42.7	57.4
	I	Btu/ft ² -d	772	1034	1297	1522	1775	1898	1828	1686	1471	1276	924	730	1351
Midland-Odessa, TX	T _{AX}	°F	57.6	62.1	69.8	78.8	86.0	93.0	94.2	93.1	86.4	77.7	65.5	59.7	77.0
	T _{AN}	°F	29.7	33.3	40.2	49.4	58.2	66.6	69.2	68.0	61.9	51.1	39.0	32.2	49.9
	I	Btu/ft ² -d	1081	1383	1839	2192	2430	2562	2389	2210	1844	1522	1176	1000	1802
Salt Lake City, UT	T _{AX}	°F	37.4	43.7	51.5	61.1	72.4	83.3	93.2	90.0	80.0	66.7	50.2	38.9	64.0
	T _{AN}	°F	19.7	24.4	29.9	37.2	45.2	53.3	61.8	59.7	50.0	39.3	29.2	21.6	39.3
	I	Btu/ft ² -d	639	989	1454	1894	2362	2561	2590	2254	1843	1293	788	570	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	68.4
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	12.4	Kalispell	6.6
South Bend	10.3	Worcester	10.2	Missoula	6.2
Iowa		Michigan		Nebraska	
Des Moines	10.9	Alpena	8.1	Grand Island	11.9
Sioux City	11.0	Detroit	10.2	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	10.2			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	12.4	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	6.4		
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	Gunite 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
$0 < D \leq 85$	1
$85 < D \leq 100$	6
$100 < D \leq 120$	7
$120 < D \leq 135$	8
$135 < D \leq 150$	9
$150 < D \leq 170$	16
$170 < D \leq 190$	19
$190 < D \leq 220$	22
$220 < D \leq 235$	31
$235 < D \leq 270$	37
$270 < D \leq 275$	43
$275 < D \leq 290$	49
$290 < D \leq 330$	61
$330 < D \leq 360$	71
$360 < D \leq 400$	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 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 16,20.

^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 $N_{vh} = 1$ 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_L , 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).

References for Section 7.1

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9.5.2 Meat Smokehouses

9.5.2.1 General^{1-3,7-9}

Meat smokehouses are used to add flavor, color, and aroma to various meats, including pork, beef, poultry, and fish. Smokehouses were at one time used to smoke food for preservation, but refrigeration systems have effectively eliminated this use.

Four operations are typically involved in the production of smoked meat: (1) tempering or drying, (2) smoking, (3) cooking, and (4) chilling. However, not all smoked foods are cooked, thus eliminating the cooking and chilling processes from some operations. Important process parameters include cooking/smoking time, smoke generation temperature, humidity, smoke density, type of wood or liquid smoke, and product type.

The two types of smokehouses that are almost exclusively used are batch and continuous smokehouses. Figures 9.5.2-1 and 9.5.2-2 show typical batch and continuous smokehouses, respectively. Both types of systems circulate air at the desired process conditions (temperature, humidity, and smoke density) over the surface of the meat. In batch smokehouses, the meat is placed on stationary racks for the entire smoking process. In continuous smokehouses, the meat is hung on sticks or hangers and then conveyed through the various zones (smoking, heating, and chilling) within the smokehouse. Following processing in the smokehouse, the product is packaged and stored for shipment.

Several methods are used to produce the smoke used in smokehouses. The most common method is to pyrolyze hardwood chips or sawdust using smoke generators. In a typical smoke generator, hardwood chips or sawdust are fed onto a gas- or electrically-heated metal surface at 350° to 400°C (662° to 752°F). Smoke is then ducted by a smoke tube into the air recirculation system in the smokehouse. Smoke produced by this process is called natural smoke.

Liquid smoke (or artificial smoke), which is a washed and concentrated natural smoke, is also used in smokehouses. This type of smoke (as a fine aerosol) can be introduced into a smokehouse through the air recirculation system, can be mixed or injected into the meat, or can be applied by drenching, spraying, or dipping.

9.5.2.2 Emissions And Controls^{1-2,4}

Particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOC), polycyclic aromatic hydrocarbons (PAH), organic acids, acrolein, acetaldehyde, formaldehyde, and nitrogen oxides have been identified as pollutants associated with meat smokehouses. The primary source of these pollutants is the smoke used in the smokehouses. Studies cited in Reference 1 show that almost all PM from smoke has an aerodynamic diameter of less than 2.0 micrometers (μm). Acetic acid has been identified as the most prevalent organic acid present in smoke, followed by formic, propionic, butyric, and other acids. Also, acetaldehyde concentrations have been shown to be about five times greater than formaldehyde concentrations in smoke. Heating zones in continuous smokehouses (and the cooking cycle in batch smokehouses) are a source of odor that includes small amounts of VOC. The VOC are a result of the volatilization of organic compounds contained in the meat or the smoke previously applied to the meat. Heating zones are typically heated with ambient air that is passed over electrically-heated or steam-heated coils (steam from boilers used elsewhere at the facility). Therefore, heating zones are not a source of combustion products. Factors that may

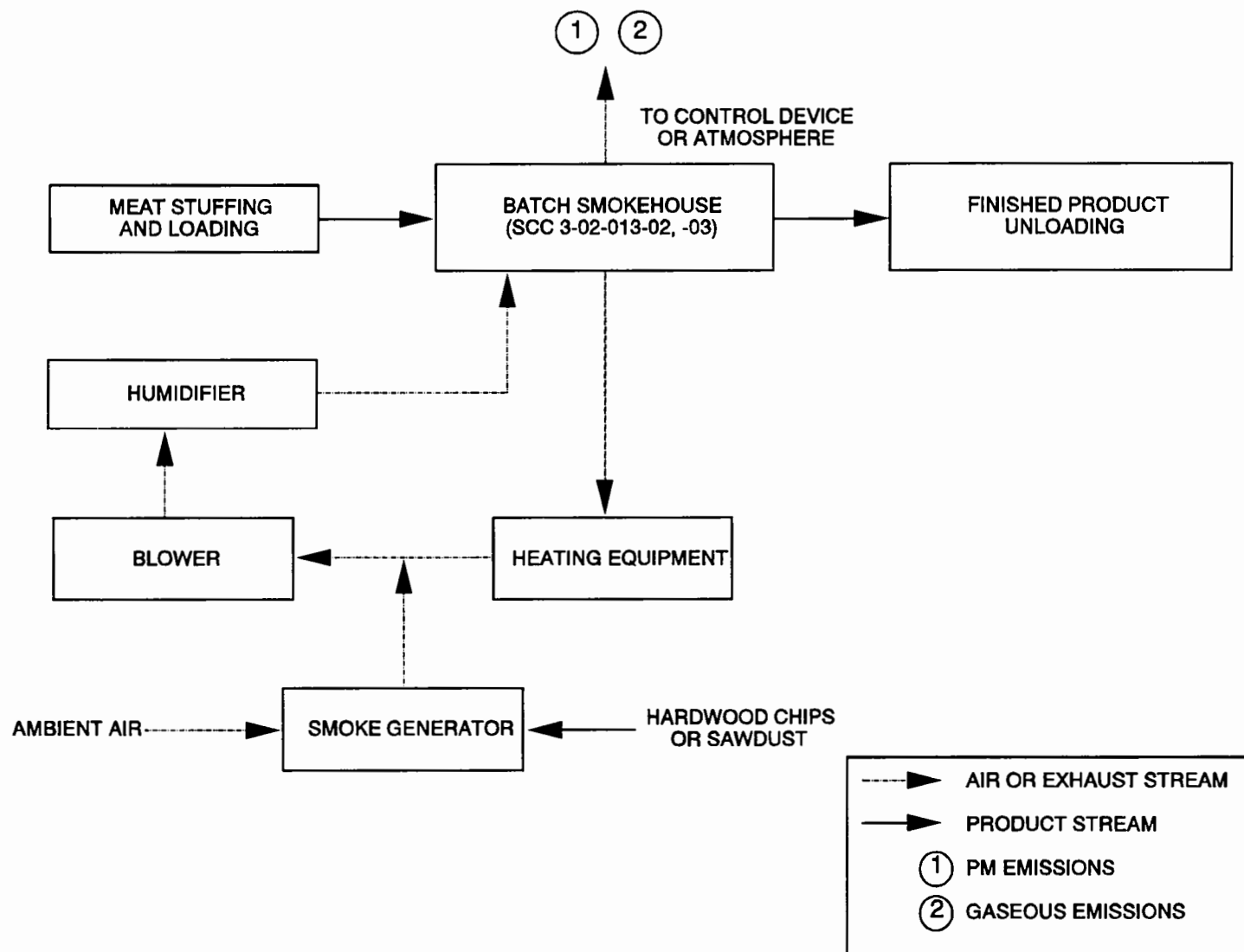


Figure 9.5.2-1. Typical batch smokehouse.¹
(Source Classification Code in parentheses.)

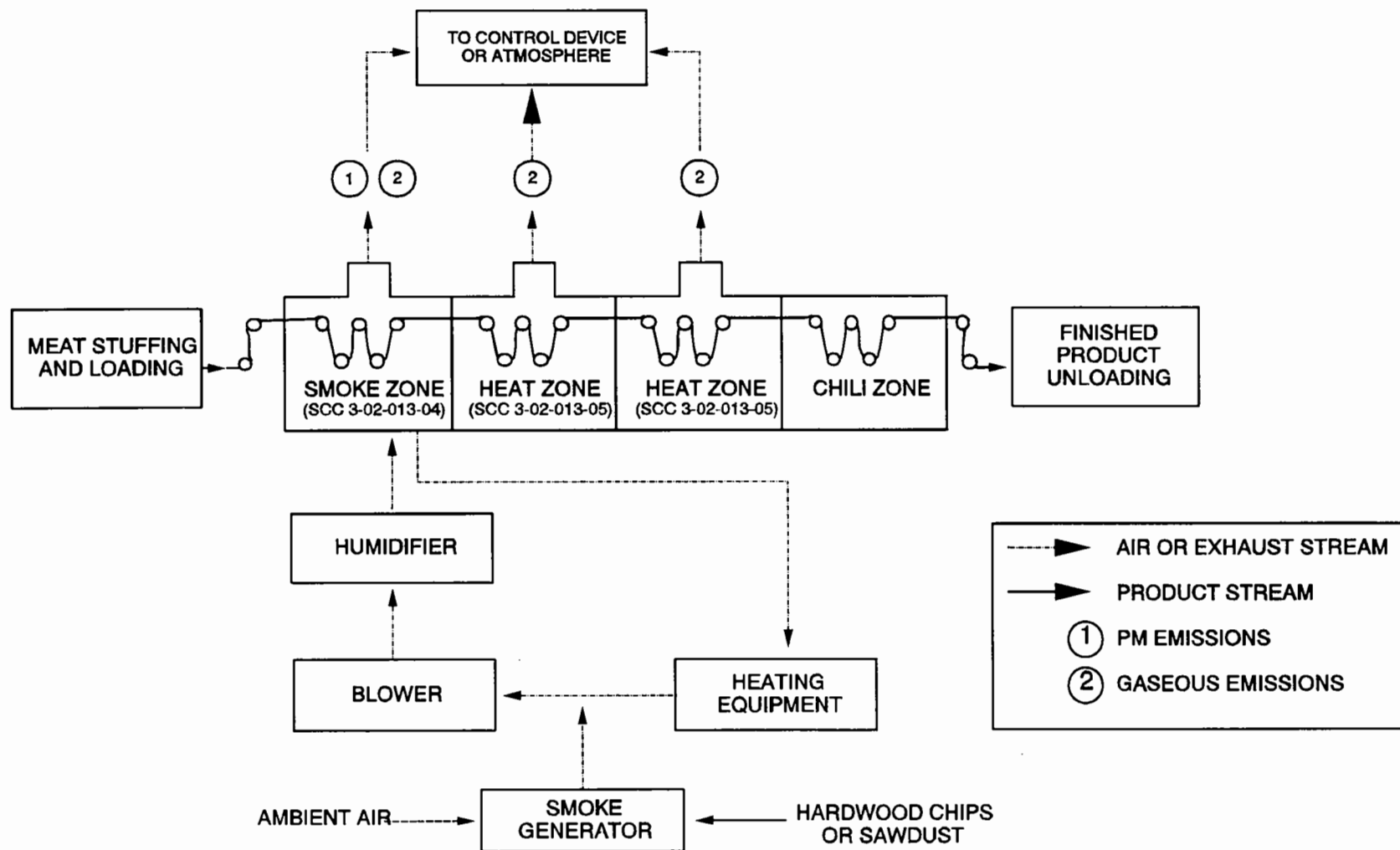


Figure 9.5.2-2. Typical continuous smokehouse.¹
(Source Classification Code in parentheses.)

effect smokehouse emissions include the amount and type of wood or liquid smoke used, the type of meat processed, the processing time, humidity, and the temperature maintained in the smoke generators.

Control technologies used at meat smokehouses include afterburners, wet scrubbers, and modular electrostatic precipitators (ESP). Emissions can also be reduced by controlling important process parameters. An example of this type of process control is maintaining a temperature not higher than about 400°C (752°F) in the smoke generator, to minimize the formation of PAH.

Afterburners are an effective control technology for PM, organic gases, and CO from smokehouses, but energy requirements may be costly for continuous smokehouse operations. Also, the additional air pollution resulting from afterburner fuel combustion makes afterburners a less desirable option for controlling smokehouse emissions.

Wet scrubbers are another effective control technology for both PM and gaseous emissions. Different types of scrubbers used include mist scrubbers, packed bed scrubbers, and vortex scrubbers. Mist scrubbers introduce a water fog into a chamber, and exhaust gases are then fed into the chamber and are absorbed. Packed bed scrubbers introduce the exhaust gases into a wetted column containing an inert packing material in which liquid/gas contact occurs. Vortex scrubbers use a whirling flow pattern to shear water into droplets, which then contact the exhaust gases. Limited test data (from Reference 4) show a vortex scrubber (followed by a demister) achieving about 51 percent formaldehyde removal, 85 percent total organic compound removal, 39 percent acetic acid removal, and 69 percent PM removal. Particulate matter removal efficiencies for scrubbers can be increased through the use of surfactants, which may enhance the capture of smoke particles that do not combine with the scrubber water.

Electrostatic precipitators are effective for controlling PM emissions. Combined control technologies, such as a wet scrubber for gaseous emission control followed by an ESP for PM removal, may also be used to control emissions from smokehouses.

Smokehouse control devices are operated during the smoking cycle and are sometimes bypassed during the cooking and cooling cycles. Continuous smokehouses may include separate vents for exhaust streams from the different zones, thus minimizing the air flow through the control device.

The average emission factors for meat smokehouses are shown in Tables 9.5.2-1 and 9.5.2-2. These emission factors are presented in units of mass of pollutant emitted per mass of wood used to generate smoke. Normally, emission factors are based on either units of raw material or units of product. In this industry, the amount of smoke flavor applied to the meats varies; consequently the emissions are dependent on the quantity of wood (or liquid smoke) used, rather than the quantity of meat processed. The emission factors presented in Tables 9.5.2-1 and 9.5.2-2 were developed using data from only two facilities and, consequently, may not be representative of the entire industry.

Table 9.5.2-1. EMISSION FACTORS FOR BATCH AND CONTINUOUS MEAT SMOKEHOUSES^a

EMISSION FACTOR RATING: D

Process	Filterable PM		Condensible PM			Total PM	
	PM	PM-10	Inorganic	Organic	Total	PM	PM-10
Batch smokehouse, smoking cycle ^b (SCC 3-02-013-02)	23	ND ^c	11	19	30	53	ND ^c
Continuous smokehouse, smoke zone ^d (SCC 3-02-013-04)	66	ND ^c	36	39	75	140	ND ^c
Continuous smokehouse, smoke zone, with vortex wet scrubber and demister ^d (SCC 3-02-013-04)	13	ND ^c	9.8	6.0	16	29	ND ^c

^a Emission factor units are lb/ton of wood or sawdust used. ND = no data available. SCC = Source Classification Code.

^b Reference 5.

^c Although data are not directly available, Reference 1 states that all PM from smoke is less than 2 micrometers in aerodynamic diameter.

^d References 4-6.

Table 9.5.2-2. EMISSION FACTORS FOR BATCH AND CONTINUOUS MEAT SMOKEHOUSES^a

Process	VOC	EMISSION FACTOR RATING	Formaldehyde	EMISSION FACTOR RATING	Acetic Acid	EMISSION FACTOR RATING
Batch smokehouse, smoking cycle ^b (SCC 3-02-013-02)	44	D	ND	NA	ND	NA
Batch smokehouse, cooking cycle (SCC 3-02-013-03)	ND	NA	ND	NA	ND	NA
Continuous smokehouse, smoke zone ^c (SCC 3-02-013-04)	17	D	1.3	E	4.5	E
Continuous smokehouse, smoke zone, with vortex wet scrubber and demister ^d (SCC 3-02-013-04)	4.4	E	0.62	E	2.8	E
Continuous smokehouse, heat zone (SCC 3-02-013-05)	ND	NA	ND	NA	ND	NA

^a Emission factor units are lb/ton of wood or sawdust used, unless noted. ND = no data available. NA = not applicable. SCC = Source Classification Code.

^b Reference 5. VOC, measured as methane.

^c References 5-6. VOC, measured as methane.

^d Reference 4. VOC, measured as methane. VOCs were measured on a gas chromatograph calibrated against acetaldehyde, and the results were converted to a methane basis.

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9.5.3 Meat Rendering Plants

9.5.3.1 General¹

Meat rendering plants process animal by-product materials for the production of tallow, grease, and high-protein meat and bone meal. Plants that operate in conjunction with animal slaughterhouses or poultry processing plants are called integrated rendering plants. Plants that collect their raw materials from a variety of offsite sources are called independent rendering plants. Independent plants obtain animal by-product materials, including grease, blood, feathers, offal, and entire animal carcasses, from the following sources: butcher shops, supermarkets, restaurants, fast-food chains, poultry processors, slaughterhouses, farms, ranches, feedlots, and animal shelters.

The two types of animal rendering processes are edible and inedible rendering. Edible rendering plants process fatty animal tissue into edible fats and proteins. The plants are normally operated in conjunction with meat packing plants under U. S. Department of Agriculture, Food Safety and Inspection Services (USDA/FSIS) inspection and processing standards. Inedible rendering plants are operated by independent renderers or are part of integrated rendering operations. These plants produce inedible tallow and grease, which are used in livestock and poultry feed, soap, and production of fatty-acids.

9.5.3.2 Process Description¹⁻³

Raw Materials —

Integrated rendering plants normally process only one type of raw material, whereas independent rendering plants often handle several raw materials that require either multiple rendering systems or significant modifications in the operating conditions for a single system.

Edible Rendering —

A typical edible rendering process is shown in Figure 9.5.3-1. Fat trimmings, usually consisting of 14 to 16 percent fat, 60 to 64 percent moisture, and 22 to 24 percent protein, are ground and then belt conveyed to a melt tank. The melt tank heats the materials to about 43°C (110°F), and the melted fatty tissue is pumped to a disintegrator, which ruptures the fat cells. The proteinaceous solids are separated from the melted fat and water by a centrifuge. The melted fat and water are then heated with steam to about 93°C (200°F) by a shell and tube heat exchanger. A second-stage centrifuge then separates the edible fat from the water, which also contains any remaining protein fines. The water is discharged as sludge, and the "polished" fat is pumped to storage. Throughout the process, direct heat contact with the edible fat is minimal and no cooking vapors are emitted. For this reason, no emission points are designated in Figure 9.5.3-1.

Inedible Rendering —

There are two processes for inedible rendering: the wet process and the dry process. Wet rendering is a process that separates fat from raw material by boiling in water. The process involves addition of water to the raw material and the use of live steam to cook the raw material and accomplish separation of the fat. Dry rendering is a batch or continuous process that dehydrates raw material in order to release fat. Following dehydration in batch or continuous cookers, the melted fat and protein solids are separated. At present, only dry rendering is used in the United States. The wet rendering process is no longer used because of the high cost of energy and of an adverse effect

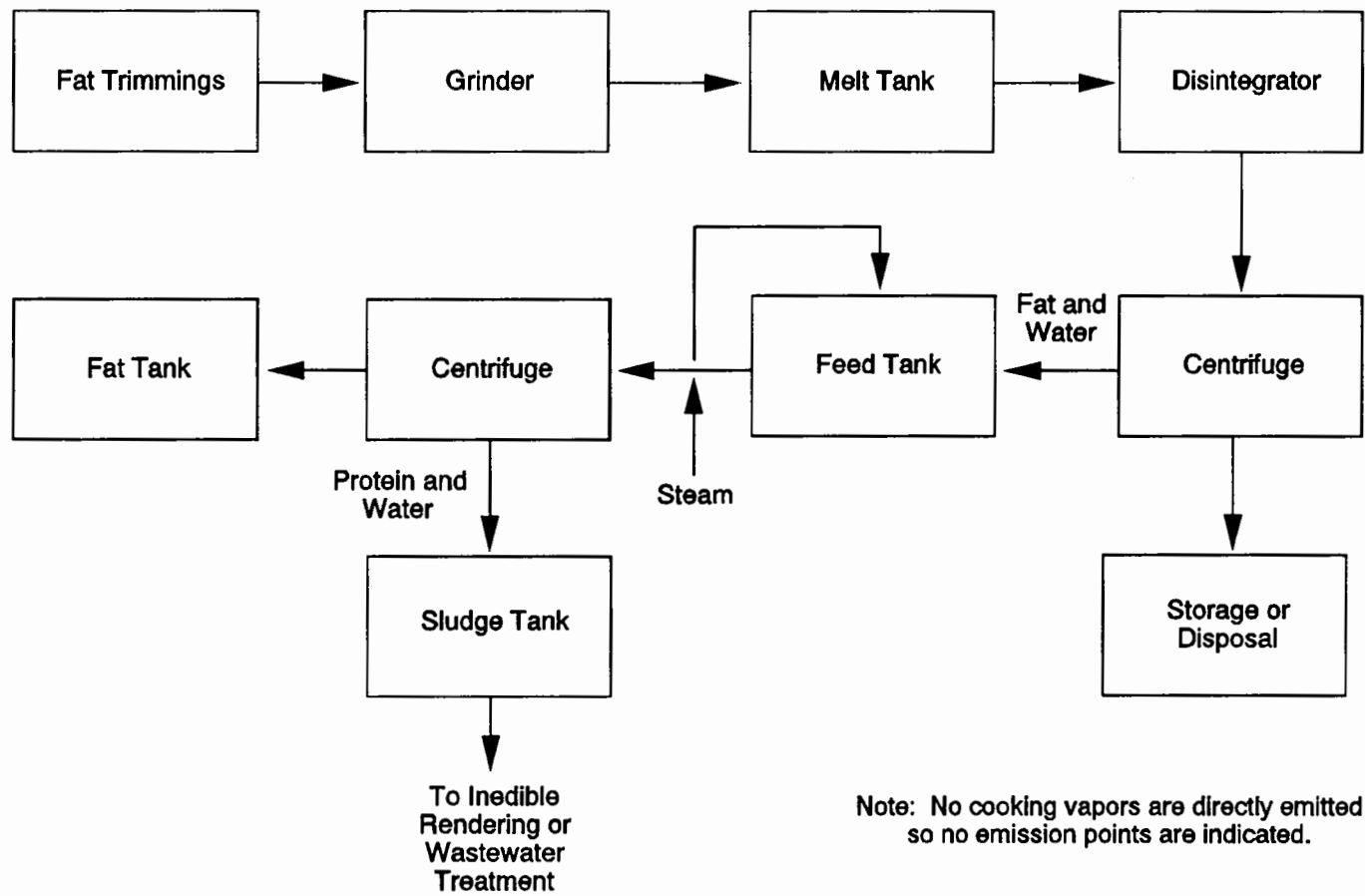


Figure 9.5.3-1. Edible rendering process.

on the fat quality. Table 9.5.3-1 shows the fat, protein, and moisture contents for several raw materials processed by inedible rendering plants.

Batch Rendering Process —

In the batch process, the raw material from the receiving bin is screw conveyed to a crusher where it is reduced to 2.5 to 5 centimeters (cm) (1 to 2 inches [in.]) in size to improve cooking efficiency. Cooking normally requires 1.5 to 2.5 hr, but adjustments in the cooking time and temperature may be required to process the various materials. A typical batch cooker is a horizontal, cylindrical vessel equipped with a steam jacket and an agitator. To begin the cooking process the cooker is charged with raw material, and the material is heated to a final temperature ranging from 121° to 135°C (250° to 275°F). Following the cooking cycle, the contents are discharged to the percolator drain pan. Vapor emissions from the cooker pass through a condenser where the water vapor is condensed and noncondensibles are emitted as VOC emissions.

The percolator drain pan contains a screen that separates the liquid fat from the protein solids. From the percolator drain pan, the protein solids, which still contain about 25 percent fat, are conveyed to the screw press. The screw press completes the separation of fat from solids, and yields protein solids that have a residual fat content of about 10 percent. These solids, called cracklings, are then ground and screened to produce protein meal. The fat from both the screw press and the percolator drain pan is pumped to the crude animal fat tank, centrifuged or filtered to remove any remaining protein solids, and stored in the animal fat storage tank.

Continuous Rendering Process —

Since the 1960, continuous rendering systems have been installed to replace batch systems at some plants. Figure 9.5.3-2 shows the basic inedible rendering process using the continuous process. The system is similar to a batch system except that a single, continuous cooker is used rather than several parallel batch cookers. A typical continuous cooker is a horizontal, steam-jacketed cylindrical vessel equipped with a mechanism that continuously moves the material horizontally through the cooker. Continuous cookers cook the material faster than batch cookers, and typically produce a higher quality fat product. From the cooker, the material is discharged to the drainer, which serves the same function as the percolator drain pan in the batch process. The remaining operations are generally the same as the batch process operations.

Current continuous systems may employ evaporators operated under vacuum to remove moisture from liquid fat obtained using a preheater and a press. In this system, liquid fat is obtained by precooking and pressing raw material and then dewatered using a heated evaporator under vacuum. The heat source for the evaporator is hot vapors from the cooker/dryer. The dewatered fat is then recombined with the solids from the press prior to entry into the cooker/dryer.

Blood Processing And Drying —

Whole blood from animal slaughterhouses, containing 16 to 18 percent total protein solids, is processed and dried to recover protein as blood meal. At the present time, less than 10 percent of the independent rendering plants in the U. S. process whole animal blood. The blood meal is a valuable ingredient in animal feed because it has a high lysine content. Continuous cookers have replaced batch cookers that were originally used in the industry because of the improved energy efficiency and product quality provided by continuous cookers. In the continuous process, whole blood is introduced into a steam-injected, inclined tubular vessel in which the blood solids coagulate. The coagulated blood solids and liquid (serum water) are then separated in a centrifuge, and the blood solids dried in either a continuous gas-fired, direct-contact ring dryer or a steam tube, rotary dryer.

**Table 9.5.3-1. COMPOSITION OF RAW MATERIALS FOR
INEDIBLE RENDERING^a**

Source	Tallow/Grease, wt %	Protein Solids, wt %	Moisture, wt %
Packing house offal^b and bone			
Steers	30-35	15-20	45-55
Cows	10-20	20-30	50-70
Calves	10-15	15-20	65-75
Sheep	25-30	20-25	45-55
Hogs	25-30	10-15	55-65
Poultry offal	10	25	65
Poultry feathers	None	33	67
Dead stock (whole animals)			
Cattle	12	25	63
Calves	10	22	68
Sheep	22	25	53
Hogs	30	28	42
Butcher shop fat and bone	31	32	37
Blood	None	16-18	82-84
Restaurant grease	65	10	25

^a Reference 1.

^b Waste parts; especially the entrails and similar parts from a butchered animal.

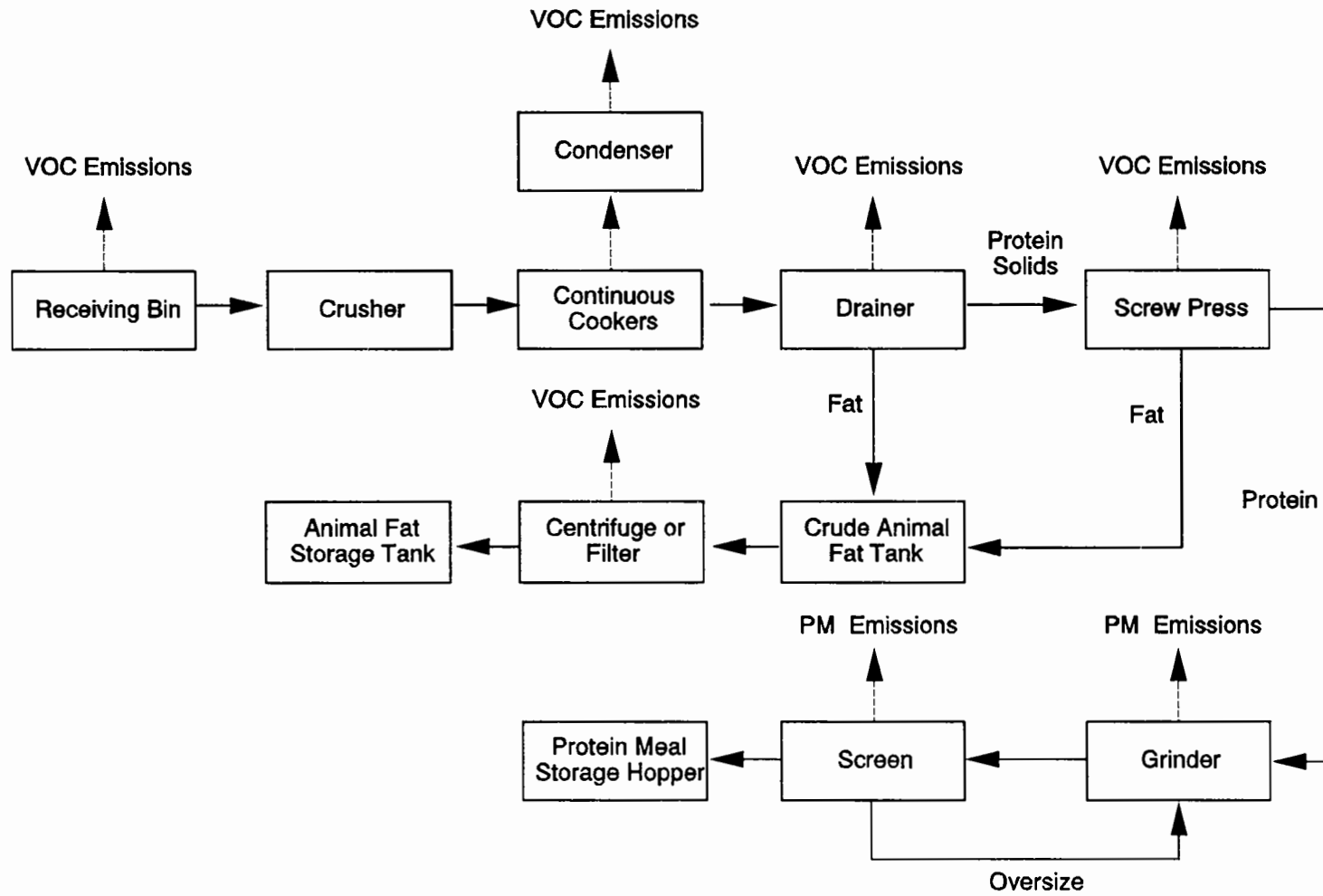


Figure 9.5.3-2. Continuous rendering process.

Poultry Feathers And Hog Hair Processing —

The raw material is introduced into a batch cooker, and is processed for 30 to 45 minutes at temperatures ranging from 138° to 149°C (280° to 300°F) and pressures ranging from (40 to 50 psig). This process converts keratin, the principal component of feathers and hog hair, into amino acids. The moist meal product, containing the amino acids, is passed either through a hot air, ring-type dryer or over steam-heated tubes to remove the moisture from the meal. If the hot air dryer is used, the dried product is separated from the exhaust by cyclone collectors. In the steam-heated tube system, fresh air is passed countercurrent to the flow of the meal to remove the moisture. The dried meal is transferred to storage. The exhaust gases are passed through controls prior to discharge to the atmosphere.

Grease Processing —

Grease from restaurants is recycled as another raw feed material processed by rendering plants. The grease is bulk loaded into vehicles, transported to the rendering plant, and discharged directly to the grease processing system. During processing, the melted grease is first screened to remove coarse solids, and then heated to about 93°C (200°F) in vertical processing tanks. The material is then stored in the processing tank for 36 to 48 hr to allow for gravity separation of the grease, water, and fine solids. Separation normally results in four phases: (1) solids, (2) water, (3) emulsion layer, and (4) grease product. The solids settle to the bottom and are separated from the water layer above. The emulsion is then processed through a centrifuge to remove solids and another centrifuge to remove water and any remaining fines; the grease product is skimmed off the top.

9.5.3.3 Emissions And Controls¹⁻⁵

Emissions —

Volatile organic compounds (VOCs) are the primary air pollutants emitted from rendering operations. The major constituents that have been qualitatively identified as potential emissions include organic sulfides, disulfides, C-4 to C-7 aldehydes, trimethylamine, C-4 amines, quinoline, dimethyl pyrazine, other pyrazines, and C-3 to C-6 organic acids. In addition, lesser amounts of C-4 to C-7 alcohols, ketones, aliphatic hydrocarbons, and aromatic compounds are potentially emitted. No quantitative emission data were presented. Historically, the VOCs are considered an odor nuisance in residential areas in close proximity to rendering plants, and emission controls are directed toward odor elimination. The odor detection threshold for many of these compounds is low; some as low as 1 part per billion (ppb). Of the specific constituents listed, only quinoline is classified as a hazardous air pollutant (HAP). In addition to emissions from rendering operations, VOCs may be emitted from the boilers used to generate steam for the operation.

Emissions from the edible rendering process are not considered to be significant because no cooking vapors are emitted and direct heat contact with the edible fat is minimal. Therefore, these emissions are not discussed further.

For inedible rendering operations, the primary sources of VOC emissions are the cookers and the screw press. Other sources of VOC emissions include blood and feather processing operations, dryers, centrifuges, tallow processing tanks, and percolator pans that are not enclosed. Raw material may also be a source of VOC emissions, but if the material is processed in a timely manner, these emissions are minimal.

In addition to VOC emissions, particulate matter (PM) is emitted from grinding and screening of the solids (cracklings) from the screw press and other rendering operations such as dryers processing blood and feathers. No emission data quantifying VOC, HAP, or PM emissions from the

rendering process are available for use in developing emission factors. Only test data for a blood dryer operation were identified.

Controls —

Emissions control at rendering plants is based primarily on the elimination of odor. These controls are divided into two categories: (1) those controlling high intensity odor emissions from the rendering process, and (2) those controlling plant ventilating air emissions. The control technologies that are typically used for high intensity odors from rendering plant process emissions are waste heat boilers (incinerators) and multistage wet scrubbers.

Boiler incinerators are a common control technology because boilers can be used not only as control devices but also to generate steam for cooking and drying operations. In waste heat boilers, the waste stream can be introduced into the boiler as primary or secondary combustion air. Primary combustion air is mixed with fuel before ignition to allow for complete combustion, and secondary combustion air is mixed with the burner flame to complete combustion. Gaseous waste streams that contain noncondensibles are typically "cleaned" in a combination scrubber and entrainment separator before use as combustion air.

Multistage wet scrubbers are equally as effective as incineration for high intensity odor control and are used to about the same extent as incinerators. Sodium hypochlorite is considered to be the most effective scrubbing agent for odor removal, although other oxidants can be used. Recently, chlorine dioxide has been used as an effective scrubbing agent. Venturi scrubbers are often used to remove PM from waste streams before treatment by the multistage wet scrubbers. Plants that are located near residential or commercial areas may treat process and fugitive emissions by ducting the plant ventilation air through a single-stage wet scrubbing system to minimize odorous emissions.

In addition to the conventional scrubber control technology, activated carbon adsorption and catalytic oxidation potentially could be used to control odor; however, no rendering plants currently use these technologies. Recently, some plants have installed biofilters to control emissions.

No data are currently available for VOC or particulate emissions from rendering plants. The only available data are for emissions from blood dryers, which is an auxiliary process in meat rendering operations. Less than 10 percent of the independent rendering plants in the U. S. process whole blood. Table 9.5.3-2 provides controlled emission factors in English units for particulate matter (filterable and condensable), hydrogen sulfide, and ammonia from natural gas, direct-fired blood dryers. The filterable PM was found to be 100 percent PM-10. Emission factors are calculated on the basis of the weight of dried blood meal product. In addition to natural gas, direct-fired dryers, steam-coil, indirect blood dryers (SCC 3-02-038-12) are also used in meat rendering plants. No emission data were found for this type of dryer. The emission control system in Reference 4 consisted of a cyclone separator for collection of the blood meal product followed by a venturi wet scrubber and three packed bed scrubbers in series. The scrubbing medium for the three packed bed scrubbers was a sodium hypochlorite solution. The emission control system in Reference 5 was a mechanical centrifugal separator.

Table 9.5.3-2. EMISSION FACTORS FOR CONTROLLED BLOOD DRYERS

EMISSION FACTOR RATING: E

Pollutant	Emissions, lb/ton ^a
Filterable PM-10 ^b (SCC 3-02-038-11)	0.76
Condensable PM ^b (SCC 3-02-038-11)	0.46
Hydrogen sulfide ^c (SCC 3-02-038-11)	0.08
Ammonia ^c (SCC 3-02-038-11)	0.60

^a Emission factors based on weight of dried blood meal product. Emissions are for natural gas, direct-fired dryers.

^b References 4-5.

^c Reference 4.

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9.8.1 Canned Fruits And Vegetables

9.8.1.1 General¹⁻²

The canning of fruits and vegetables is a growing, competitive industry, especially the international export portion. The industry is made up of establishments primarily engaged in canning fruits, vegetables, fruit and vegetable juices; processing ketchup and other tomato sauces; and producing natural and imitation preserves, jams, and jellies.

9.8.1.2 Process Description³⁻⁶

The primary objective of food processing is the preservation of perishable foods in a stable form that can be stored and shipped to distant markets during all months of the year. Processing also can change foods into new or more usable forms and make foods more convenient to prepare.

The goal of the canning process is to destroy any microorganisms in the food and prevent recontamination by microorganisms. Heat is the most common agent used to destroy microorganisms. Removal of oxygen can be used in conjunction with other methods to prevent the growth of oxygen-requiring microorganisms.

In the conventional canning of fruits and vegetables, there are basic process steps that are similar for both types of products. However, there is a great diversity among all plants and even those plants processing the same commodity. The differences include the inclusion of certain operations for some fruits or vegetables, the sequence of the process steps used in the operations, and the cooking or blanching steps. Production of fruit or vegetable juices occurs by a different sequence of operations and there is a wide diversity among these plants. Typical canned products include beans (cut and whole), beets, carrots, corn, peas, spinach, tomatoes, apples, peaches, pineapple, pears, apricots, and cranberries. Typical juices are orange, pineapple, grapefruit, tomato, and cranberry. Generic process flow diagrams for the canning of fruits, vegetables, and fruit juices are shown in Figures 9.8.1-1, 9.8.1-2, and 9.8.1-3. The steps outlined in these figures are intended to the basic processes in production. A typical commercial canning operation may employ the following general processes: washing, sorting/grading, preparation, container filling, exhausting, container sealing, heat sterilization, cooling, labeling/casing, and storage for shipment. In these diagrams, no attempt has been made to be product specific and include all process steps that would be used for all products. Figures 9.8.1-1 and 9.8.1-2 show optional operations, as dotted line steps, that are often used but are not used for all products. One of the major differences in the sequence of operations between fruit and vegetable canning is the blanching operation. Most of the fruits are not blanched prior to can filling whereas many of the vegetables undergo this step. Canned vegetables generally require more severe processing than do fruits because the vegetables have much lower acidity and contain more heat-resistant soil organisms. Many vegetables also require more cooking than fruits to develop their most desirable flavor and texture. The methods used in the cooking step vary widely among facilities. With many fruits, preliminary treatment steps (e. g., peeling, coring, halving, pitting) occur prior to any heating or cooking step but with vegetables, these treatment steps often occur after the vegetable has been blanched. For both fruits and vegetables, peeling is done either by a mechanical peeler, steam peeling, or lye peeling. The choice depends upon the type of fruit or vegetable or the choice of the company.

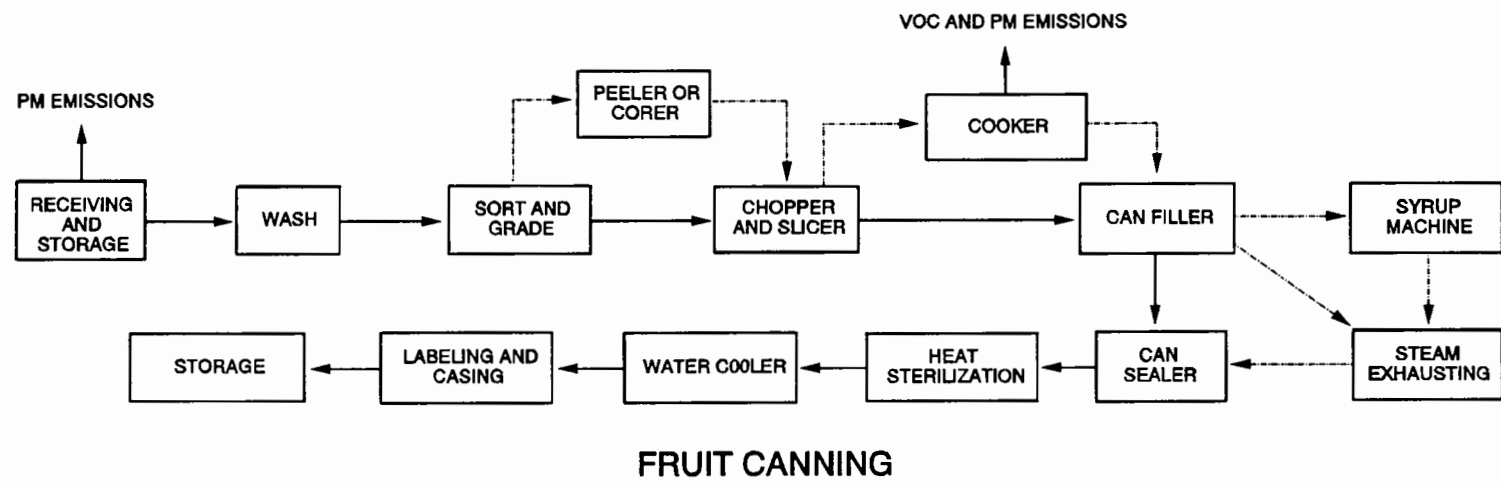


Figure 9.8.1-1. Generic process diagram for fruit canning.

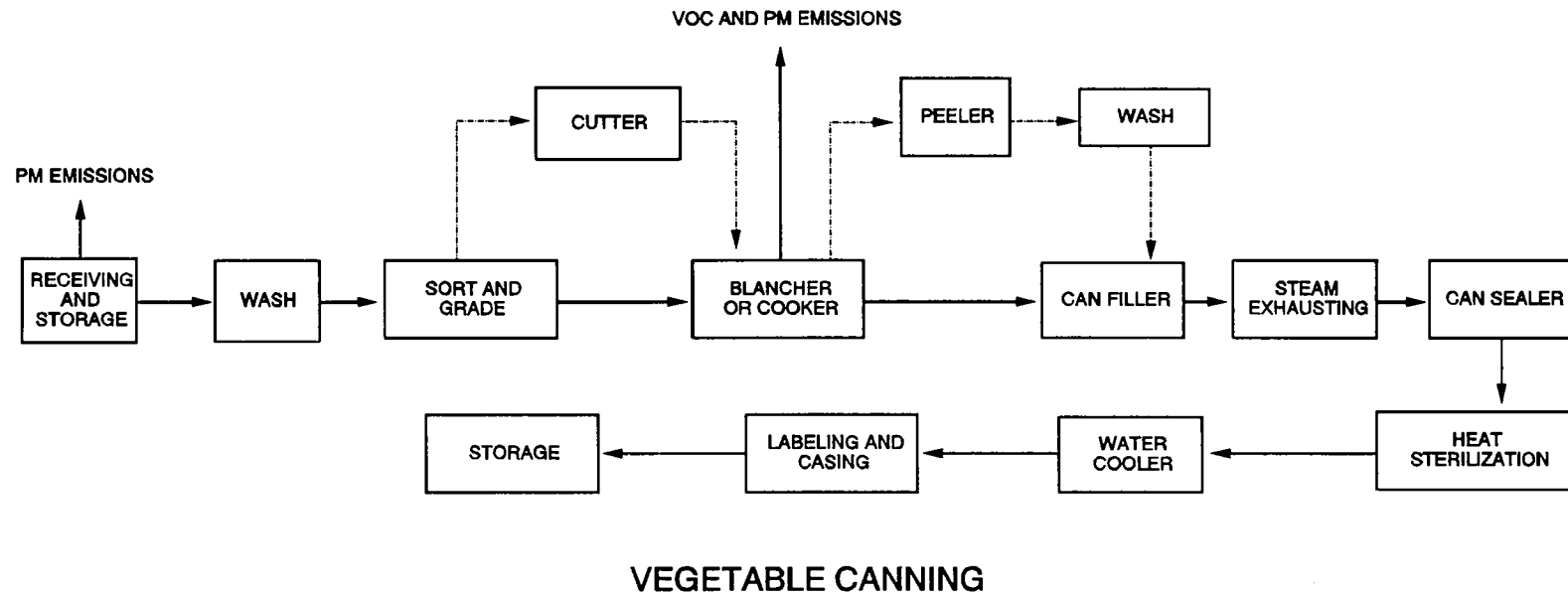


Figure 9.8.1-2. Generic process diagram for vegetable canning.

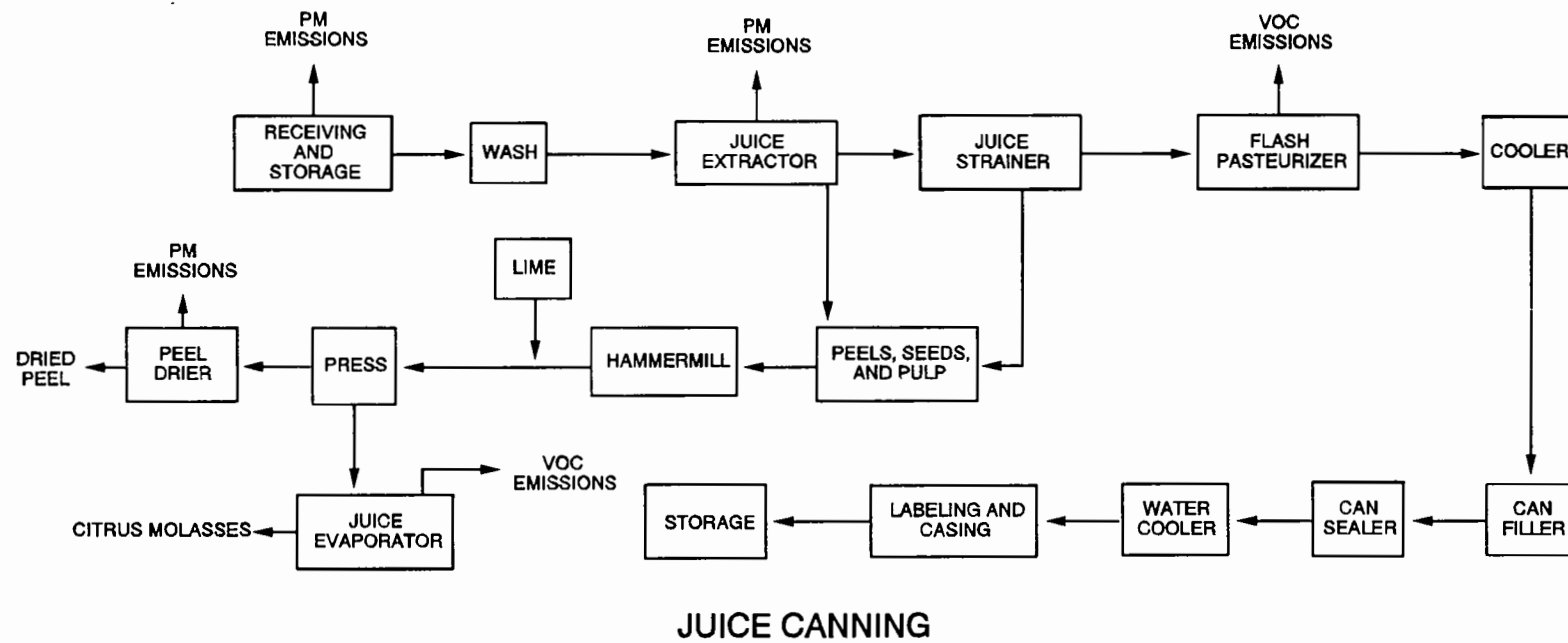


Figure 9.8.1-3. Generic process diagram for juice canning.

Some citrus fruit processors produce dry citrus peel, citrus molasses and D-limonene from the peels and pulp residue collected from the canning and juice operations. Other juice processing facilities use concentrates and raw commodity processing does not occur at the facility. The peels and residue are collected and ground in a hammermill, lime is added to neutralize the acids, and the product pressed to remove excess moisture. The liquid from the press is screened to remove large particles, which are recycled back to the press, and the liquid is concentrated to molasses in an evaporator. The pressed peel is sent to a direct-fired hot-air drier. After passing through a condenser to remove the D-limonene, the exhaust gases from the drier are used as the heat source for the molasses evaporator.

Equipment for conventional canning has been converting from batch to continuous units. In continuous retorts, the cans are fed through an air lock, then rotated through the pressurized heating chamber, and subsequently cooled through a second section of the retort in a separate cold-water cooler. Commercial methods for sterilization of canned foods with a pH of 4.5 or lower include use of static retorts, which are similar to large pressure cookers. A newer unit is the agitating retort, which mechanically moves the can and the food, providing quicker heat penetration. In the aseptic packaging process, the problem with slow heat penetration in the in-container process are avoided by sterilizing and cooling the food separate from the container. Presterilized containers are then filled with the sterilized and cooled product and are sealed in a sterile atmosphere.

To provide a closer insight into the actual processes that occur during a canning operation, a description of the canning of whole tomatoes is presented in the following paragraphs. This description provides more detail for each of the operations than is presented in the generic process flow diagrams in Figures 9.8.1-1, 9.8.1-2, and 9.8.1-3.

Preparation –

The principal preparation steps are washing and sorting. Mechanically harvested tomatoes are usually thoroughly washed by high-pressure sprays or by strong-flowing streams of water while being passed along a moving belt or on agitating or revolving screens. The raw produce may need to be sorted for size and maturity. Sorting for size is accomplished by passing the raw tomatoes through a series of moving screens with different mesh sizes or over differently spaced rollers. Separation into groups according to degree of ripeness or perfection of shape is done by hand; trimming is also done by hand.

Peeling And Coring –

Formerly, tomatoes were initially scalded followed by hand peeling, but steam peeling and lye peeling have also become widely used. With steam peeling, the tomatoes are treated with steam to loosen the skin, which is then removed by mechanical means. In lye peeling, the fruit is immersed in a hot lye bath or sprayed with a boiling solution of 10 to 20 percent lye. The excess lye is then drained and any lye that adheres to the tomatoes is removed with the peel by thorough washing.

Coring is done by a water-powered device with a small turbine wheel. A special blade mounted on the turbine wheel spins and removes the tomato cores.

Filling –

After peeling and coring, the tomatoes are conveyed by automatic runways, through washers, to the point of filling. Before being filled, the can or glass containers are cleaned by hot water, steam, or air blast. Most filling is done by machine. The containers are filled with the solid product and then usually topped with a light puree of tomato juice. Acidification of canned whole tomatoes with 0.1 to 0.2 percent citric acid has been suggested as a means of increasing acidity to a safer and

more desirable level. Because of the increased sourness of the acidified product, the addition of 2 to 3 percent sucrose is used to balance the taste. The addition of salt is important for palatability.

Exhausting –

The objective of exhausting containers is to remove air so that the pressure inside the container following heat treatment and cooling will be less than atmospheric. The reduced internal pressure (vacuum) helps to keep the can ends drawn in, reduces strain on the containers during processing, and minimizes the level of oxygen remaining in the headspace. It also helps to extend the shelf life of food products and prevents bulging of the container at high altitudes.

Vacuum in the can may be obtained by the use of heat or by mechanical means. The tomatoes may be preheated before filling and sealed hot. For products that cannot be preheated before filling, it may be necessary to pass the filled containers through a steam chamber or tunnel prior to the sealing machine to expel gases from the food and raise the temperature. Vacuum also may be produced mechanically by sealing containers in a chamber under a high vacuum.

Sealing –

In sealing lids on metal cans, a double seam is created by interlocking the curl of the lid and flange of the can. Many closing machines are equipped to create vacuum in the headspace either mechanically or by steam-flow before lids are sealed.

Heat Sterilization –

During processing, microorganisms that can cause spoilage are destroyed by heat. The temperature and processing time vary with the nature of the product and the size of the container.

Acidic products, such as tomatoes, are readily preserved at 100°C (212°F). The containers holding these products are processed in atmospheric steam or hot-water cookers. The rotary continuous cookers, which operate at 100°C (212°F), have largely replaced retorts and open-still cookers for processing canned tomatoes. Some plants use hydrostatic cookers and others use continuous-pressure cookers.

Cooling –

After heat sterilization, containers are quickly cooled to prevent overcooking. Containers may be quickly cooled by adding water to the cooker under air pressure or by conveying the containers from the cooker to a rotary cooler equipped with a cold-water spray.

Labeling And Casing –

After the heat sterilization, cooling, and drying operations, the containers are ready for labeling. Labeling machines apply glue and labels in one high-speed operation. The labeled cans or jars are then packed into shipping cartons.

9.8.1.3 Emissions And Controls^{4,6-9}

Air emissions may arise from a variety of sources in the canning of fruits and vegetables. Particulate matter (PM) emissions result mainly from solids handling, solids size reduction, drying (e. g., citrus peel driers). Some of the particles are dusts, but others (particularly those from thermal processing operations) are produced by condensation of vapors and may be in the low-micrometer or submicrometer particle-size range.

The VOC emissions may potentially occur at almost any stage of processing, but most usually are associated with thermal processing steps, such as cooking, and evaporative concentration. The cooking technologies in canning processes are very high moisture processes so the predominant emissions will be steam or water vapor. The waste gases from these operations may contain PM or, perhaps, condensable vapors, as well as malodorous VOC. Particulate matter, condensable materials, and the high moisture content of the emissions may interfere with the collection or destruction of these VOC. The condensable materials also may be malodorous.

Wastewater treatment ponds may be another source of odors, even from processing of materials that are not otherwise particularly objectionable. Details on the processes and technologies used in waste water collection, treatment, and storage are presented in AP-42 Section 4.3; that section should be consulted for detailed information on the subject.

No emission data quantifying VOC, HAP, or PM emissions from the canned fruits and vegetable industry are available for use in the development of emission factors. Data on emissions from fruit and vegetable canning are extremely limited. Woodroof and Luh discussed the presence of VOC in apricots, cranberry juice, and cherry juice. Van Langenhove, et al., identified volatile compounds emitted during the blanching process of Brussels sprouts and cauliflower under laboratory and industrial conditions. Buttery, et al., studied emissions of volatile aroma compounds from tomato paste.

A number of emission control approaches are potentially available to the canning industry. These include wet scrubbers, dry sorbants, and cyclones. No information is available on controls actually used at canning facilities.

Control of VOC from a gas stream can be accomplished using one of several techniques but the most common methods are absorption, adsorption, and afterburners. Absorptive methods encompass all types of wet scrubbers using aqueous solutions to absorb the VOC. Most scrubber systems require a mist eliminator downstream of the scrubber.

Adsorptive methods could include one of four main adsorbents: activated carbon, activated alumina, silica gel, or molecular sieves. Of these four, activated carbon is the most widely used for VOC control while the remaining three are used for applications other than pollution control. Gas adsorption is a relatively expensive technique and may not be applicable to a wide variety of pollutants.

Particulate control commonly employs methods such as venturi scrubbers, dry cyclones, wet or dry electrostatic precipitators (ESPs), or dry filter systems. The most common controls are likely to be the venturi scrubbers or dry cyclones. Wet or dry ESPs could be used depending upon the particulate loading of the gas stream.

Condensation methods and scrubbing by chemical reaction may be applicable techniques depending upon the type of emissions. Condensation methods may be either direct contact or indirect contact with the shell and tube indirect method being the most common technique. Chemical reactive scrubbing may be used for odor control in selective applications.

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9.8.2 Dehydrated Fruits And Vegetables

9.8.2.1 General¹⁻²

Dehydration of fruit and vegetables is one of the oldest forms of food preservation techniques known to man and consists primarily of establishments engaged in sun drying or artificially dehydrating fruits and vegetables. Although food preservation is the primary reason for dehydration, dehydration of fruits and vegetables also lowers the cost of packaging, storing, and transportation by reducing both the weight and volume of the final product. Given the improvement in the quality of dehydrated foods, along with the increased focus on instant and convenience foods, the potential of dehydrated fruits and vegetables is greater than ever.

9.8.2.2 Process Description¹⁻²

Dried or dehydrated fruits and vegetables can be produced by a variety of processes. These processes differ primarily by the type of drying method used, which depends on the type of food and the type of characteristics of the final product. In general, dried or dehydrated fruits and vegetables undergo the following process steps: predrying treatments, such as size selection, peeling, and color preservation; drying or dehydration, using natural or artificial methods; and postdehydration treatments, such as sweating, inspection, and packaging.

Predrying Treatments -

Predrying treatments prepare the raw product for drying or dehydration and include raw product preparation and color preservation. Raw product preparation includes selection and sorting, washing, peeling (some fruits and vegetables), cutting into the appropriate form, and blanching (for some fruits and most vegetables). Fruits and vegetables are selected; sorted according to size, maturity, and soundness; and then washed to remove dust, dirt, insect matter, mold spores, plant parts, and other material that might contaminate or affect the color, aroma, or flavor of the fruit or vegetable. Peeling or removal of any undesirable parts follows washing. The raw product can be peeled by hand (generally not used in the United States due to high labor costs), with lye or alkali solution, with dry caustic and mild abrasion, with steam pressure, with high-pressure washers, or with flame peelers. For fruits, only apples, pears, bananas, and pineapples are usually peeled before dehydration. Vegetables normally peeled include beets, carrots, parsnips, potatoes, onions, and garlic. Prunes and grapes are dipped in an alkali solution to remove the natural waxy surface coating which enhances the drying process. Next, the product is cut into the appropriate shape or form (i. e., halves, wedges, slices, cubes, nuggets, etc.), although some items, such as cherries and corn, may by-pass this operation. Some fruits and vegetables are blanched by immersion in hot water (95° to 100°C [203° to 212°F]) or exposure to steam.

The final step in the predehydration treatment is color preservation, also known as sulfuring. The majority of fruits are treated with sulfur dioxide (SO₂) for its antioxidant and preservative effects. The presence of SO₂ is very effective in retarding the browning of fruits, which occurs when the enzymes are not inactivated by the sufficiently high heat normally used in drying. In addition to preventing browning, SO₂ treatment reduces the destruction of carotene and ascorbic acid, which are the important nutrients for fruits. Sulfuring dried fruits must be closely controlled so that enough sulfur is present to maintain the physical and nutritional properties of the product throughout its expected shelf life, but not so large that it adversely affects flavor. Some fruits, such as apples, are treated with solutions of sulfite (sodium sulfite and sodium bisulfite in approximately equal

proportions) before dehydration. Sulfite solutions are less suitable for fruits than burning sulfur (SO_2 gas), however, because the solution penetrates the fruit poorly and can leach natural sugar, flavor, and other components from the fruit.

Although dried fruits commonly use SO_2 gas to prevent browning, this treatment is not practical for vegetables. Instead, most vegetables (potatoes, cabbage, and carrots) are treated with sulfite solutions to retard enzymatic browning. In addition to color preservation, the presence of a small amount of sulfite in blanched, cut vegetables improves storage stability and makes it possible to increase the drying temperature during dehydration, thus decreasing drying time and increasing the drier capacity without exceeding the tolerance for heat damage.

Drying Or Dehydration -

Drying or dehydration is the removal of the majority of water contained in the fruit or vegetable and is the primary stage in the production of dehydrated fruits and vegetables. Several drying methods are commercially available and the selection of the optimal method is determined by quality requirements, raw material characteristics, and economic factors. There are three types of drying processes: sun and solar drying; atmospheric dehydration including stationary or batch processes (kiln, tower, and cabinet driers) and continuous processes (tunnel, continuous belt, belt-trough, fluidized-bed, explosion puffing, foam-mat, spray, drum, and microwave-heated driers); and subatmospheric dehydration (vacuum shelf, vacuum belt, vacuum drum, and freeze driers).

Sun drying (used almost exclusively for fruit) and solar drying (used for fruit and vegetables) of foods use the power of the sun to remove the moisture from the product. Sun drying of fruit crops is limited to climates with hot sun and dry atmosphere, and to certain fruits, such as prunes, grapes, dates, figs, apricots, and pears. These crops are processed in substantial quantities without much technical aid by simply spreading the fruit on the ground, racks, trays, or roofs and exposing them to the sun until dry. Advantages of this process are its simplicity and its small capital investment. Disadvantages include complete dependence on the elements and moisture levels no lower than 15 to 20 percent (corresponding to a limited shelf life). Solar drying utilizes black-painted trays, solar trays, collectors, and mirrors to increase solar energy and accelerate drying.

Atmospheric forced-air driers artificially dry fruits and vegetables by passing heated air with controlled relative humidity over the food to be dried, or by passing the food to be dried through the heated air, and is the most widely used method of fruit and vegetable dehydration. Various devices are used to control air circulation and recirculation. Stationary or batch processes include kiln, tower (or stack), and cabinet driers. Continuous processes are used mainly for vegetable dehydration and include tunnel, continuous belt, belt-trough, fluidized-bed, explosion puffing, foam-mat, spray, drum, and microwave-heated driers. Tunnel driers are the most flexible, efficient, and widely used dehydration system available commercially.

Subatmospheric (or vacuum) dehydration occurs at low air pressures and includes vacuum shelf, vacuum drum, vacuum belt, and freeze driers. The main purpose of vacuum drying is to enable the removal of moisture at less than the boiling point under ambient conditions. Because of the high installation and operating costs of vacuum driers, this process is used for drying raw material that may deteriorate as a result of oxidation or may be modified chemically as a result of exposure to air at elevated temperatures. There are two categories of vacuum driers. In the first category, moisture in the food is evaporated from the liquid to the vapor stage, and includes vacuum shelf, vacuum drum, and vacuum belt driers. In the second category of vacuum driers, the moisture of the food is removed from the product by sublimation, which is converting ice directly into water vapor. The advantages of freeze drying are high flavor retention, maximum retention of nutritional value,

minimal damage to the product texture and structure, little change in product shape and color, and a finished product with an open structure that allows fast and complete rehydration. Disadvantages include high capital investment, high processing costs, and the need for special packing to avoid oxidation and moisture gain in the finished product.

Postdehydration Treatments -

Treatments of the dehydrated product vary according to the type of fruit or vegetable and the intended use of the product. These treatments may include sweating, screening, inspection, instantization treatments, and packaging. Sweating involves holding the dehydrated product in bins or boxes to equalize the moisture content. Screening removes dehydrated pieces of unwanted size, usually called "fines". The dried product is inspected to remove foreign materials, discolored pieces, or other imperfections such as skin, carpel, or stem particles. Instantization treatments are used to improve the rehydration rate of the low-moisture product. Packaging is common to most all dehydrated products and has a great deal of influence on the shelf life of the dried product. Packaging of dehydrated fruits and vegetables must protect the product against moisture, light, air, dust, microflora, foreign odor, insects, and rodents; provide strength and stability to maintain original product size, shape, and appearance throughout storage, handling, and marketing; and consist of materials that are approved for contact with food. Cost is also an important factor in packaging. Package types include cans, plastic bags, drums, bins, and cartons, and depend on the end-use of the product.

9.8.2.3 Emissions And Controls^{1,3-6}

Air emissions may arise from a variety of sources in the dehydration of fruits and vegetables. Particulate matter (PM) emissions may result mainly from solids handling, solids size reduction, and drying. Some of the particles are dusts, but other are produced by condensation of vapors and may be in the low-micrometer or submicrometer particle-size range.

The VOC emissions may potentially occur at almost any stage of processing, but most usually are associated with thermal processing steps, such as blanching, drying or dehydration, and sweating. Particulate matter and condensable materials may interfere with the collection or destruction of these VOC. The condensable materials also may be malodorous. The color preservation (sulfuring) stage can produce SO₂ emissions as the fruits and vegetables are treated with SO₂ gas or sulfide solution to prevent discoloration or browning.

Wastewater treatment ponds may be another source of VOC, even from processing of materials that are not otherwise particularly objectionable. Details on the processes and technologies used in wastewater collection, treatment, and storage are presented in AP-42 Section 4.3. That section should be consulted for detailed information on the subject.

No emission data quantifying VOC, HAP, or PM emissions from the dehydrated fruit and vegetable industry are available for use in the development of emission factors. However, some data have been published on VOC emitted during the blanching process for two vegetables and for volatiles from fresh tomatoes. Van Langenhove, et al., identified volatiles emitted during the blanching process of Brussels sprouts and cauliflower under laboratory and industrial conditions. In addition, Buttery, et al., performed a quantitative study on aroma volatiles emitted from fresh tomatoes.

A number of VOC and particulate emission control techniques are available to the dehydrated fruit and vegetable industry. No information is available on the actual usage of emission control

devices in this industry. Potential options include the traditional approaches of wet scrubbers, dry sorbents, and cyclones.

Control of VOC from a gas stream can be accomplished using one of several techniques but the most common methods are absorption and adsorption. Absorptive methods encompass all types of wet scrubbers using aqueous solutions to absorb the VOC. Most scrubber systems require a mist eliminator downstream of the scrubber.

Adsorptive methods could include one of four main adsorbents: activated carbon, activated alumina, silica gel, or molecular sieves. Of these four, activated carbon is the most widely used for VOC control while the remaining three are used for applications other than pollution control. Gas adsorption is a relatively expensive technique and may not be applicable to a wide variety of pollutants.

Particulate control commonly employs methods such as venturi scrubbers, dry cyclones, wet or dry electrostatic precipitators (ESPs), or dry filter systems. The most common controls are likely to be the venturi scrubbers or dry cyclones. Wet or dry ESPs could be used depending upon the particulate loading of the gas stream.

Condensation methods and scrubbing by chemical reaction may be applicable techniques depending upon the type of emissions. Condensation methods may be either direct contact or indirect contact with the shell and tube indirect method being the most common technique. Chemical reactive scrubbing may be used for odor control in selective applications.

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9.8.3 Pickles, Sauces, and Salad Dressings

9.8.3.1 General¹

This industry includes facilities that produce pickled fruits and vegetables, salad dressings, relishes, various sauces, and seasonings. The two vegetables that account for the highest production volume in the U. S. are cucumbers (pickles) and cabbage (sauerkraut). Sauces entail a wide diversity of products but two of the more common types are Worcestershire sauce and hot pepper sauces. Salad dressings are generally considered to be products added to and eaten with salads. In 1987, 21,500 thousand people were employed in the industry. California, Georgia, Michigan, and Pennsylvania are the leading employment States in the industry.

9.8.3.2 Process Description²⁻³

Pickled Vegetables —

In the U. S., vegetables are pickled commercially using one of two general processes: brining or direct acidification (with or without pasteurization), or various combinations of these processes. For sodium chloride brining, fresh vegetables are placed in a salt solution or dry salt is added to cut or whole vegetables whereupon the vegetables undergo a microbial fermentation process activated by the lactic acid bacteria, yeasts, and other microorganisms. Direct acidification of fresh or brined vegetables, through the addition of vinegar, is a major component of commercial pickling. This process may be accompanied by pasteurization, addition of preservatives, refrigeration, or a combination of these treatments. While cucumbers, cabbage, and olives constitute the largest volume of vegetables brined or pickled in the U. S., other vegetables include peppers, onions, beans, cauliflower, and carrots.

In the United States, the term "pickles" generally refers to pickled cucumbers. Three methods currently are used to produce pickles from cucumbers: brine stock, fresh pack, and refrigerated. Smaller quantities are preserved by specialized brining methods to produce pickles for delicatessens and other special grades of pickles. Pickling cucumbers are harvested and transported to the processing plants. The cucumbers may be field graded and cooled, if necessitated by the temperature, prior to transport to the plants.

The brine stock process begins with brining the cucumbers through the addition of salt or a sodium chloride brining solution. The cucumbers undergo a fermentation process in which lactic acid is formed. During fermentation, the cucumbers are held in 5 to 8 percent salt; after fermentation, the salt content is increased weekly in 0.25 to 0.5 percent increments until the final holding strength is 8 to 16 percent salt. The cucumbers, called brine stock, are then graded and cut (optional), before being desalted by washing in an open tank with water at ambient temperature to obtain the desired salt level and processed into dill, sour, sweet, or other pickle products. Containers are filled with the cut or whole pickles, and sugar and vinegars are added. Preservatives are also added if the product is not pasteurized. The containers are then vacuum sealed and pasteurized (optional) until the temperature at the center of the cucumbers reaches about 74°C (165°F) for about 15 minutes. The product is then cooled, and the containers are labeled, packaged, and stored.

The fresh pack process begins with grading of the pickling cucumbers, followed by washing with water. The cucumbers are then either cut and inspected before packaging, or are sometimes "blanched" if they are to be packaged whole. The "blanching" consists of rinsing the cucumber with

warm water to make it more pliable and easier to pack in the container. It is not a true blanching process. Containers are filled with the cut or whole cucumbers, and then salt, spices, and vinegars are added. The containers are then vacuum sealed and heated (pasteurized) until the temperature at the center of the cucumbers reaches about 74°C (165°F) for about 15 minutes. The product is then cooled, and the containers are labeled, packaged, and stored.

The refrigerated process begins with grading of the pickling cucumbers, followed by washing with water. The washed cucumbers are packed into containers, and then salt, spices, vinegars, and preservatives (primarily sodium benzoate) are added. The containers are then vacuum sealed, labeled, and refrigerated at 34° to 40°F. In this process, the cucumbers are not heat-processed before or after packing.

In the sauerkraut process the cabbage is harvested, transported to the processing plant, washed, and prepared for the fermentation by coring, trimming, and shredding. The shredded cabbage is conveyed to a fermentation tank where salt is added up to a final concentration of 2 to 3 percent (preferably 2.25 percent), by weight. After salt addition, the mixture is allowed to ferment at ambient temperature in a closed tank. If insufficient salt is added or air is allowed to contact the surface of the cabbage, yeast and mold will grow on the surface and result in a softening of the final sauerkraut product. When fermentation is complete, the sauerkraut contains 1.7 to 2.3 percent acid, as lactic acid. Following fermentation, the sauerkraut is packaged in cans, plastic bags, or glass containers; cans are the most prevalent method. In the canning process, the sauerkraut, containing the original or diluted fermentation liquor, is heated to 85° to 88°C (185° to 190°F) by steam injection in a thermal screw and then packed into cans. The cans are steam exhausted, sealed, and cooled. After cooling, the cans are labeled, packed, and stored for shipment. In the plastic bag process, the sauerkraut, containing the fermentation liquor, is placed in plastic bags and chemical additives (benzoic acid, sorbic acid, and sodium bisulfite) introduced as preservatives. The bags are sealed and refrigerated. Small quantities, approximately 10 percent of the production, are packaged in glass containers, which may be preserved by heating or using chemical additives.

Sauces —

A typical sauce production operation involves the mixture of several ingredients, often including salts, vinegars, sugar, vegetables, and various spices. The mixture is allowed to ferment for a period of time, sealed in containers, and pasteurized to prevent further fermentation. The production processes for Worcestershire sauce and hot pepper sauces are briefly described as examples of sauce production.

The name "Worcestershire Sauce" is now a generic term for a type of food condiment that originated in India. In the preparation of the true sauce, a mixture of vinegar, molasses, sugar, soy, anchovies, tamarinds, eschalots, garlic, onions, and salt is prepared and well mixed. Spices, flavorings, and water are added and the mixture transferred to an aging tank, sealed, and allowed to mature and ferment over a period of time. The fermenting mixture is occasionally agitated to ensure proper blending. After fermentation is complete, the mixture is processed by filtration through a mesh screen which allows the finer particles of the mixture to remain in the liquid. The product is then pasteurized prior to bottling to prevent further fermentation. Following bottling, the product is cooled, labeled, and packaged.

Hot sauce or pepper sauce is a generic name given to a large array of bottled condiments produced by several manufacturers in the U. S. The hot peppers, usually varieties of *Capsicum annum* and *Capsicum frutescens*, give the products their heat and characteristic flavor; vinegar is the usual liquid medium. Manufacturing processes vary by producer; however, in most, the harvested

hot peppers are washed and either ground for immediate use or stored whole in brine for several months until processed. In processing, the whole peppers are ground, salt and vinegar added, and the mixture passed through a filter to remove seeds and skin. The end-product, a stable suspension of the pulp from the pepper, vinegar, and salt, is then bottled, labeled, and stored for shipment.

Salad Dressings —

Salad dressings (except products modified in calories, fat, or cholesterol) are typically made up of oil, vinegar, spices, and other food ingredients to develop the desired taste. These dressings are added to many types of foods to enhance flavor. There are U. S. FDA Standards of Identity for three general classifications of salad dressings: mayonnaise, spoonable (semisolid) salad dressing, and French dressing. All other dressings are nonstandardized and are typically referred to as "pourable".

Mayonnaise is a semisolid emulsion of edible vegetable oil, egg yolk or whole egg, acidifying ingredients (vinegar, lemon or lime juice), seasonings (e. g., salt, sweeteners, mustard, paprika), citric acid, malic acid, crystallization inhibitors, and sequestrants to preserve color and flavor. Mayonnaise is an oil-in-water type emulsion where egg is the emulsifying agent and vinegar and salt are the principal bacteriological preservatives. The production process begins with mixing water, egg, and dry ingredients and slowly adding oil while agitating the mixture. Vinegar is then added to the mixture and, after mixing is complete, containers are filled, capped, labeled, and stored or shipped. Improved texture and uniformity of the final product is achieved through the use of colloidalizing or homogenizing machines.

Salad dressing is a spoonable (semisolid) combination of oil, cooked starch paste base, and other ingredients. During salad dressing production, the starch paste base is prepared by mixing starch (e. g., food starch, tapioca, wheat or rye flours) with water and vinegar. Optional ingredients include salt, nutritive carbohydrate sweeteners (e. g., sugar, dextrose, corn syrup, honey), any spice (except saffron and tumeric) or natural flavoring, monosodium glutamate, stabilizers and thickeners, citric and/or malic acid, sequestrants, and crystallization inhibitors. To prepare the salad dressing, a portion of the starch paste and other optional ingredients, except the oil, are blended and then the oil is slowly added to form a "preemulsion". When one-half of the oil is incorporated, the remainder of the starch paste is added at the same rate as the oil. After all of the starch paste and oil have been added, the mixture continues to blend until the ingredients are thoroughly mixed and then the mixture is milled to a uniform consistency. The salad dressing is placed into containers that are subsequently capped, labeled, and stored or shipped.

Liquid dressings, except French dressing, do not have a FDA Standard of Identity. They are pourable products that contain vegetable oil as a basic ingredient. Dressings may also contain catsup, tomato paste, vinegars, cheese, sherry, spices, and other natural ingredients. Liquid dressings are packaged either as separable products with distinct proportions of oil and aqueous phases or as homogenized dressings that are produced by the addition of stabilizers and emulsifiers. The homogenized dressings are then passed through a homogenizer or colloidalizing machine prior to bottling.

9.8.3.3 Emissions And Controls⁴

No source tests have been performed to quantify emissions resulting from the production of pickles, sauerkraut, sauces, or salad dressings. For most of these industries, processes are conducted in closed tanks or other vessels and would not be expected to produce significant emissions. For some products, in certain instances, the potential exists for emissions of particulate matter (PM) or odor (VOC).

Emissions of PM potentially could result from solids handling, solids size reduction, and cooking. If raw vegetables are transported directly from the field, the unloading of these vegetables could result in emissions of dust or vegetative matter. For those products that involve cooking or evaporative condensation in open vessels, PM emissions may be produced by condensation of vapors and may be in the low-micrometer or submicrometer particle-size range.

The VOC emissions are most usually associated with thermal processing steps (e. g., cooking or evaporative condensation) or other processing steps performed in open vessels. Thermal processing steps conducted in closed vessels generally do not result in VOC emissions. Gaseous compounds emitted from those steps conducted in open vessels may contain malodorous VOC.

Because no emission data are available that quantify any VOC, HAP, or PM emissions from any of these industries, emission factors cannot be developed.

A number of VOC and particulate emission control techniques are potentially available to these industries. These include the traditional approaches of wet scrubbers, dry sorbants, and cyclones. No information is available on controls actually used in these industries. The controls discussed in this section are ones that theoretically could be used. The applicability of controls and the specific type of control device or combination of devices would vary from facility to facility depending upon the particular nature of the emissions and the pollutant concentration in the gas stream.

For general industrial processes, control of VOC from a gas stream can be accomplished using one of several techniques but the most common methods are absorption, adsorption, and afterburners. Absorptive methods encompass all types of wet scrubbers using aqueous solutions to absorb the VOC. The most common scrubber systems are packed columns or beds, plate columns, spray towers, or other types of towers. Adsorptive methods could include one of four main adsorbents: activated carbon, activated alumina, silica gel, or molecular sieves; activated carbon is the most widely used for VOC control. Afterburners may be either thermal incinerators or catalytic combustors.

Particulate control commonly employs methods such as venturi scrubbers, dry cyclones, wet or dry electrostatic precipitators (ESPs), or dry filter systems. The most common controls are likely to be the venturi scrubbers or dry cyclones. Wet or dry ESPs could be used depending upon the particulate loading of the gas stream.

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1. 1987 Census of Manufacturers, MC87-1-20-C, Industries Series, Preserved Fruits And Vegetables.
2. G. Fuller and G. G. Dull, "Processing Of Horticultural Crops In The United States", in *Handbook Of Processing And Utilization In Agriculture*, CRC Press, Inc., Boca Raton, FL, 1983.
3. N.W. Desrosier, *Elements Of Food Technology*, AVI Publishing Company, Westport, CT, 1977.
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9.9.1 Grain Elevators And Processes

[Work In Progress]

The recommended interim AP-42 Section on Grain Elevators And Processes is available either through the Technology Transfer Network Bulletin Board System (TTN BBS) of EPA's Office Of Air Quality Planning And Standards or from the Emission Factor And Inventory Group's *Fax CHIEF* service.

The BBS can be accessed with a computer and modem at (919) 541-5407. The interim Section is found on the BBS in the "Q&A's/Policies/Recommendations" area under the "AP-42/EF Guidance" area of the "Clearinghouse For Emission Inventories And Factors" technical area.

The interim Section can be obtained also from the *Fax CHIEF* service by calling (919) 541-0548 or -5626 from the telephone handset of a facsimile machine and following the directions provided to request a document.

For assistance with either of these procedures, call the *Info CHIEF* help desk, (919) 541-5285, between 9:00 am and 4:00 pm Eastern time, Tuesday through Friday.

The interim emission factors for Grain Elevators And Processes are subject to change pending completion of emission source testing being conducted in early 1996.

9.9.2 Cereal Breakfast Food

9.9.2.1 General¹

Breakfast cereal products were originally sold as milled grains of wheat and oats that required further cooking in the home prior to consumption. In this century, due to efforts to reduce the amount of in-home preparation time, breakfast cereal technology has evolved from the simple procedure of milling grains for cereal products that require cooking to the manufacturing of highly sophisticated ready-to-eat products that are convenient and quickly prepared.

9.9.2.2 Process Description¹⁻³

Breakfast cereals can be categorized into traditional (hot) cereals that require further cooking or heating before consumption and ready-to-eat (cold) cereals that can be consumed from the box or with the addition of milk. The process descriptions in this section were adapted primarily from reference 3 and represent generic processing steps. Actual processes may vary considerably between plants, even those manufacturing the same type of cereal.

Traditional Cereals –

Traditional cereals are those requiring cooking or heating prior to consumption and are made from oats, farina (wheat), rice, and corn. Almost all (99 percent) of the traditional cereal market are products produced from oats (over 81 percent) and farina (approximately 18 percent). Cereals made from rice, corn (excluding corn grits), and wheat (other than farina) make up less than 1 percent of traditional cereals.

Oat cereals. The three types of oat cereals are old-fashioned oatmeal, quick oatmeal, and instant oatmeal. Old-fashioned oatmeal is made of rolled oat groats (dehulled oat kernels) and is prepared by adding water and boiling for up to 30 minutes. Quick oat cereal consists of thinner flakes made by rolling cut groats and is prepared by cooking for 1 to 15 minutes. Instant oatmeal is similar to quick oats but with additional treatments, such as the incorporation of gum to improve hydration; hot water is added but no other cooking is required. The major steps in the production of traditional oat cereal include grain receiving, cleaning, drying, hulling, groat processing, steaming, and flaking. Figure 9.9.2-1 is a generic process flow diagram for traditional oat cereal production.

Oats arrive at the mill via bulk railcar or truck and are sampled to ensure suitable quality for milling. Once the grain is deemed acceptable, it is passed over a receiving separator to remove coarse and fine material and binned according to milling criteria. Raw grain handling and processing is discussed in AP-42 Section 9.9.1, Grain Elevators and Processes.

Cleaning removes foreign material, such as dust, stems, and weed seeds, and oats that are unsuitable for milling. The cleaning process utilizes several devices to take advantage of particular physical properties of the grain. For example, screens utilize the overall size of the grain, aspirators and gravity tables utilize grain density, and discs with indent pockets and/or indent cylinders utilize the grain length or shape. After completing the cleaning process, the grain is called clean milling oats or green oats.

In the hulling process, most facilities use the impact huller, which separates the hull from the groat by impact, rather than traditional stone hulling. The groat is the portion of the oat that remains

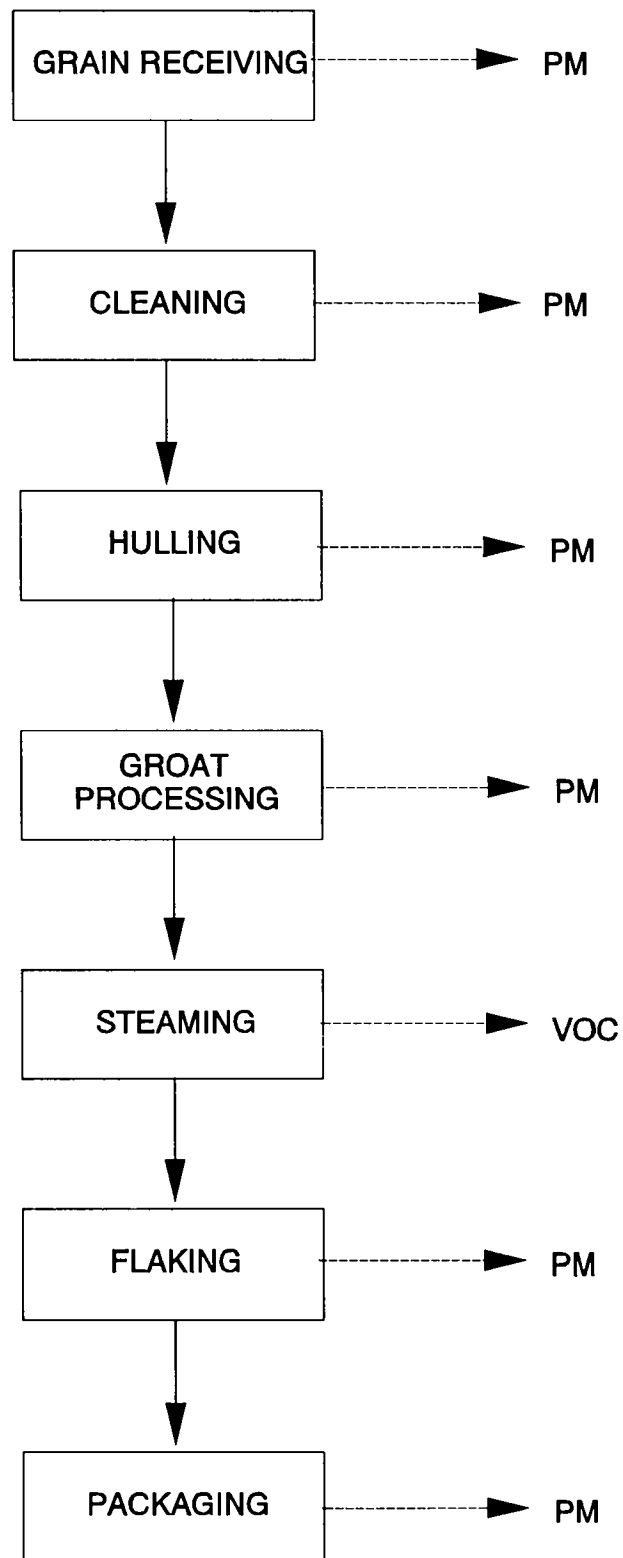


Figure 9.9.2-1. Traditional oat cereal production.

after the hull has been removed and is the part processed for human consumption. In impact hulling, the oats are fed through a rotating disc and flung out to strike the wall of the cylindrical housing tangentially, which separates the hull from the groat. The mixed material then falls to the bottom of the huller and is subjected to aspiration to separate the hulls from the groats. Impact hulling does not require predrying of the oats, although some facilities still use the traditional dry-pan process to impart a more nutty and less raw or green flavor to the final product. In the traditional dry-pan process, the green oats are dried in a stack of circular pans heated indirectly by steam to a surface temperature of 93° to 100°C (200° to 212°F). However, most facilities utilize enclosed vertical or horizontal grain conditioners or kilns to dry the groat after it has been separated from the hull because of the inefficiency of drying hulls. The grain conditioners have both direct (sparging) steam and indirect steam to heat the oats and impart flavor to the groats comparable to that resulting from the pan drying process.

After the groats are hulled, they are sized to separate the largest groats from the average-sized groats. The large groats are used to make the so-called old-fashioned oats and the other groats are cut using steel cutters to make quick oats. After groat processing, the groats (either whole or cut pieces, depending on the end product) typically pass through an atmospheric steamer located above the rollers. The groats must remain in contact with the live steam long enough to achieve a moisture content increase from 8 to 10 percent up to 10 to 12 percent, which is sufficient to provide satisfactory flakes when the whole or steel-cut groats are rolled.

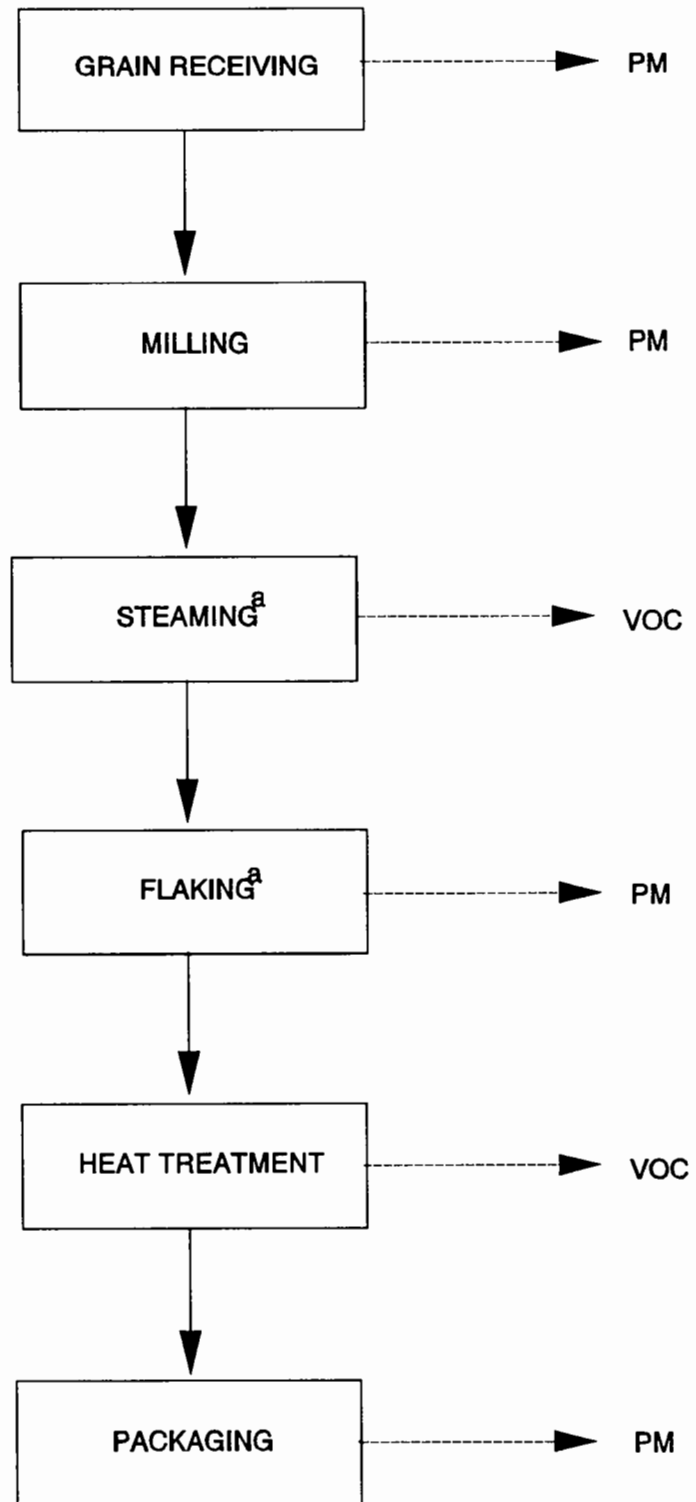
The production of old-fashioned oat and quick oat flakes is the same, except for the starting material (old-fashioned oats start with whole groats and quick oats start with steel-cut groats). Both products are rolled between two cast iron equal-speed rolls in rigid end frames. Quick-oat products are rolled thinner than old-fashioned oats. Following rolling, the flakes are typically cooled and directed to packaging bins for holding.

Instant oatmeal is processed similarly to quick oatmeal through the steaming stage. After the groats are steamed, they are rolled thinner than those of quick oatmeal. The final product, along with specific amounts of hydrocolloid gum, salt, and other additives, is packaged into premeasured individual servings. The most important difference between instant oatmeal and other oatmeal products is the addition of hydrocolloid gum, which replaces the natural oat gums that would be leached from the flakes during traditional cooking, thus accelerating hydration of the flakes.

The standard package for old-fashioned and quick oatmeal is the spirally wound two-ply fiber tube with a paper label. Folded cartons are also used to package old-fashioned and quick oatmeal. Most of the instant hot cereals are packed in individual, single-serving pouches.

Farina cereals. Cereals made from farina are the second largest segment of the traditional hot cereal market, making up 18 percent. Farina is essentially wheat endosperm in granular form that is free from bran and germ. The preferred wheat for producing farina is hard red or winter wheat because the granules of endosperm for these types of wheat stay intact when hot cereals are prepared at home. As shown in Figure 9.9.2-2, farina cereal production begins with the receiving and milling of wheat. Information on wheat receiving, handling, and milling can be found in AP-42 Section 9.9.1, Grain Elevators and Processes. After milling, traditional farina cereals are packaged. Quick cook farina cereals are prepared primarily by the addition of disodium phosphate, with or without the further addition of a proteolytic enzyme. An instant (cook-in-the-bowl) product may be made by wetting and pressure-cooking the farina, then flaking and redrying prior to portion packaging.

Wheat, rice, and corn cereals. Other traditional cereals include whole wheat cereals, rice products, and corn products. These cereals make up less than 1 percent of the traditional cereal



^aNot required for traditional or quick-cooking farina cereals.

Figure 9.9.2-2. Typical instant cook farina cereal production.

market. Whole wheat traditional cereals include milled, rolled, and cracked wheat products. Milled cereals are made in a hard wheat flour mill by drawing off medium-grind milled streams. Rice products have yet to find acceptance as a hot cereal, although rice can be ground into particles about the size of farina and cooked into a hot cereal resembling farina. Corn products include corn grits, cornmeal, corn flour, and corn bran. Corn grits are served primarily as a vegetable accompaniment to the main breakfast item and are not usually classified as a breakfast cereal although they can be consumed as such. Cornmeal, corn flour, and corn bran are used primarily as ingredients in the preparation of other foods and are not classified as breakfast cereals.

Ready-To-Eat Cereals –

In the United States, the word "cereal" is typically synonymous with a processed product that is suitable for human consumption with or without further cooking at home and is usually eaten at breakfast. Ready-to-eat cereals are typically grouped by cereal form rather than the type of grain used. These groups are flaked cereals, extruded flaked cereals, gun-puffed whole grains, extruded gun-puffed cereals, oven-puffed cereals, shredded whole grains, extruded shredded cereals, and granola cereals.

Flaked cereals. Flaked cereals are made directly from whole grain kernels or parts of kernels of corn, wheat, or rice and are processed in such a way as to obtain particles, called flaking grits, that form one flake each. The production of flaked cereals involves preprocessing, mixing, cooking, delumping, drying, cooling and tempering, flaking, toasting, and packaging. A general process flow diagram for cereal flake production is presented in Figure 9.9.2-3. Grain preparation, including receiving, handling, cleaning, and hulling, for flaked cereal production is similar to that discussed under traditional cereal production and in AP-42 Section 9.9.1, Grain Elevators and Processes. Before the grains can be cooked and made into flakes, they must undergo certain preprocessing steps. For corn, this entails dry milling regular field corn to remove the germ and the bran from the kernel, leaving chunks of endosperm. Wheat is preprocessed by steaming the kernels lightly and running them through a pair of rolls to break open the kernels. Care is taken not to produce flour or fine material. Rice does not require any special preprocessing steps for the production of rice flakes other than those steps involved in milling rough rice to form the polished head rice that is the normal starting material.

The corn, wheat, or rice grits are mixed with a flavor solution that includes sugar, malt, salt, and water. Weighed amounts of raw grits and flavor solution are then charged into rotating batch cookers. After the grits are evenly coated with the flavor syrup, steam is released into the rotating cooker to begin the cooking process. The cooking is complete when each kernel or kernel part has been changed from a hard, chalky white to a soft, translucent, golden brown. When the cooking is complete, rotation stops, the steam is turned off, and vents located on the cooker are opened to reduce the pressure inside the cooker to ambient conditions and to cool its contents. The exhaust from these vents may be connected to a vacuum system for more rapid cooling. After pressure is relieved, the cooker is uncapped and the rotation restarted. The cooked grits are then dumped onto moving conveyor belts located under the cooker discharge. The conveyors then pass through delumping equipment to break and size the loosely held-together grits into mostly single grit particles. Large volumes of air are typically drawn through the delumping equipment to help cool the product. It may be necessary to perform delumping and cooling in different steps to get proper separation of the grits so that they are the optimum size for drying; in this case, cooling is typically performed first to stop the cooking action and to eliminate stickiness from the grit surface. After cooking and delumping, the grits are metered in a uniform flow to the dryer. Drying is typically performed at temperatures below 121°C (250°F) and under controlled humidity, which prevents case hardening of the grit and greatly decreases the time needed for drying to the desired moisture level. After drying, the grits are cooled to ambient temperature, usually in an unheated section of the dryer. After they are cooled, the grits are tempered by holding them in large accumulating bins to allow the moisture

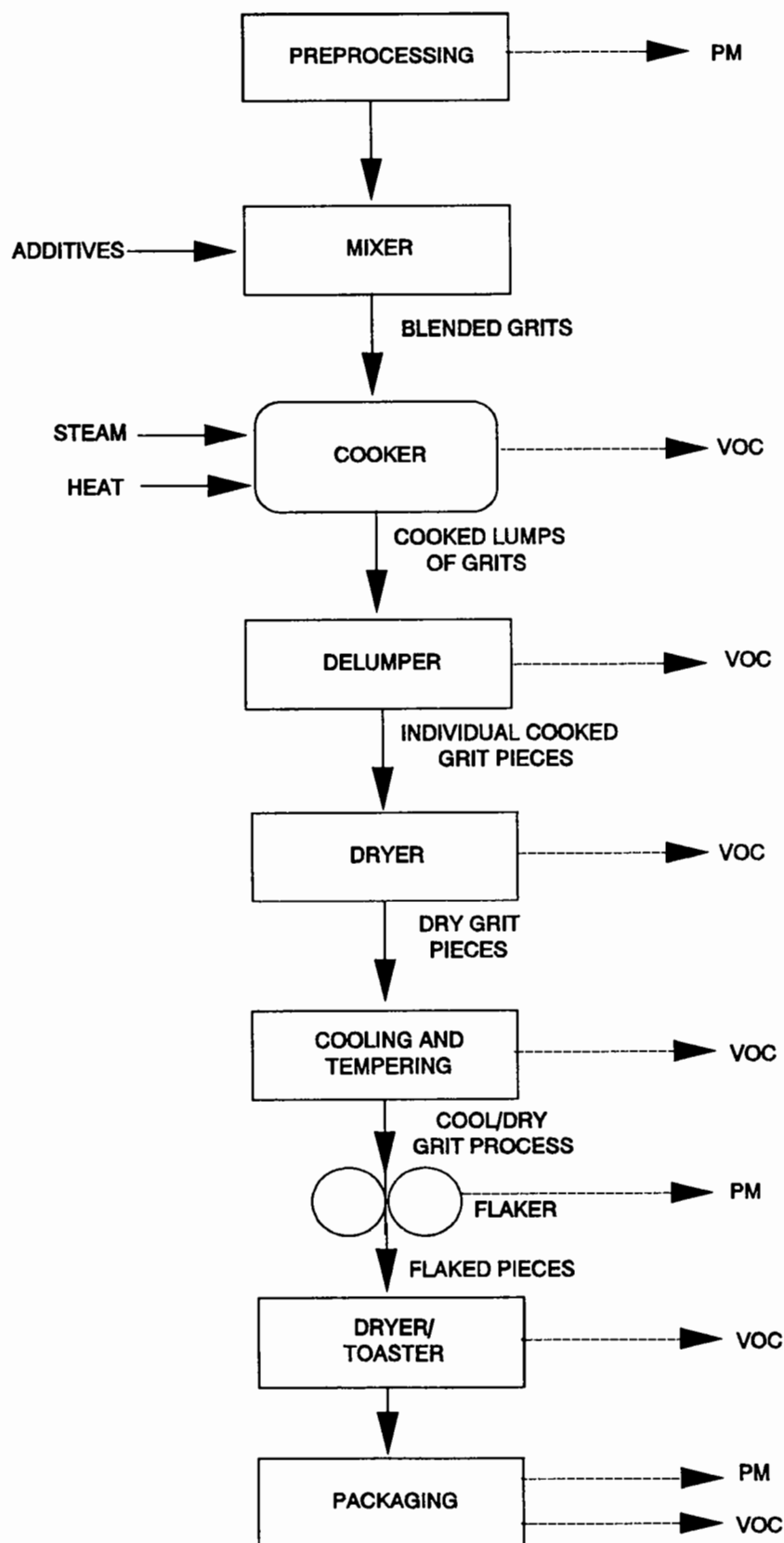


Figure 9.9.2-3. Process diagram for cereal flake production.¹

content to equilibrate between the grit particles as well as from the center of the individual particles to the surface. After tempering, the grits pass between pairs of very large metal rolls that press them into very thin flakes. Flakes are toasted by suspending them in a hot air stream, rather than by laying them onto a flat baking surface. The ovens, sloped from feed end to discharge end, are perforated on the inside to allow air flow. These perforations are as large as possible for good air flow but small enough so that flakes cannot catch in them. The toasted flakes are then cooled and sent to packaging.

Extruded flake cereals. Extruded flakes differ from traditional flakes in that the grit for flaking is formed by extruding mixed ingredients through a die and cutting pellets of the dough into the desired size. The steps in extruded flake production are preprocessing, mixing, extruding, drying, cooling and tempering, flaking, toasting, and packaging. Figure 9.9.2-4 presents a generic process flow diagram for the production of extruded flake cereals. The primary difference between extruded flake production and traditional flake production is that extruded flakes replace the cooking and delumping steps used in traditional flake production with an extruding step. The extruder is a long, barrel-like apparatus that performs several operations along its length. The first part of the barrel kneads or crushes the grain and mixes the ingredients together. The flavor solution may be added directly to the barrel of the extruder by means of a metering pump. Heat input to the barrel of the extruder near the feed point is kept low to allow the ingredients to mix properly before any cooking or gelatinization starts. Heat is applied to the center section of the extruder barrel to cook the ingredients. The die is located at the end of the last section, which is generally cooler than the rest of the barrel. The dough remains in a compact form as it extrudes through the die and a rotating knife slices it into properly-sized pellets. The remaining steps for extruded flakes (drying, cooling, flaking, toasting, and packaging) are the same as for traditional flake production.

Gun-puffed whole grain cereals. Gun-puffed whole grains are formed by cooking the grains and then subjecting them to a sudden large pressure drop. As steam under pressure in the interior of the grain seeks to equilibrate with the surrounding lower-pressure atmosphere, it forces the grains to expand quickly or "puff." Rice and wheat are the only types of grain used in gun-puffed whole grain production, which involves pretreatment, puffing, screening, drying, and cooling. A general process flow diagram is shown in Figure 9.9.2-5. Wheat requires pretreating to prevent the bran from loosening from the grain in a ragged, haphazard manner, in which some of the bran adheres to the kernels and other parts to be blown partially off the kernels. One form of pretreatment is to add 4 percent, by weight, of a saturated brine solution (26 percent salt) to the wheat. Another form of pretreatment, called pearling, removes part of the bran altogether before puffing. The only pretreatment required for rice is normal milling to produce head rice. Puffing can be performed with manual single-shot guns, automatic single-shot, automatic multiple-shot guns, or continuous guns. In manual single-shot guns, grain is loaded into the opening of the gun and the lid is closed and sealed. As the gun begins to rotate, gas burners heat the sides of the gun body causing the moisture in the grain to convert to steam. When the lid is opened, the sudden change in pressure causes the grain to puff. Automatic single-shot guns operate on the same principle, except that steam is injected directly into the gun body. Multiple-shot guns have several barrels mounted on a slowly rotating wheel so that each barrel passes the load and fire positions at the correct time. The load, steam, and fire process for any one barrel is identical to that of the single-shot gun. After the grain is puffed, it is screened and dried before it is packaged. The final product is very porous and absorbs moisture rapidly and easily so it must be packaged in materials that possess good moisture barrier qualities.

Extruded gun-puffed cereals. Extruded gun-puffed cereals use a meal or flour as the starting ingredient instead of whole grains. The dough cooks in the extruders and is then formed into the desired shape when extruded through a die. The extrusion process for gun-puffed cereals is similar to that for extruded flake production. After the dough is extruded, it is dried and tempered. It then undergoes the same puffing and final processing steps as described for whole grain gun-puffed cereals.

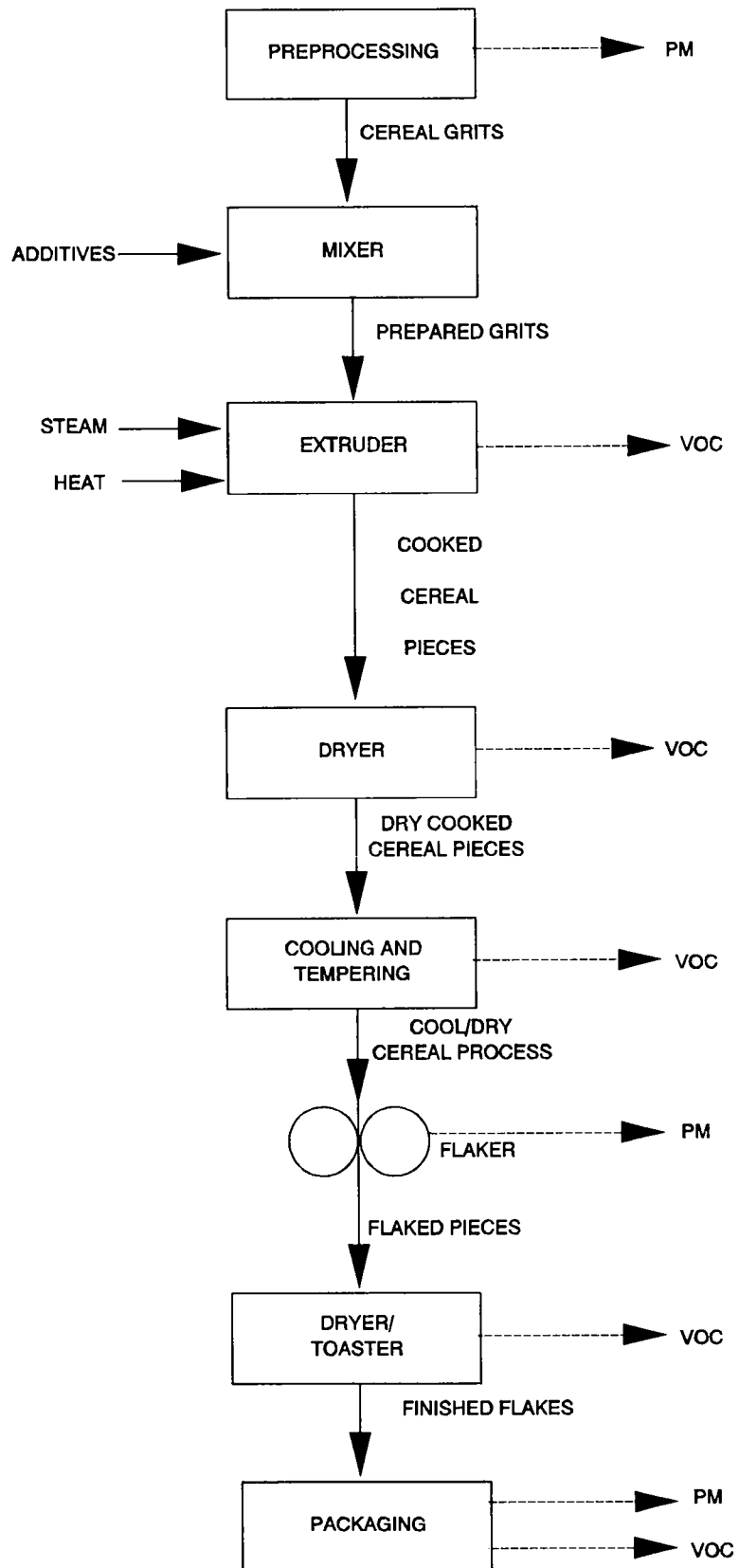


Figure 9.9.2-4. Process diagram for extruded flake production.¹

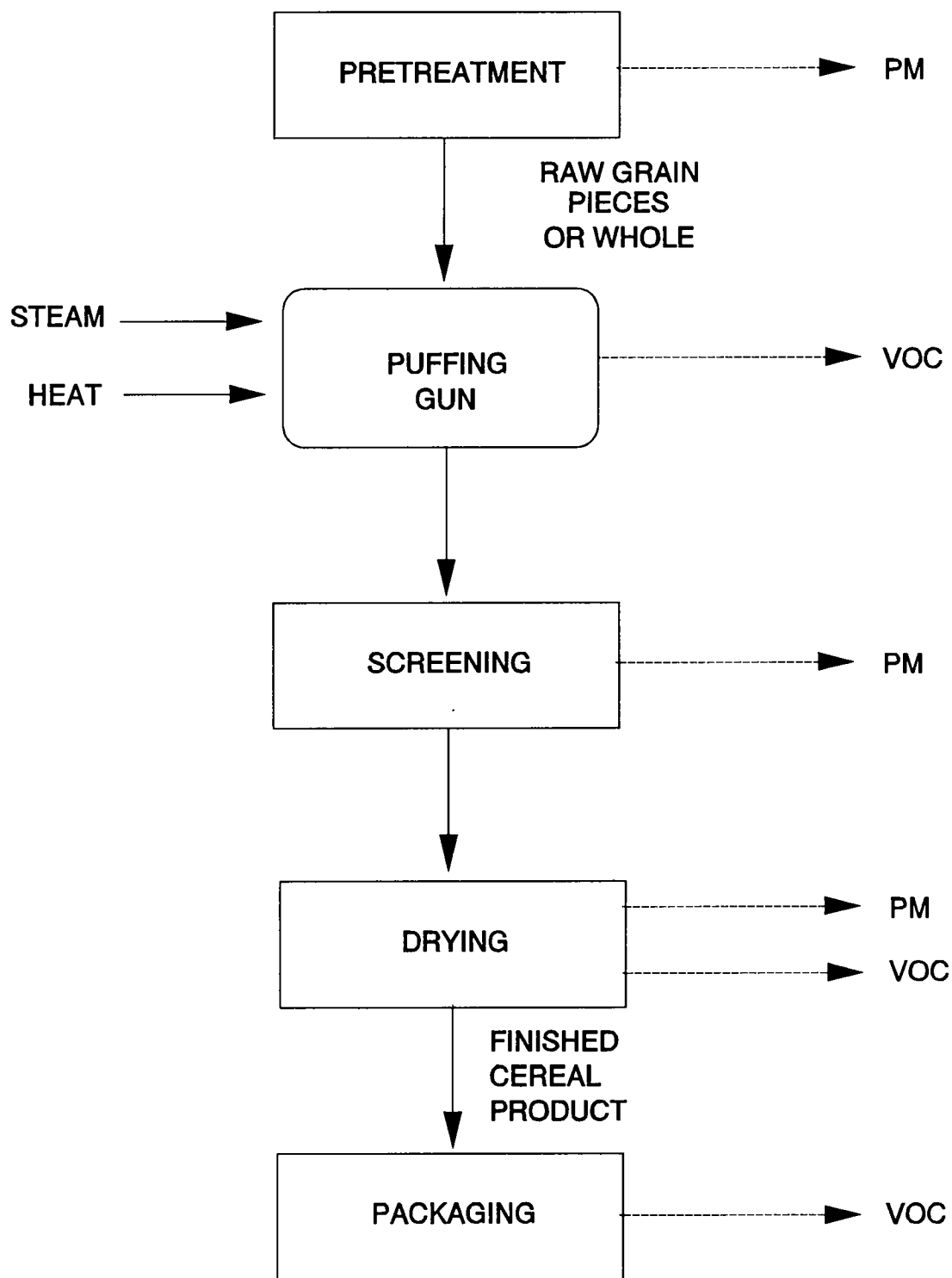


Figure 9.9.2-5. Gun-puffed whole grain production.¹

Oven-puffed cereals. Oven-puffed cereals are made almost exclusively using whole-grain rice or corn, or mixtures of these two grains, because rice and corn inherently puff in the presence of high heat and the proper moisture content. The grains are mixed with sugar, salt, water, and malt and then pressure-cooked. After cooking, the grain is conveyed through a cooling and sizing operation. After cooling and sizing, the kernels are dried and tempered. The kernels are then passed through flaking rolls to flatten them slightly. The kernels are dried again and then oven-puffed, which requires a proper balance between kernel moisture content and oven temperature. After puffing, the cereal is cooled, fortified with vitamins (if necessary), and frequently treated with antioxidants to preserve freshness. The final product is then packaged.

Whole-grain shredded cereals. Wheat (white wheat) is primarily used to produce shredded whole grains. The steps involved in producing whole-grain shredded cereal are grain cleaning, cooking, cooling and tempering, shredding, biscuit formation, biscuit baking, and packaging. A generic process flow diagram for shredded cereal production is presented in Figure 9.9.2-6. Cooking is typically performed in batches with excess water at temperatures slightly below the boiling point at atmospheric pressure. Cooking vessels usually have horizontal baskets big enough to hold 50 bushels of raw wheat. Steam is injected directly into the water to heat the grain. After the cooking cycle is completed, the water is drained from the vessel and the cooked wheat is dumped and conveyed to cooling units, which surface-dry the wheat and reduce the temperature to ambient levels, thus stopping the cooking process. After the grain is cooled, it is placed in large holding bins and allowed to temper. The shredding process squeezes the wheat kernels between one roll with a smooth surface and another roll with a grooved surface. A comb is positioned against the grooved roll and the comb teeth pick the wheat shred from the groove. There are many variations in the grooved roll. After the shreds are produced, they fall in layers onto a conveyer moving under the rolls. After the web of many layers of shreds reaches the end of the shredder, it is fed through a cutting device to form the individual biscuits. The edges of the cutting device are dull, rather than sharp, so that the cutting action compresses the edges of the biscuit together to form a crimped joint, which holds the shreds together in biscuit form. After the individual biscuits are formed, they are baked in a band or continuous conveyor-belt oven. After the biscuits are baked and dried, they are ready for packaging.

Extruded shredded cereals. Extruded shredded cereals are made in much the same way as whole-grain shredded cereals except that extruded shredded cereals use a meal or flour as a raw material instead of whole grains. Raw grains include wheat, corn, rice, and oats, and, because the grains are used in flour form, they can be used alone or in mixtures. The steps involved in extruded shredded cereal production are grain preprocessing (including grain receiving, handling, and milling), mixing, extruding, cooling and tempering, shredding, biscuit formation, baking, drying, and packaging. The preprocessing, mixing, extruding, and cooling and tempering steps are the same as those discussed for other types of cereal. Shredding, biscuit formation, baking, drying, and packaging are the same as for whole-grain shredded cereal. Extruded shredded cereals are typically made into small, bite-size biscuits, instead of the larger biscuits of whole-grain shredded wheat.

Granola cereals. Granola cereals are ready-to-eat cereals that are prepared by taking regular, old-fashioned whole-rolled oats or quick-cooking oats and mixing them with other ingredients, such as nut pieces, coconut, brown sugar, honey, malt extract, dried milk, dried fruits, water, cinnamon, nutmeg, and vegetable oil. This mixture is then spread in a uniform layer onto the band of a continuous dryer or oven. The toasted layer is then broken into chunks.

Packaging –

The package materials for ready-to-eat breakfast cereals include printed paperboard cartons, protective liners, and the necessary adhesives. The cartons are printed and produced by carton suppliers and are delivered, unfolded and stacked on pallets, to the breakfast cereal manufacturers.

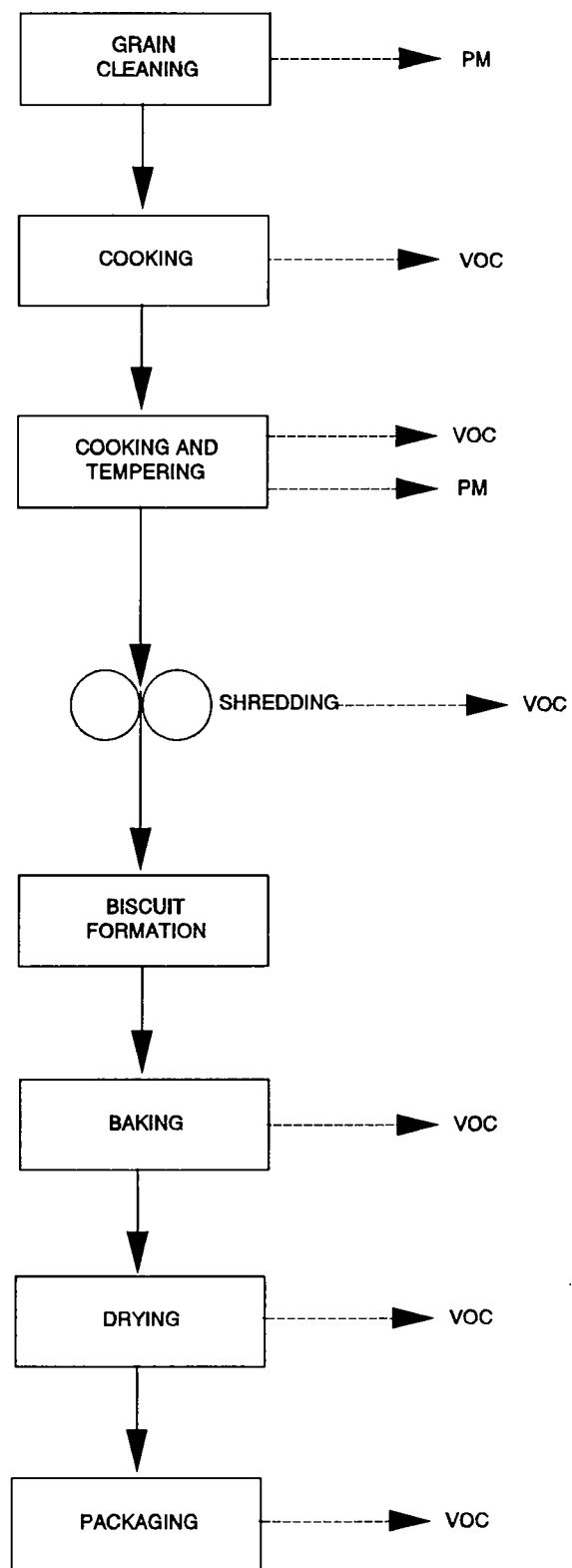


Figure 9.9.2-6. Whole grain shredded cereal production.

The liners, also supplied by outside sources, must be durable and impermeable to moisture or moisture vapor. However, cereals that are not hygroscopic and/or retain satisfactory texture in moisture equilibrium with ambient atmosphere do not require moisture-proof liners. The most common type of liners used today are made of high-density polyethylene (HDPE) film. The adhesives used in cereal packaging are water-based emulsions and hot melts. The cereal industry is the second largest user of adhesives for consumer products. Several variations of packaging lines may be used in the ready-to-eat breakfast cereal industry, including lines that fill the liners either before or after they have been inserted into the carton and lines that utilize more manual labor and less automated equipment.

9.9.2.3 Emissions And Controls

Air emissions may arise from a variety of sources in breakfast cereal manufacturing. Particulate matter (PM) emissions result mainly from solids handling and mixing. For breakfast cereal manufacturing, PM emissions occur during the milling and processing of grain, as the raw ingredients are dumped, weighed, and mixed, as the grains are hulled, and possibly during screening, drying, and packaging. Emission sources associated with grain milling and processing include grain receiving, precleaning and handling, cleaning house separators, milling, and bulk loading. Applicable emission factors for these processes are presented in AP-42 Section 9.9.1, Grain Elevators and Processes. There are no data on PM emissions from mixing of ingredients or packaging for breakfast cereal production.

Volatile organic compound (VOC) emissions may potentially occur at almost any stage in the production of breakfast cereal, but most usually are associated with thermal processing steps, such as drying, steaming, heat treatment, cooking, toasting, extruding, and puffing. Adhesives used during packaging of the final product may also be a source of VOC emissions. No information is available, however, on any VOC emissions resulting from these processes of breakfast cereal manufacturing.

Control technology to control PM emissions from breakfast cereal manufacturing is similar to that discussed in AP-42 Section 9.9.1, Grain Elevators and Processes. Because of the operational similarities, emission control methods are similar in most grain milling and processing plants. Cyclones or fabric filters are often used to control emissions from 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. No information exists for VOC emission control technology for breakfast cereal manufacturing.

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9.9.5 Pasta Manufacturing

9.9.5.1 General¹⁻²

Although pasta products were first introduced in Italy in the 13th century, efficient manufacturing equipment and high-quality ingredients have been available only since the 20th century. Prior to the industrial revolution, most pasta products were made by hand in small shops. Today, most pasta is manufactured by continuous, high capacity extruders, which operate on the auger extrusion principle in which kneading and extrusion are performed in a single operation. The manufacture of pasta includes dry macaroni, noodle, and spaghetti production.

9.9.5.2 Process Description¹⁻²

Pasta products are produced by mixing milled wheat, water, eggs (for egg noodles or egg spaghetti), and sometimes optional ingredients. These ingredients are typically added to a continuous, high capacity auger extruder, which can be equipped with a variety of dies that determine the shape of the pasta. The pasta is then dried and packaged for market.

Raw Materials —

Pasta products contain milled wheat, water, and occasionally eggs and/or optional ingredients. Pasta manufacturers typically use milled durum wheat (semolina, durum granulars, and durum flour) in pasta production, although farina and flour from common wheat are occasionally used. Most pasta manufacturers prefer semolina, which consists of fine particles of uniform size and produces the highest quality pasta product. The water used in pasta production should be pure, free from off-flavors, and suitable for drinking. Also, since pasta is produced below pasteurization temperatures, water should be used of low bacterial count. Eggs (fresh eggs, frozen eggs, dry eggs, egg yolks, or dried egg solids) are added to pasta to make egg noodles or egg spaghetti and to improve the nutritional quality and richness of the pasta. Small amounts of optional ingredients, such as salt, celery, garlic, and bay leaves, may also be added to pasta to enhance flavor. Disodium phosphate may be used to shorten cooking time. Other ingredients, such as gum gluten, glyceryl monostearate, and egg whites, may also be added. All optional ingredients must be clearly labeled on the package.

Wheat Milling —

Durum wheat is milled into semolina, durum granular, or durum flour using roll mills. Semolina milling is unique in that the objective is to prepare granular middlings with a minimum of flour production. Grain milling is discussed in AP-42 Section 9.9.1, Grain Elevators and Processes. After the wheat is milled, it is mixed with water, eggs, and any other optional ingredients.

Mixing —

In the mixing operation, water is added to the milled wheat in a mixing trough to produce dough with a moisture content of approximately 31 percent. Eggs and any optional ingredients may also be added. Most modern pasta presses are equipped with a vacuum chamber to remove air bubbles from the pasta before extruding. If the air is not removed prior to extruding, small bubbles

will form in the pasta which diminish the mechanical strength and give the finished product a white, chalky appearance.

Extruding —

After the dough is mixed, it is transferred to the extruder. The extrusion auger not only forces the dough through the die, but it also kneads the dough into a homogeneous mass, controls the rate of production, and influences the overall quality of the finished product. Although construction and dimension of extrusion augers vary by equipment manufacturers, most modern presses have sharp-edged augers that have a uniform pitch over their entire length. The auger fits into a grooved extrusion barrel, which helps the dough move forward and reduces friction between the auger and the inside of the barrel. Extrusion barrels are equipped with a water cooling jacket to dissipate the heat generated during the extrusion process. The cooling jacket also helps to maintain a constant extrusion temperature, which should be approximately 51°C (124°F). If the dough is too hot (above 74°C [165°F]), the pasta will be damaged.

Uniform flow rate of the dough through the extruder is also important. Variances in the flow rate of the dough through the die cause the pasta to be extruded at different rates. Products of nonuniform size must be discarded or reprocessed, which adds to the unit cost of the product. The inside surface of the die also influences the product appearance. Until recently, most dies were made of bronze, which was relatively soft and required repair or periodic replacement. Recently, dies have been improved by fitting the extruding surface of the die with Teflon® inserts to extend the life of the dies and improve the quality of the pasta.

Drying —

Drying is the most difficult and critical step to control in the pasta production process. The objective of drying is to lower the moisture content of the pasta from approximately 31 percent to 12 to 13 percent so that the finished product will be hard, retain its shape, and store without spoiling. Most pasta drying operations use a preliminary drier immediately after extrusion to prevent the pasta from sticking together. Predrying hardens the outside surface of the pasta while keeping the inside soft and plastic. A final drier is then used to remove most of the moisture from the product.

Drying temperature and relative humidity increments are important factors in drying. Since the outside surface of the pasta dries more rapidly than the inside, moisture gradients develop across the surface to the interior of the pasta. If dried too quickly, the pasta will crack, giving the product a poor appearance and very low mechanical strength. Cracking can occur during the drying process or as long as several weeks after the product has left the drier. If the pasta is dried too slowly, it tends to spoil or become moldy during the drying process. Therefore, it is essential that the drying cycle be tailored to meet the requirements of each type of product. If the drying cycle has been successful, the pasta will be firm but also flexible enough so that it can bend to a considerable degree before breaking.

Packaging —

Packaging keeps the product free from contamination, protects the pasta from damage during shipment and storage, and displays the product favorably. The principal packaging material for noodles is the cellophane bag, which provides moisture-proof protection for the product and is used easily on automatic packaging machines, but is difficult to stack on grocery shelves. Many manufacturers utilize boxes instead of bags to package pasta because boxes are easy to stack, provide good protection for fragile pasta products, and offer the opportunity to print advertising that is easier to read than on bags.

9.9.5.3 Emissions and Controls

Air emissions may arise from a variety of sources in pasta manufacturing. Particulate matter (PM) emissions result mainly from solids handling and mixing. For pasta manufacturing, PM emissions occur during the wheat milling process, as the raw ingredients are mixed, and possibly during packaging. Emission sources associated with wheat milling include grain receiving, precleaning/handling, cleaning house, milling, and bulk loading. Applicable emission factors for these processes are presented in AP-42 Section 9.9.1, Grain Elevators and Processes. There are no data for PM emissions from mixing of ingredients or packaging for pasta production.

Volatile organic compound (VOC) emissions may potentially occur at almost any stage in the production of pasta, but most usually are associated with thermal processing steps, such as pasta extruding or drying. No information is available on any VOC emissions due to the heat generated during pasta extrusion or drying.

Control of PM emissions from pasta manufacturing is similar to that discussed in AP-42 Section 9.9.1, Grain Elevators and Processes. 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, may be applied where the effluent gas stream has a high moisture content.

References for Section 9.9.5

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9.11.1 Vegetable Oil Processing

9.11.1.1 General¹⁻⁵

The industry group producing fats and oils includes cottonseed oil mills, soybean oil mills, vegetable oil mills (other than corn, cottonseed, and soybean), and other mills. Wet corn mills are the primary producers of corn oil. Approximately 137 vegetable oil plants operate in the United States. Soybean processing, which dominates the industry, produces approximately 80 percent of the volume of vegetable oil and is concentrated in the states of Iowa, Illinois, Missouri, Kansas, Indiana, and Minnesota, but also found across the nation. Likewise, wet corn mills are concentrated in Corn Belt states. Cottonseed oil mills are found in southern states and California.

9.11.1.2 Process Description⁶⁻⁹

The following process description discusses only soybean oil manufacture, because emission factors are available only for that activity. Corn, cottonseed, and peanut oil processing are similar to soybean processing, except for differences in the soybean preparation for oil extraction. The process for soybeans typically consists of five steps: oilseed handling/elevator operations, preparation of soybeans for solvent extraction, solvent extraction and oil desolventizing, flake desolventizing, and oil refining.

Oilseed Handling/Elevator Operations -

Figure 9.11.1-1 is a schematic diagram of a typical soybean handling/elevator operation that precedes the preparation of soybeans for the solvent extraction process.

Soybeans received at the facility by truck or rail are sampled and analyzed for moisture content, foreign matter, and damaged seeds. Then the beans are weighed and conveyed to large concrete silos or metal tanks for storage prior to processing. When the facility is ready to process the soybeans, the beans are removed from the silo or tank and cleaned of foreign materials and loose hulls. Screens typically are used to remove foreign materials such as sticks, stems, pods, tramp metal, sand, and dirt. An aspiration system is used to remove loose hulls from the soybeans; these hulls may be combined later with hulls from the dehulling aspiration step. The beans are passed through dryers to reduce their moisture content to approximately 10 to 11 percent by weight and then are conveyed to process bins for temporary storage and tempering for 1 to 5 days in order to facilitate dehulling.

Preparation Of Soybeans For Solvent Extraction -

Figure 9.11.1-2 is a schematic diagram of the process used to prepare soybeans for the solvent extraction process. The process, which is fairly well-standardized, consists of four principal operations: cracking, dehulling/hull removal, conditioning, and flaking.

Soybeans are conveyed from the process bins to the mill by means of belts or mass flow conveyors and bucket elevators. In the mill, the beans may be aspirated again, weighed, cleaned of tramp metal by magnets, and fed into corrugated cracking rolls. The cracking rolls "crack" each bean into four to six particles, which are passed through aspirators to remove the hulls (processed separately after the removal of residual bean chips). These hulls may be combined with the hulls from the grain cleaning step.

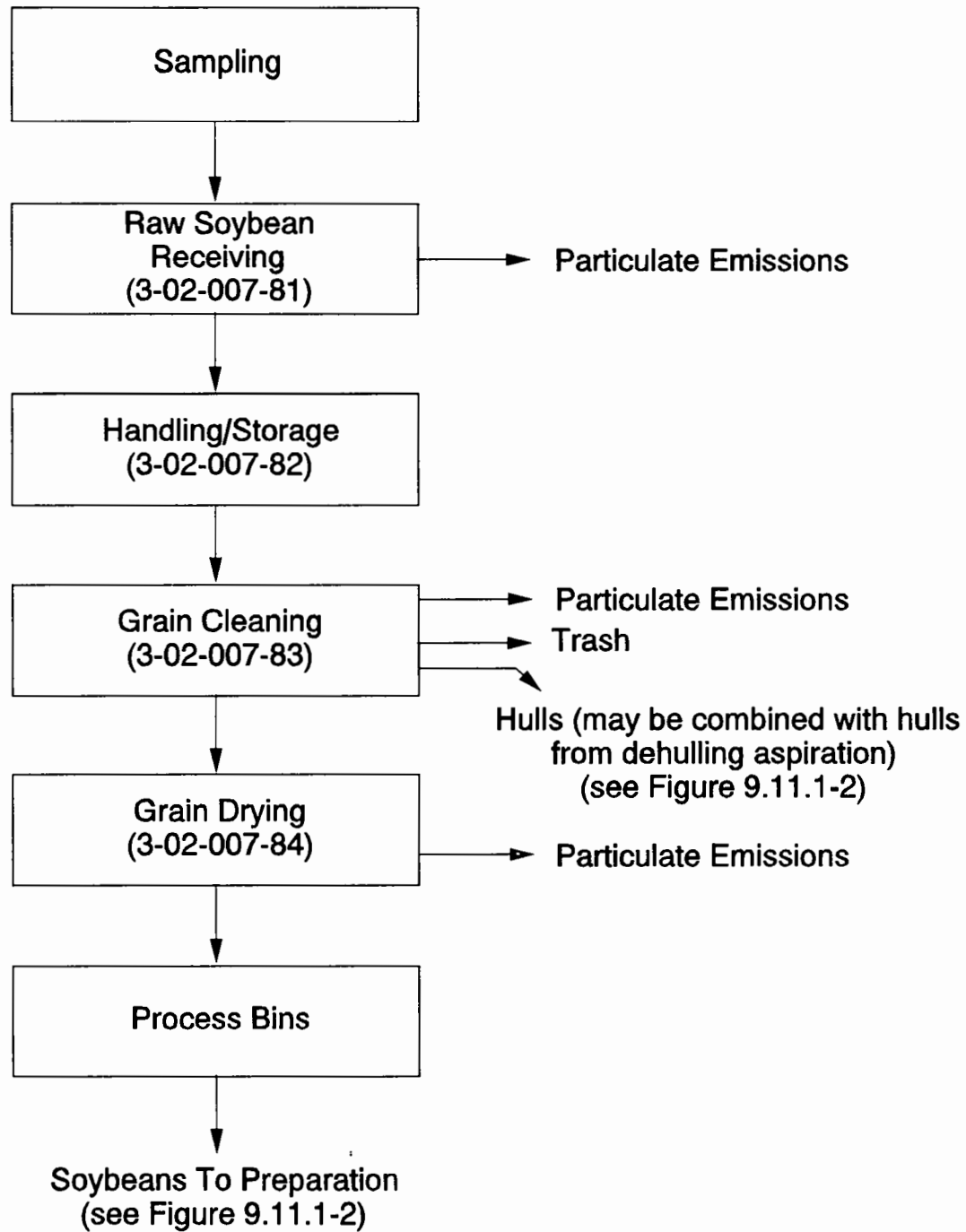


Figure 9.11.1-1. Flow diagram of typical soybean handling/elevator operations.
(Source Classification Codes in parentheses.)

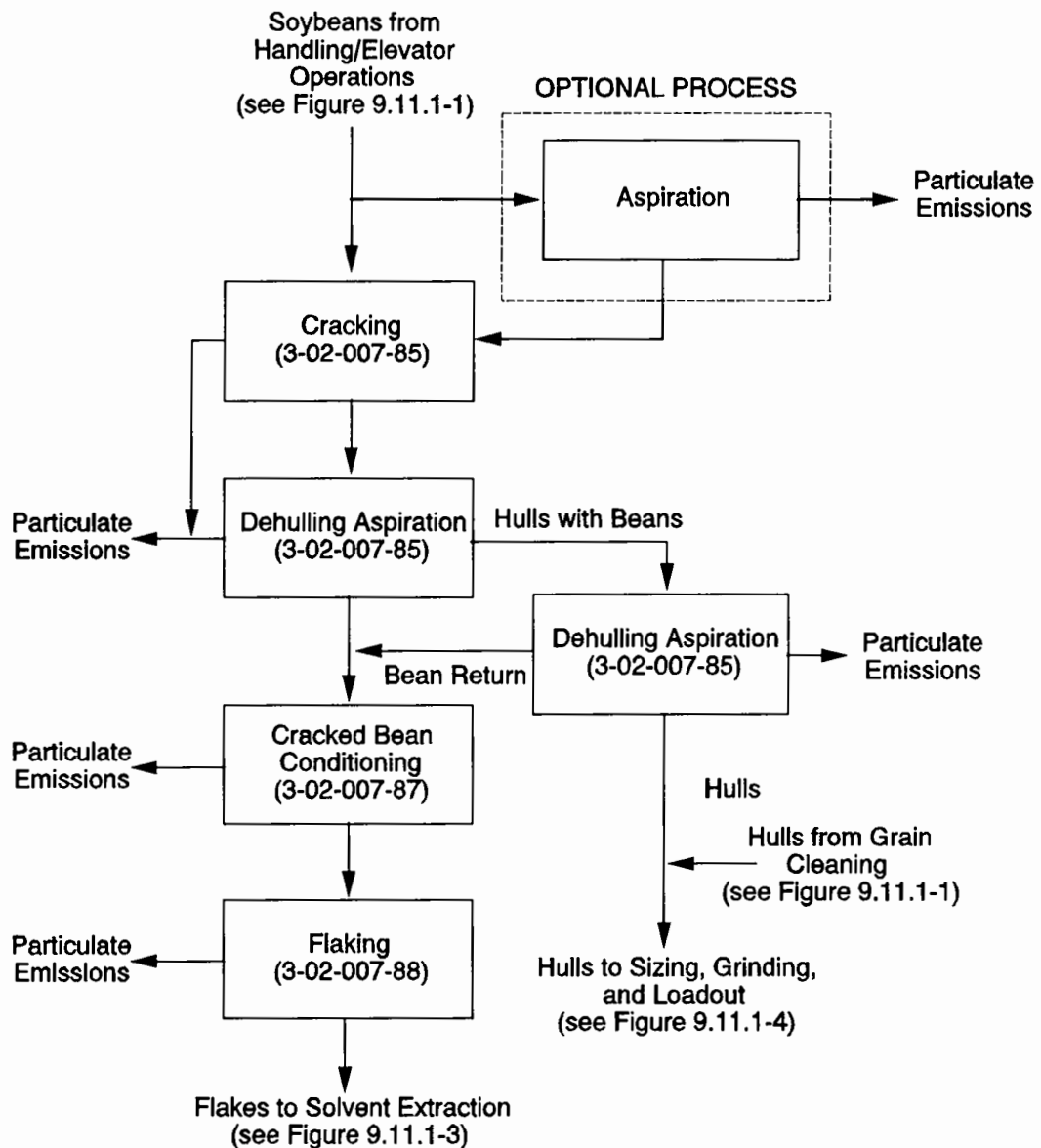


Figure 9.11.1-2. Flow diagram of the typical process for preparing soybeans for solvent extraction.
(Source Classification Codes in parentheses.)

Next, the cracked beans and bean chips are conveyed to the conditioning area, where they are put either into a rotary steam tubed device or into a stacked cooker and are heated to "condition" them (i. e., make them pliable and keep them hydrated). Conditioning is necessary to permit the flaking of the chips and to prevent their being broken into smaller particles. Finally, the heated, cracked beans are conveyed and fed to smooth, cylindrical rolls that press the particles into smooth "flakes", which vary in thickness from approximately 0.25 to 0.51 millimeters (0.010 to 0.020 inches). Flaking allows the soybean oil cells to be exposed and the oil to be more easily extracted.

Solvent Extraction and Oil Desolventizing -

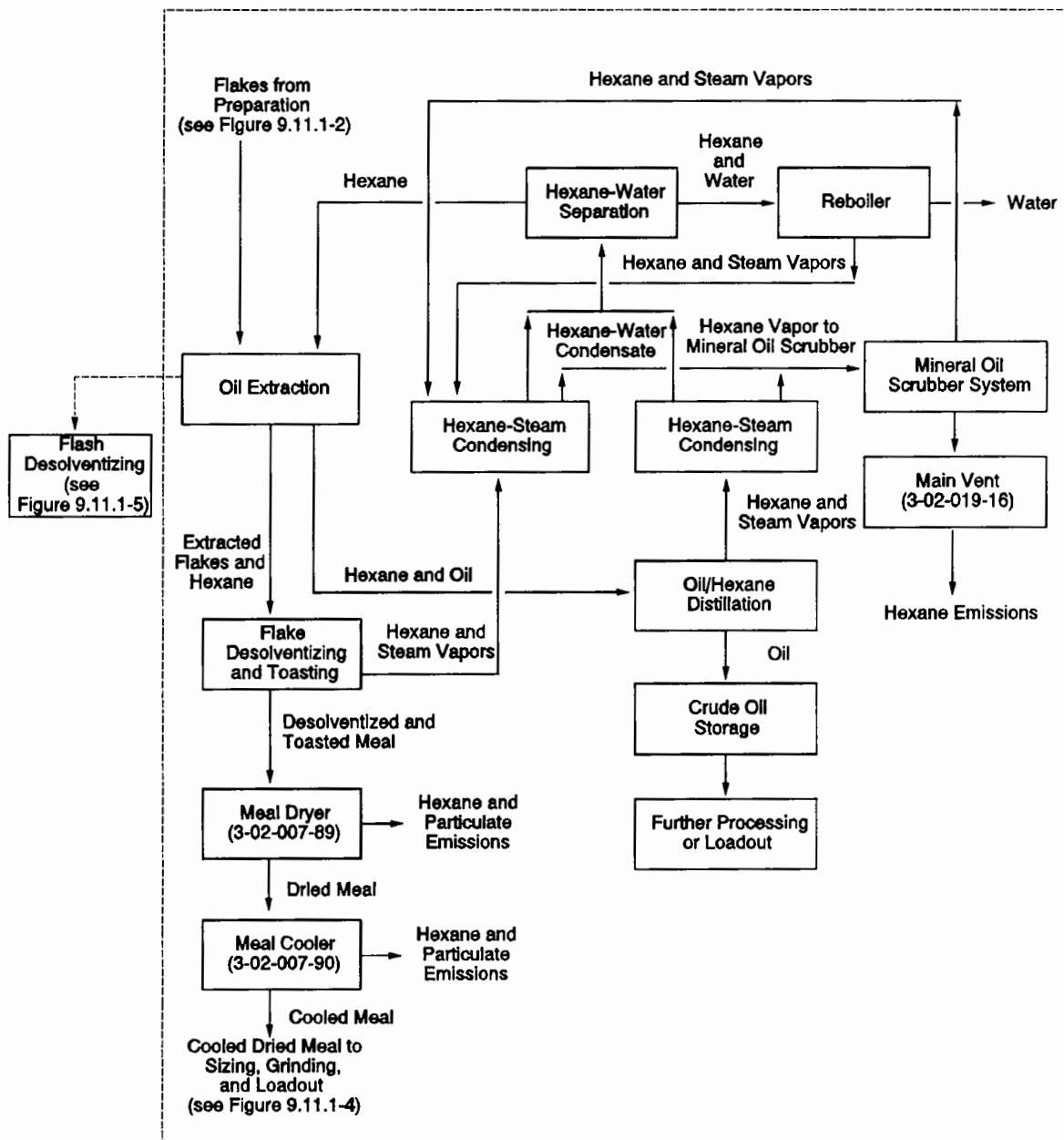
The extraction process consists of "washing" the oil from the soybean flakes with hexane solvent in a countercurrent extractor. Then the solvent is evaporated (i. e., desolventized) from both the solvent/oil mixture (micella) and the solvent-laden, defatted flakes (see Figure 9.11.1-3). The oil is desolventized by exposing the solvent/oil mixture to steam (contact and noncontact). Then the solvent is condensed, separated from the steam condensate, and reused. Residual hexane not condensed is removed with mineral oil scrubbers. The desolventized oil, called "crude" soybean oil, is stored for further processing or loadout.

Desolventizing Flakes -

The flakes leaving the extractor contain up to 35 to 40 percent solvent and must be desolventized before use. Flakes are desolventized in one of two ways: either "conventional" desolventizing or specialty or "flash" desolventizing. The method used depends upon the end use of the flakes. Flakes that are flash desolventized are typically used for human foods, while conventionally desolventized flakes are used primarily in animal feeds.

Conventional desolventizing takes place in a desolventizer-toaster (DT), where both contact and noncontact steam are used to evaporate the hexane. In addition, the contact steam "toasts" the flakes, making them more usable for animal feeds. The desolventized and toasted flakes then pass to a dryer, where excess moisture is removed by heat, and then to a cooler, where ambient air is used to reduce the temperature of the dried flakes. The desolventized, defatted flakes are then ground for use as soybean meal (see Figure 9.11.1-4).

Flash desolventizing is a special process that accounts for less than 5 percent by volume of the annual nationwide soybean crush. The production of flakes for human consumption generally follows the flow diagram in Figure 9.11.1-3 for the "conventional" process, except for the desolventizing step. In this step, the flakes from the oil extraction step are "flash" desolventized in a vacuum with noncontact steam or superheated hexane. This step is followed by a final solvent stripping step using steam. Both the hexane vapor from the flash/vacuum desolventizer and the hexane and steam vapors from the stripper are directed to a condenser. From the condenser, hexane vapors pass to the mineral oil scrubber and the hexane-water condensate goes to the separator, as shown in Figure 9.11.1-3. The flakes produced by the flash process are termed "white flakes". A process flow diagram for the flash desolventizing portion of the soybean process is shown in Figure 9.11.1-5. From the stripper, the white flakes pass through a cooker (an optional step) and a cooler prior to further processing steps similar to the "conventional" process. A plant that uses specialty or "flash" desolventizing requires different equipment and is far less efficient in energy consumption and solvent recovery than a plant that uses conventional desolventizing. Given these facts, solvent emissions are considerably higher for a specialty desolventizing process than for a similar-sized conventional desolventizing process.



Soybean Extraction Facility--Total Hexane Losses
(3-02-019-97)
(3-02-019-98)

Figure 9.11.1-3. Flow diagram of the "conventional" solvent extraction process.
(Source Classification Codes in parentheses.)

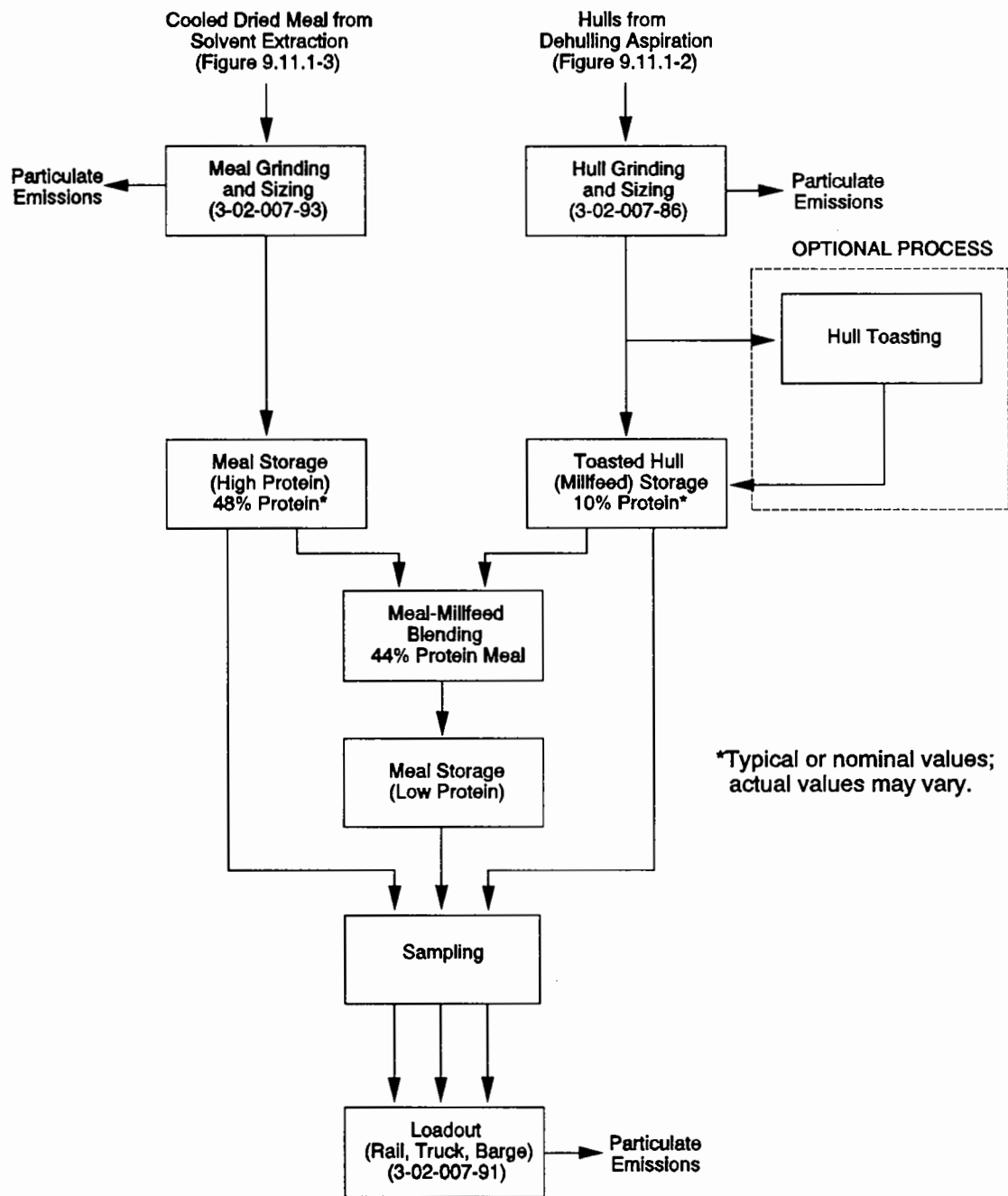


Figure 9.11.1-4. Flow diagram for "conventional" process of dry material sizing, grinding, and loadout.
(Source Classification Codes in parentheses.)

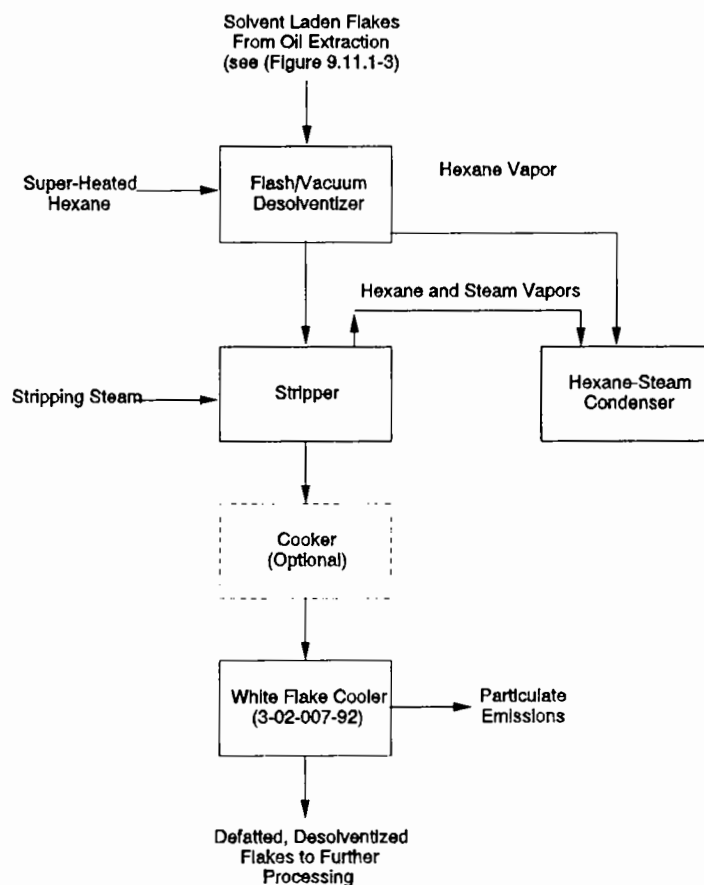


Figure 9.11.1-5. Flow diagram of the flash desolventizing process.
(Source Classification Code in parentheses.)

Vegetable Oil Refining -

Crude oil is typically shipped for refining to establishments engaged in the production of edible vegetable oils, shortening, and margarine. Crude vegetable oils contain small amounts of naturally occurring materials such as proteinaceous material, free fatty acids, and phosphatides. Phosphatides are removed for lecithin recovery or to prepare the crude oil for export. The most common method of refining oil is by reacting it with an alkali solution which neutralizes the free fatty acids and reacts with the phosphatides. These reacted products and the proteinaceous materials are then removed by centrifuge. Following alkali refining, the oil is washed with water to remove residual soap, caused by saponification of small amounts of the triglycerides (oil). Color-producing substances within an oil (i. e., carotenoids, chlorophyll) are removed by a bleaching process, which employs the use of adsorbents such as acid-activated clays. Volatile components are removed by deodorization, which uses steam injection under a high vacuum and temperature. The refined oil is then filtered and stored until used or transported.

9.11.1.3 Emissions And Controls^{6,10-20}

Emissions -

Particulate matter and volatile organic compounds are the principal emissions from vegetable oil processing. Particulate matter (PM) results from the transfer, handling, and processing of raw seed. VOC emissions are the oil extraction solvent, hexane, which is classified as a hazardous air pollutant. Particulate emissions from grain handling are discussed in the Interim AP-42 Section 9.9.1, "Grain Elevators And Processes".

Solvent emissions arise from several sources within vegetable oil processing plants. There are potential solvent emissions from the transfer and storage of hexane on site as well as potential leaks from piping and vents. Small quantities of solvent (up to 0.2 percent by volume of oil) are present in the crude vegetable oil after the solvent is recovered by film evaporators and the distillation stripper. This hexane may volatilize during the oil-refining process; however, no emission data are available. Trace quantities of solvent are present and available for volatilization in waste water collected from the condensation of steam used in the distillation stripper and desolventizer-toaster. Emission data from waste water also are not available.

Vents are another source of emissions. Solvent is discharged from three vents: the main vent from the solvent recovery section, the vent from the meal dryer, and the vent from the meal cooler. The main vent receives gases from the oil extractor, the film evaporator and distillation stripper, and the desolventizer-toaster. Vents for the meal dryer and meal cooler typically vent to atmosphere.

Hexane Emissions -

The recommended method for estimating annual hexane emissions from soybean solvent extraction facilities is to obtain the annual hexane usage from the specific plant's records, and to assume that all hexane make-up is due to losses to the air (SCC 3-02-019-97). (Some hexane leaves the facilities as a small fraction of the oil or meal products, but this amount has not been quantified.) If the hexane usage is determined from purchase records and the purchased amount accounts for any change in quantities stored on-site, then storage tank losses would already be accounted for in the loss estimate. If the usage is determined from the amount metered out of the storage tanks, then the storage tank losses should be calculated separately, and in addition to, the usage losses, using the equations in AP-42 Chapter 7 or in the TANKS software. Careful application of such a material balance approach should produce emission estimates comparable in quality to those derived from a B-rated emission factor.

The mean total hexane loss reported by the plants in References 11 through 19 was 3.3 L/Mg (0.89 gal/ton [4.9 lb/ton]) of raw soybeans processed (SCC 3-02-019-98). This represents an overall total loss factor for soybean oil processing, encompassing all sources of vented and fugitive emissions (and storage tanks), as well as any hexane leaving the facility as part of the oil or meal products. For a new facility or if plant-specific usage data are unavailable, this factor, rated D, can be used as a default value until the relevant data for the facility become available. The default value should be used only until the facility can compile the data needed to develop a plant-specific hexane loss for the period of interest.

Particulate Emissions -

Table 9.11.1-1 presents emission factors for total PM emissions resulting from handling and processing soybeans in vegetable oil manufacturing. Emission factors are provided for PM-generating processes for the meal production process, including meal drying and cooling.

Table 9.11.1-1. TOTAL PARTICULATE EMISSION FACTORS FOR SOYBEAN MILLING^a

EMISSION FACTOR RATING: E

Process	Control Device	Emission Factor (lb/ton) ^b
Receiving ^c (SCC 3-02-007-81)	None	0.15
Handling (SCC 3-02-007-82)	ND	ND
Cleaning (SCC 3-02-007-83)	ND	ND
Drying (SCC 3-02-007-84)	ND	ND
Cracking/dehulling (SCC 3-02-007-85)	Cyclone	0.36
Hull grinding (SCC 3-02-007-86)	Cyclone	0.20
Bean conditioning (SCC 3-02-007-87)	Cyclone	0.010
Flaking rolls (SCC 3-02-007-88)	Cyclone	0.037
White flake cooler (SCC 3-02-007-92)	Cyclone	0.95
Meal cooler (SCC 3-02-007-90)	Cyclone	0.19
Meal dryer (SCC 3-02-007-89)	Cyclone	0.18
Meal grinder/sizing (SCC 3-02-007-93)	Cyclone	0.34
Meal loadout ^d (SCC 3-02-007-91)	None	0.27

^a Emission factors are based on pounds per ton of soybeans processed by the unit. Factors represent controlled emissions, except as noted. Divide the lb/ton factor by two to obtain kg/Mg. SCC = Source Classification Code, ND = No Data.

^b Reference 21. These data were obtained from unpublished emission test data and from industry questionnaires. Because these are secondary data, the test data and the questionnaire results were weighed equally and the emission factors were calculated as arithmetic means of the data. The emission factor rating is a reflection of the source of the data.

^c See Interim AP-42 Section 9.9.1, "Grain Elevators And Processes".

^d Reference 22.

Controls -

Hexane is recovered and reused in the oil-extraction process because of its cost. The steam and hexane exhausts from the solvent extractor, desolventizer-toaster, and oil/hexane stripping are passed through condensers to recover hexane. Residual hexane from the condensers is captured by mineral oil scrubbers. The most efficient recovery or control device is a mineral oil scrubber (MOS), which is approximately 95 percent efficient. The meal dryer and cooler vents are typically exhausted to the atmosphere with only cyclone control to reduce particulate matter. Process controls to reduce breakdowns and leaks can be used effectively to reduce emissions. Quantities of hexane may be lost through storage tanks, leaks, shutdowns, or breakdowns. These losses are included in the material balance.

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2. J. M. Farren, *et al.*, *U. S. Industrial Outlook '92*, U. S. Department Of Commerce, Washington, DC, 1992.
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5. *95-96 Soya Bluebook Plus - Annual Directory Of The World Oilseed Industry*, Soyatech, Inc., Bar Harbor, ME; data supplied by the National Oilseed Processors Association, September 1995.
6. *Control Of Volatile Organic Emissions From Manufacture Of Vegetable Oils*, EPA-450/2-78-035, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1978.
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8. Written communication from D. C. Ailor, Director Of Regulatory Affairs, National Oilseed Processors Association, Washington, DC, to D. Reisdorph, Midwest Research Institute, Kansas City, MO, September 20, 1992.
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10. R. L. Chessin, "Investigating Sources Of Hexane Emissions", *Oil Mill Gazetteer*, 86(2):35-36, 38-39, August 1981.
11. *Vegetable Oil Production (Meal Processing) Emission Test Report, Cargill Incorporated (East Plant), Cedar Rapids, Iowa*, PEDCo Environmental Inc., Cincinnati, OH, June 1979.
12. *Vegetable Oil Production (Meal Processing) Emission Test Report, Cargill Incorporated (West Plant), Cedar Rapids, Iowa*, PEDCo Environmental Inc., Cincinnati, OH, June 1979.
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15. *Vegetable Oil Manufacturing Emission Test Report, Central Soya Inc., Delphos, Ohio*, EMB Report 78-VEG-4, Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, July 1979.

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21. *Emissions Control In The Grain And Feed Industry, Volume I - Engineering And Cost Study*, EPA-450/3-73-003a, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1973.
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9.12.2 Wines And Brandy

9.12.2.1 General

Wine is an alcoholic beverage produced by the fermentation of sugars in fruit juices, primarily grape juice. In general, wines are classified into two types based on alcohol content: table wines (7 percent to 14 percent, by volume) and dessert wines (14 percent to 24 percent, by volume). Table wines are further subdivided into still and sparkling categories, depending upon the carbon dioxide (CO_2) content retained in the bottled wine. Still table wines are divided into three groups: red, rosé (blush), and white, based on the color of the wine.

9.12.2.2 Process Description¹⁻⁴

The production of still table wines is discussed in the following paragraphs, followed by more concise discussions of the production of sweet table wines, sparkling wines, dessert wines, and brandy.

Still Table Wines -

The basic steps in vinification (wine production) include harvesting, crushing, pressing, fermentation, clarification, aging, finishing, and bottling. A simplified process diagram outlining the basic steps in the production of still table wines is shown in Figure 9.12.2-1.

Harvesting of grapes is usually conducted during the cooler periods of the day to prevent or retard heat buildup and flavor deterioration in the grape. Most wineries transport the whole grapes but some crush the grapes in the vineyard and transport the crushed fruit to the winery. Stemming and crushing are commonly conducted as soon as possible after harvest. These two steps are currently done separately using a crusher-stemmer, which contains an outer perforated cylinder to allow the grapes to pass through but prevents the passage of stems, leaves, and stalks. Crushing the grapes after stemming is accomplished by any one of many procedures. The three processes generally favored are: (1) pressing grapes against a perforated wall; (2) passing grapes through a set of rollers; or (3) using centrifugal force. Generally, 25 to 100 milligrams (mg) of liquified sulfur dioxide (SO_2) are added per liter of the crushed grape mass to control oxidation, wild yeast contamination, and spoilage bacteria.

Maceration is the breakdown of grape solids following crushing of the grapes. The major share of the breakdown results from the mechanical crushing but a small share results from enzymatic breakdown. In red and rosé wine production, the slurry of juice, skins, seeds, and pulp is termed the "must". In white wine production, the skins, seeds, and pulp are separated from the juice before inoculation with yeast and only the juice is fermented. A fermenting batch of juice is also called "must". Thus, the term "must" can refer to either the mixture of juice, seeds, skins, and pulp for red or rosé wines or only the juice for white wines. Maceration is always involved in the initial phase of red wine fermentation. The juice from the grapes may be extracted from the "must" in a press. Additionally, gravity flow juicers may be used initially to separate the majority of the juice from the crushed grapes and the press used to extract the juice remaining in the mass of pulp, skins, and seeds (pomace). There are many designs of dejuicers but, generally, they consist of a tank fitted with a perforated basket at the exit end. After gravity dejuicing has occurred, the pomace is placed in a press and the remaining juice extracted. There are three major types of presses. The horizontal press is used for either crushed or uncrushed grapes. A pneumatic press can be used for either crushed or

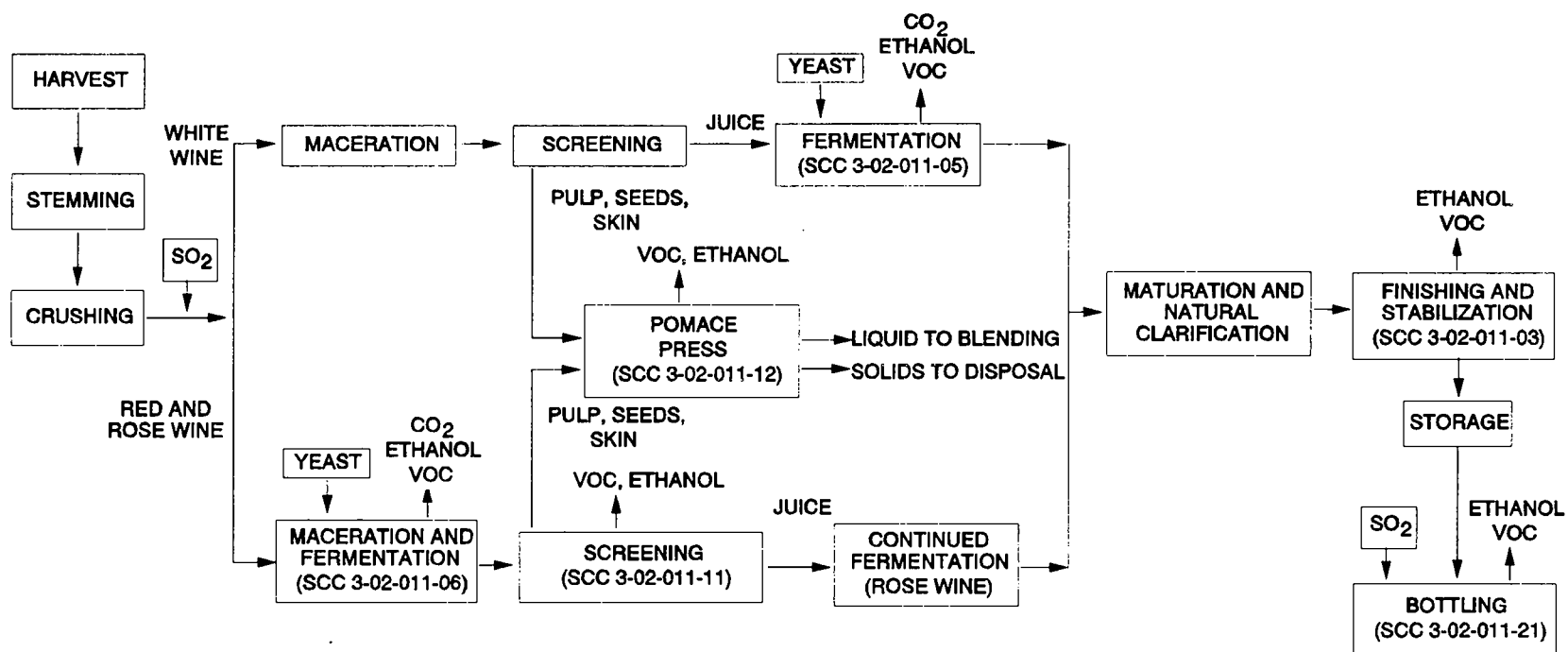


Figure 9.12.2.-1. Basic steps in still table wine production.
(Source Classification Codes in parentheses.)

uncrushed grapes as well as for fermented "must". In the continuous screw press, the "must" is pumped into the press and forced in the pressing chamber where perforated walls allow the juice to escape. After pressing, white "must" is typically clarified and/or filtered prior to fermentation to retain the fruity character. The white juice is commonly allowed to settle for up to 12 hours but may be centrifuged to speed the clarification.

Fermentation is the process whereby the sugars (glucose and fructose) present in the "must" undergo reaction by yeast activity to form ethyl alcohol (ethanol) and CO₂ according to the equation:



In the U. S., the sugar content of the juice is commonly measured with a hydrometer in units of degree Brix (°B), which is grams (g) of sugar per 100 grams of liquid. Fermentation may be initiated by the addition of yeast inoculation to the "must". The fermentation process takes place in tanks, barrels, and vats of a wide variety of shapes, sizes, and technical designs. Tanks are different from vats in that tanks are enclosed, whereas vats have open tops. In most of the larger wineries, tanks have almost completely replaced vats. Since the 1950s, the move has been away from the use of wooden tanks, primarily to stainless steel tanks. Lined concrete tanks are also used, and fiberglass tanks are becoming more popular because of their light weight and lower cost.

The fermentation process is an exothermic reaction and requires temperature control of the fermenting "must". Red wines are typically fermented at 25° to 28°C (70° to 82°F) and white wines at 8° to 15°C (46° to 59°F). Almost all of the fermentation is conducted by the batch process and continuous fermentors are rarely used in the U. S. Size of the fermentors is based primarily on the volume of "must" to be fermented. During fermentation of red wines, the CO₂ released by the yeast metabolism becomes entrapped in the pomace (layer of skins and seeds) and causes it to rise to the top of the tank where it forms a cap. The pomace cap is periodically covered with the "must" to increase color removal, aerate the fermenting "must", limit growth of spoilage organisms in the cap, and help equalize the temperature in the fermenting "must". For white wines, the main technical requirement is efficient temperature control. Temperature is one of the most influential factors affecting the fermentation process. During fermentation of both white and red "must", the CO₂, water vapor, and ethanol are released through a vent in the top of the tank. Malolactic fermentation sometimes follows the primary fermentation and results in a reduction in acidity and increased pH. There are very diverse opinions about this step because the fermentation, to varying degrees, can improve or reduce wine quality.

After fermentation, all wines undergo a period of adjustment (maturation) and clarification prior to bottling. The process of maturation involves the precipitation of particulate and colloidal material from the wine as well as a complex range of physical, chemical, and biological changes that tend to maintain and/or improve the sensory characteristics of the wine. The major adjustments are acidity modification, sweetening, dealcoholization, color adjustment, and blending. Following the fermentation process, a preliminary clarification step is commonly accomplished by decanting the wine from one vessel to another, called racking, in order to separate the sediment (lees) from the wine. Current racking practices range from manually decanting wine from barrel to barrel to highly sophisticated, automated, tank-to-tank transfers. In all cases, separation occurs with minimal agitation to avoid resuspending the particulate matter. The residue from racking may be filtered to recover wine otherwise lost with the lees or may be used "as is" for brandy production.

Stabilization and further clarification steps follow maturation and initial clarification to produce a permanently clear wine with no flavor faults. The steps entail various stabilization

procedures, additional clarification (fining), and a final filtration prior to bottling. The most common stabilization technique used for many red wines and some white wines is aging the wine for a period of months or years. Vessels used to store and age wine, termed cooperage, are produced in a wide range of sizes, depending on their intended use. White oak has traditionally been used for the barrels to age wine, but currently its usage is reserved primarily for the production of premium white and red wines and some fortified wines. Water and ethanol are lost through the barrel surfaces and a partial vacuum develops in the space created by this loss. Each barrel is periodically opened and topped off with wine to fill the void created by the ethanol and water loss. Cooperage constructed from materials other than wood has many advantages and is less expensive to maintain. Stainless steel is often preferred, but fiberglass and concrete are also used. In addition to aging, other stabilization procedures are used to prevent formation of potassium bitartrate or calcium tartrate crystals, haziness (casse) resulting from protein coalescence, casse resulting from oxidation of tannins present in the wine, and haziness due to metal ions such as iron and copper. Enzyme mixtures are used to remove polysaccharides which can cause filtration problems and haze formation. Most wines contain viable but dormant microorganisms. Racking is used as an initial step in microbial stabilization but long-term stability frequently requires use of sulfur dioxide as the antimicrobial agent. Other methods include pasteurization and filter sterilization. Sulfur dioxide may be added at various stages in wine production to prevent microbial growth and oxidation. Finishing (fining) agents are commonly added to accelerate the precipitation of suspended material in wine. Prior to bottling, a final clarification step is used to remove any remaining suspended material and microbes in the wine. This step involves only physical methods of clarification, generally a filtration procedure.

Glass bottles are the container of choice for premium quality wines and for sparkling wines. Because of disadvantages such as weight and breakage, glass bottles are sometimes being replaced by new containers, such as bag-in-box, for many standard quality, high volume wines. To protect the wine against microbial spoilage, and to limit oxidation, the SO₂ content in the wine is adjusted to a final level of 50 mg/L before filling. Precaution is taken to minimize contact with air during filling and thereby to reduce oxidation. This is done by either flushing the bottle with inert gas before filling or flushing the headspace with inert gas after filling.

Sweet Table Wines -

The most famous of the sweet wines are those made from noble-rotted, *Botrytis*-infected grapes. These wines are produced to a limited extent in the United States. The *Botrytis* mold acts to loosen the grape's skin so moisture loss occurs rapidly and the sugar concentration increases in the grape. The grapes are then selectively picked, followed by pressing, and fermentation. Fermentation is a slow process, however, because of the high sugar content and the use of SO₂ to retard the growth of undesirable molds and microorganisms. Nonbotrytized sweet wines are also produced by drying the grapes. Drying involves allowing the grapes to dehydrate on mats or trays in the shade for weeks or months and then crushing the grapes and fermenting the concentrated juice. Heating, boiling, or freezing is also used to concentrate juice for semisweet wines.

Sparkling Wines -

Most sparkling wines obtain CO₂ supersaturation using a second alcoholic fermentation, typically induced by adding yeast and sugar to dry white wine. There are three principal methods of sparkling wine production: the *methode champenoise*, the transfer method, and the bulk method. In the *methode champenoise*, both red and white grapes may be used, but most sparkling wines are white. The grapes are harvested earlier than those used for still table wines and pressed whole without prior stemming or crushing to extract the juice with a minimum of pigment and tannin extraction. This is important for producing white sparkling wines from red-skinned grapes. Primary fermentation is carried out at approximately 15°C (59°F) and bentonite and/or casein may be added

to aid the process and improve clarity. The blending of wines produced from different sites, varieties, and vintages distinguishes the traditional method. Before preparing the blend (*cuvée*), the individual base wines are clarified and stabilized. Aging typically takes place in stainless steel tanks but occasionally takes place in oak cooperage. The secondary fermentation requires inoculation of the *cuvée* wine with a special yeast strain. A concentrated sucrose solution is added to the *cuvée* just prior to the yeast inoculation. The wine is then bottled, capped, and stacked horizontally at a stable temperature, preferably between 10° to 15°C (50° to 59°F), for the second fermentation. After fermentation, the bottles are transferred to a new site for maturation and stored at about 10°C (50°F).

Riddling is the technique used to remove the yeast sediment (lees). The process involves loosening and suspending the cells by manual or mechanical shaking and turning, and positioning the bottle to move the lees toward the neck. Disgorging takes place about 1 or 2 years after bottling. The bottles are cooled and the necks immersed in an ice/CaCl₂ or ice/glycol solution to freeze the sediment. The disgorging machine rapidly removes the cap on the bottle, allowing for ejection of the frozen yeast plug. The mouth of the bottle is quickly covered and the fluid level is adjusted. Small quantities of SO₂ or ascorbic acid may be added to prevent subsequent in-bottle fermentation and limit oxidation. Once the volume adjustment and other additions are complete, the bottles are sealed with special corks, the wire hoods added, and the bottles agitated to disperse the additions. The bottles are then decorated with their capsule and labels and stored for about 3 months to allow the corks to set in the necks. The transfer method is identical to the *methode champenoise* up to the riddling stage. During aging, the bottles are stored neck down. When the aging process is complete, the bottles are chilled below 0°C (32°F) before discharge into a transfer machine and passage to pressurized receiving tanks. The wine is usually sweetened, sulfited, clarified by filtration, and sterile filtered just before bottling.

In the bulk method, fermentation of the juice for the base wine may proceed until all the sugar is consumed or it may be prematurely terminated to retain sugars for the second fermentation. The yeast is removed by centrifugation and/or filtration. Once the *cuvée* is formulated, the wines are combined with yeast additives and, if necessary, sugar. The second fermentation takes place in stainless steel tanks similar to those used in the transfer process. Removal of the lees takes place at the end of the second fermentation by centrifugation and/or filtration. The sugar and SO₂ contents are adjusted just before sterile filtration and bottling.

Other methods of production of sparkling wine include the "rural" method and carbonation. The rural method involves prematurely terminating the primary fermentation prior to a second in-bottle fermentation. The injection of CO₂ (carbonation) under pressure at low temperatures is the least expensive and the least prestigious method of producing sparkling wines.

Dessert Wines -

Dessert wines are classified together because of their elevated alcohol content. The most common dessert wines are sherries and ports.

Baking is the most popular technique for producing sherries in the United States. Grapes are crushed and stemmed and SO₂ added as soon as possible to control bacteria and oxidation. The maximum amount of juice is separated from the skins and the juice is transferred to fermentors. The juice is inoculated with starter and fermented at temperatures of 25° to 30°C (77° to 86°F). The new wine is then pumped from the fermentor or settling tank to the fortification tank. High proof spirits are added to the sherry material, or shermat, to raise the alcohol content to 17 to 18 percent by volume and then the wine is thoroughly mixed, clarified, and filtered before baking. Slow baking occurs when the wine is stored in barrels exposed to the sun. More rapid baking is achieved through

the use of artificially heated storage rooms or heating coils in barrels or tanks. After baking, the sherry is cooled, clarified, and filtered. Maturation is then required and is usually carried out in oak barrels. Aging can last from 6 months to 3 years or more.

Port wines are produced by the premature termination of fermentation by addition of brandy. When the fermenting must is separated from the pomace by gravity, it is fortified with wine spirits containing about 77 percent alcohol, by volume. Most white ports are fortified when half the original sugar content has been fermented, except for semidry and dry white ports which are fortified later. The type and duration of aging depend on the desired style of wine. Blending is used to achieve the desired properties of the wine. The final blend is left to mature in oak cooperage for several months prior to fining, filtration, stabilization, and bottling.

Brandy Production —

Brandy is an alcoholic distillate or mixture of distillates obtained from the fermented juice, mash, or wine from grapes or other fruit (e. g., apples, apricots, peaches, blackberries, or boysenberries). Brandy is produced at less than 190° proof and bottled at a minimum of 80° proof. (In the United States, "proof" denotes the ethyl alcohol content of a liquid at 15.6°C (60°F), stated as twice the percent ethyl alcohol by volume.) Two types of spirits are produced from wine or wine residue: beverage brandy and "wine spirits".

In brandy production, the grapes are pressed immediately after crushing. There are major differences in the fermentation process between wine and brandy production. Pure yeast cultures are not used in the fermentation process for brandy. Brandy can be made solely from the fermentation of fruit or can be distilled either from the lees leftover from the racking process in still wine production or from the pomace cap that is leftover from still red wine fermentations.

In the United States, distillation is commenced immediately after the fermentation step, generally using continuous column distillation, usually with an aldehyde section, instead of pot stills. For a detailed discussion of the distillation and aging of distilled spirits, which include brandy and brandy spirits, refer to AP-42 Section 9.12.3, "Distilled And Blended Liquors". After distillation, the brandy is aged in oak casks for 3 to 15 years or more. During aging, some of the ethanol and water seep through the oak and evaporate, so brandy is added periodically to compensate for this loss. Caramel coloring is added to give the brandy a characteristic dark brown color. After aging, the brandy may be blended and/or flavored, and then chilled, filtered, and bottled.

9.12.2.3 Emissions And Controls⁵⁻¹¹

Ethanol and carbon dioxide are the primary compounds emitted during the fermentation step in the production of wines and brandy. Acetaldehyde, methyl alcohol (methanol), n-propyl alcohol, n-butyl alcohol, sec-butyl alcohol, isobutyl alcohol, isoamyl alcohol, and hydrogen sulfide also are emitted but in much smaller quantities compared to ethanol emissions. In addition, a large number of other compounds are formed during the fermentation and aging process. Selected examples of other types of compounds formed and potentially emitted during the fermentation process include a variety of acetates, monoterpenes, higher alcohols, higher acids, aldehydes and ketones, and organosulfides. During the fermentation step, large quantities of CO₂ are also formed and emitted.

Fugitive ethanol emissions also occur during the screening of the red wine, pressing of the pomace cap, aging in oak cooperage, and the bottling process. In addition, as a preservative, small amounts of liquified SO₂ are often added to the grapes after harvest, to the "must" prior to

fermentation, or to the wine after the fermentation is completed; SO₂ emissions can occur during these steps. There is little potential for VOC emissions before the fermentation step in wine production.

Except for harvesting the grapes and possibly unloading the grapes at the winery, there is essentially no potential for particulate (PM) emissions from this industry.

Emission controls are not currently used during the production of wines or brandy. Five potential control systems have been considered and three have been the subject of pilot-scale emission test studies at wineries or universities in California. The five systems are (1) carbon adsorption, (2) water scrubbers, (3) catalytic incineration, (4) condensation, and (5) temperature control. All of the systems have disadvantages in either low control efficiency, cost effectiveness, or overall applicability to the wide variety of wineries.

Emission factors for VOC and hydrogen sulfide emissions from the fermentation step in wine production are shown in Table 9.12.2-1. The emission factors for controlled ethanol emissions and the uncontrolled emissions of hydrogen sulfide and other VOCs from the fermentation step should be used with caution because the factors are based on a small number of tests and fermentation conditions vary considerably from one winery to another.

The only emission factors for wine production processes other than fermentation, were obtained from a 1982 test.⁷ These factors represent uncontrolled fugitive ethanol emissions during handling processes. The factor for fugitive emissions from the pomace screening for red wine (SCC 3-02-011-11) is 0.5 lb/1,000 gal of juice. An ethanol emission factor for the pomace press is applicable only to red wine because the juice for white wine goes through the pomace press before the fermentation step. The emission factor for red wine (SCC 3-02-011-12) is 0.02 lb/ton of pomace. Although fugitive emissions occur during the bottling of both red and white wines, an emission factor is available only for the bottling of white wine. The factor for white wine bottling (SCC 3-02-011-21) is 0.1 lb/1,000 gal of wine. All of these factors are rated E. These emission factors should be used with extreme caution because they are based on a limited number of tests conducted at one winery. There is no emission factor for fugitive emissions from the finishing and stabilization step (aging).

There are no available data that can be used to estimate emission factors for the production of sweet table wines, dessert wines, sparkling wines, or brandy.

Table 9.12.2-1. EMISSION FACTORS FOR WINE FERMENTATION^a

EMISSION FACTOR RATING: E

Wine type	Type of control	Ethyl alcohol, lb/10 ³ gal	Methyl alcohol, lb/10 ³ gal	n-Propyl alcohol, lb/10 ³ gal	n-Butyl alcohol, lb/10 ³ gal	Sec-Butyl alcohol, lb/10 ³ gal	Isobutyl alcohol, lb/10 ³ gal	Isoamyl alcohol, lb/10 ³ gal	Acet-aldehyde, lb/10 ³ gal	Hydrogen sulfide, lb/10 ³ gal
Red (SCC 3-02-011-06)	None ^b	4.6 ^c	0.0025	0.0034	5.5E-5	4.5E-5	0.0036	0.014	0.0027	0.0017
	Carbon adsorption ^d	0.17 ^c	ND	ND	ND	ND	ND	ND	ND	ND
	Catalytic incineration ^e	1.1	ND	ND	ND	ND	ND	ND	ND	ND
	Wet scrubber ^e	0.056	ND	ND	ND	ND	ND	ND	ND	ND
White (SCC 3-02-011-05)	None ^b	1.8 ^c	6.4E-4	0.0023	ND	ND	6.9E-4	0.0051	7.2E-5	0.0014
	Carbon adsorption ^d	0.092 ^c	ND	ND	ND	ND	ND	ND	ND	ND
	Catalytic incineration ^e	0.15	ND	ND	ND	ND	ND	ND	ND	ND
	Wet scrubber ^e	0.083	ND	ND	ND	ND	ND	ND	ND	ND

^a Emission factor units are lb/1,000 gal of fermented juice produced. SCC = Source Classification Code. ND = no data.^b References 8-11.^c EMISSION FACTOR RATING: C^d References 8-10.^e Reference 8.

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9.13.2 Coffee Roasting

9.13.2.1 General

The coffee roasting industry involves the processing of green coffee beans into roasted coffee products, including whole and ground beans and soluble coffee products. The Standard Industrial Classification (SIC) code for coffee roasting is 2095.

9.13.2.2 Process Description¹⁻⁶

The coffee roasting process consists essentially of cleaning, roasting, cooling, grinding, and packaging operations. Figure 9.13.2-1 shows a process flow diagram for a typical coffee roasting operation. Bags of green coffee beans are hand- or machine-opened, dumped into a hopper, and screened to remove debris. The green beans are then weighed and transferred by belt or pneumatic conveyor to storage hoppers. From the storage hoppers, the green beans are conveyed to the roaster. Roasters typically operate at temperatures between 370° and 540°C (698° and 1004°F), and the beans are roasted for a period of time ranging from a few minutes to about 30 minutes. Roasters are typically horizontal rotating drums that tumble the green coffee beans in a current of hot combustion gases; the roasters operate in either batch or continuous modes and can be indirect- or direct-fired. Indirect-fired roasters are roasters in which the burner flame does not contact the coffee beans, although the combustion gases from the burner do contact the beans. Direct-fired roasters contact the beans with the burner flame and the combustion gases. At the end of the roasting cycle, water sprays are used to "quench" the beans. Following roasting, the beans are cooled and run through a "destoner". Destoners are air classifiers that remove stones, metal fragments, and other waste not removed during initial screening from the beans. The destoners pneumatically convey the beans to a hopper, where the beans are stabilize and dry (small amounts of water from quenching exist on the surface of the beans). This stabilization process is called equilibration. Following equilibration, the roasted beans are ground, usually by multi-stage grinders. Some roasted beans are packaged and shipped as whole beans. Finally, the ground coffee is vacuum sealed and shipped.

Additional operations associated with processing green coffee beans include decaffeination and instant (soluble) coffee production. Decaffeination is the process of extracting caffeine from green coffee beans prior to roasting. The most common decaffeination process used in the United States is supercritical carbon dioxide (CO₂) extraction. In this process, moistened green coffee beans are contacted with large quantities of supercritical CO₂ (CO₂ maintained at a pressure of about 4,000 pounds per square inch and temperatures between 90° and 100°C [194° and 212°F]), which removes about 97 percent of the caffeine from the beans. The caffeine is then recovered from the CO₂, typically using an activated carbon adsorption system. Another commonly used method is solvent extraction, typically using oil (extracted from roasted coffee) or ethyl acetate as a solvent. In this process, solvent is added to moistened green coffee beans to extract most of the caffeine from the beans. After the beans are removed from the solvent, they are steam-stripped to remove any residual solvent. The caffeine is then recovered from the solvent, and the solvent is re-used. Water extraction is also used for decaffeination, but little information on this process is available. Decaffeinated coffee beans have a residual caffeine content of about 0.1 percent on a dry basis. Not all facilities have decaffeination operations, and decaffeinated green coffee beans are purchased by many facilities that produce decaffeinated coffee.

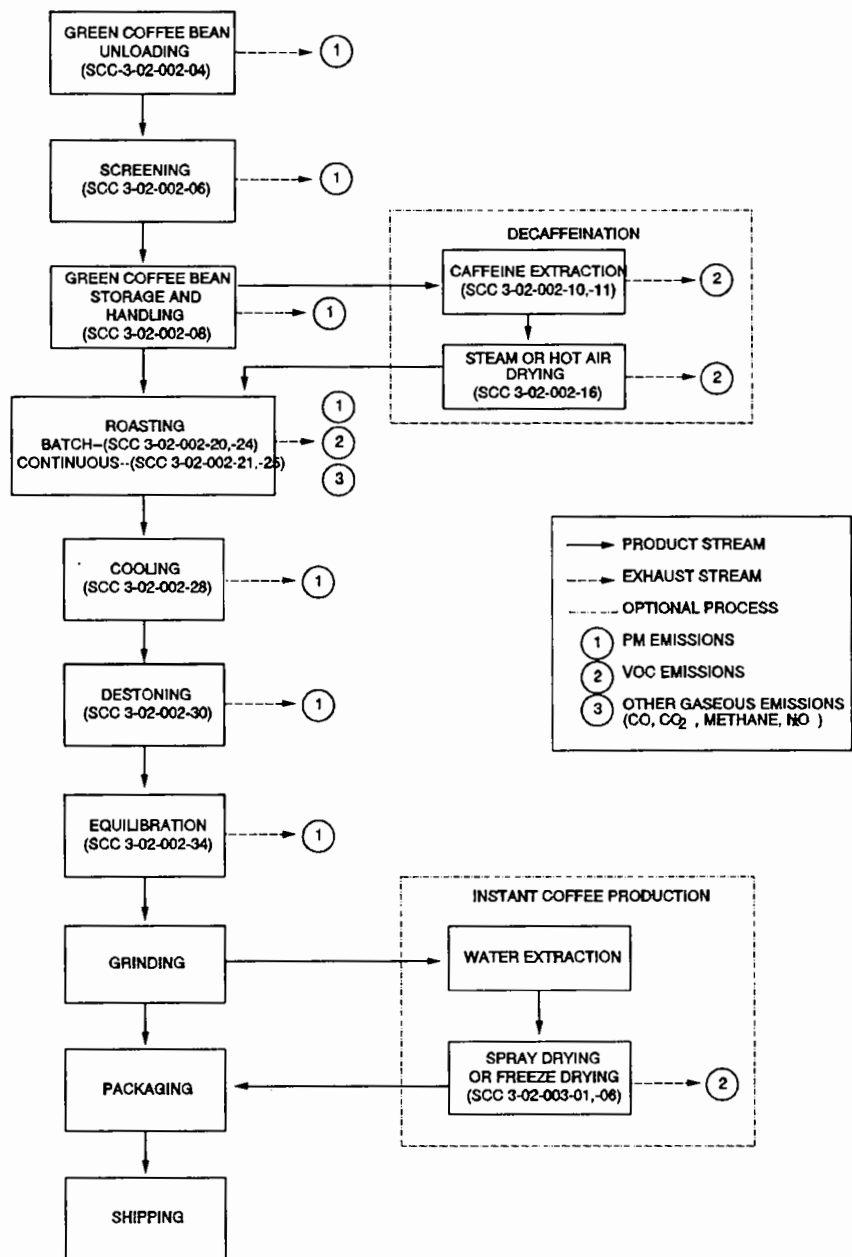


Figure 9.13.2-1. Typical coffee roasting operation.
(Source Classification Codes in parentheses.)

In the manufacture of instant coffee, extraction follows the roasting and grinding operations. The soluble solids and volatile compounds that provide aroma and flavor are extracted from the coffee beans using water. Water heated to about 175°C (347°F) under pressurized conditions (to maintain the water as liquid) is used to extract all of the necessary solubles from the coffee beans. Manufacturers use both batch and continuous extractors. Following extraction, evaporation or freeze-concentration is used to increase the solubles concentration of the extract. The concentrated extracts are then dried in either spray dryers or freeze dryers. Information on the spray drying and freeze drying processes is not available.

9.13.2.3 Emissions And Controls

Particulate matter (PM), volatile organic compounds (VOC), organic acids, and combustion products are the principal emissions from coffee processing. Several operations are sources of PM emissions, including the cleaning and destoning equipment, roaster, cooler, and instant coffee drying equipment. The roaster is the main source of gaseous pollutants, including alcohols, aldehydes, organic acids, and nitrogen and sulfur compounds. Because roasters are typically natural gas-fired, carbon monoxide (CO) and carbon dioxide (CO₂) emissions are expected as a result of fuel combustion. Decaffeination and instant coffee extraction and drying operations may also be sources of small amounts of VOC. Emissions from the grinding and packaging operations typically are not vented to the atmosphere.

Particulate matter emissions from the receiving, storage, cleaning, roasting, cooling, and stoning operations are typically ducted to cyclones before being emitted to the atmosphere. Gaseous emissions from roasting operations are typically ducted to a thermal oxidizer or thermal catalytic oxidizer following PM removal by a cyclone. Some facilities use the burners that heat the roaster as thermal oxidizers. However, separate thermal oxidizers are more efficient because the desired operating temperature is typically between 650°C and 816°C (1200°F and 1500°F), which is 93°C to 260°C (200°F to 500°F) more than the maximum temperature of most roasters. Some facilities use thermal catalytic oxidizers, which require lower operating temperatures to achieve control efficiencies that are equivalent to standard thermal oxidizers. Catalysts are also used to improve the control efficiency of systems in which the roaster exhaust is ducted to the burners that heat the roaster. Emissions from spray dryers are typically controlled by a cyclone followed by a wet scrubber.

Table 9.13.2-1 presents emission factors for filterable PM and condensible PM emissions from coffee roasting operations. Table 9.13.2-2 presents emission factors for volatile organic compounds (VOC), methane, CO, and CO₂ emissions from roasting operations. Emissions from batch and continuous roasters are shown separately, but with the exception of CO emissions, the emissions from these two types of roasters appear to be similar.

Table 9.13.2-1. EMISSION FACTORS FOR COFFEE ROASTING OPERATIONS^a

EMISSION FACTOR RATING: D

Source	Filterable PM, lb/ton	Condensable PM lb/ton
Batch roaster with thermal oxidizer ^b (SCC 3-02-002-20)	0.12	ND
Continuous cooler with cyclone ^c (SCC 3-02-002-28)	0.028	ND
Continuous roaster ^d (SCC 3-02-002-21)	0.66	ND
Continuous roaster with thermal oxidizer (SCC 3-02-002-21)	0.092 ^e	0.10 ^e
Green coffee bean screening, handling, and storage system with fabric filter ^f (SCC 3-02-002-08)	0.059	ND
Destoner (SCC 3-02-002-30)	ND	ND
Equilibration (SCC 3-02-002-34)	ND	ND

^a Emission factors are based on green coffee bean feed. Factors represent uncontrolled emissions unless noted. SCC = Source Classification Code. ND = no data. D-rated and E-rated emission factors are based on limited test data; these factors may not be representative of the industry.

^b References 12,14.

^c Reference 15.

^d References 8-9.

^e References 7-9,11,15. Includes data from thermal catalytic oxidizers.

^f Reference 16. EMISSION FACTOR RATING: E.

Table 9.13.2-2. EMISSION FACTORS FOR COFFEE ROASTING OPERATIONS^a

EMISSION FACTOR RATING: D

Source	VOC ^b , lb/ton	Methane, lb/ton	CO, lb/ton	CO ₂ , lb/ton
Batch roaster ^c (SCC 3-02-002-20)	0.86	ND	ND	180
Batch roaster with thermal oxidizer (SCC 3-02-002-20)	0.047 ^d	ND	0.55 ^d	530 ^e
Continuous roaster (SCC 3-02-002-21)	1.4 ^f	0.26 ^g	1.5 ^h	120 ⁱ
Continuous roaster with thermal oxidizer (SCC 3-02-002-21)	0.16 ^k	0.15 ^m	0.098 ^k	200 ⁿ
Decaffeination: solvent or supercritical CO ₂ extraction (SCC 3-02-002-10,-11)	ND	ND	ND	ND
Steam or hot air dryer (SCC 3-02-002-16)	ND	ND	ND	ND
Spray drying (SCC 3-02-003-01)	ND	ND	ND	ND
Freeze drying (SCC 3-02-003-06)	ND	ND	ND	ND

^a Emission factors are based on green coffee bean feed. Factors represent uncontrolled emissions unless noted. SCC = Source Classification Code. ND = no data. D-rated and E-rated emission factors are based on limited test data; these factors may not be representative of the industry.

^b Volatile organic compounds as methane. Measured using GC/FID.

^c Reference 14.

^d References 12-14.

^e References 12,14.

^f References 8-9,11,15.

^g References 8-9,11,15. EMISSION FACTOR RATING: E.

^h References 8-9,15.

ⁱ References 8-9,11,15. EMISSION FACTOR RATING: C.

^k References 8-9,11,15. Includes data from thermal catalytic oxidizers.

^m References 8-9,11,15. Includes data from thermal catalytic oxidizers. EMISSION FACTOR RATING: E.

ⁿ References 9,11,15. Includes data from thermal catalytic oxidizers.

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10.7 Charcoal

10.7.1 Process Description¹⁻⁴

Charcoal is the solid carbon residue following the pyrolysis (carbonization or destructive distillation) of carbonaceous raw materials. Principal raw materials are medium to dense hardwoods such as beech, birch, hard maple, hickory, and oak. Others are softwoods (primarily long leaf and slash pine), nutshells, fruit pits, coal, vegetable wastes, and paper mill residues. Charcoal is used primarily as a fuel for outdoor cooking. In some instances, its manufacture may be considered as a solid waste disposal technique. Many raw materials for charcoal manufacture are wastes, as noted. Charcoal manufacture is also used in forest management for disposal of refuse.

Recovery of acetic acid and methanol byproducts was initially responsible for stimulating the charcoal industry. As synthetic production of these chemicals became commercialized, recovery of acetic acid and methanol became uneconomical.

Charcoal manufacturing kilns generally can be classified as either batch or continuous multiple hearth kilns; continuous multiple hearth kilns are more commonly used than are batch kilns. Batch units such as the Missouri-type charcoal kiln (Figure 10.7-1) are small manually-loaded and -unloaded kilns producing typically 16 megagrams (Mg) (17.6 tons) of charcoal during a 3-week cycle. Continuous units (Figure 10.7-2) produce an average of 2.5 Mg per hour (Mg/hr) (2.75 tons per hour [tons/hr]) of charcoal. During the manufacturing process, the wood is heated, driving off water and highly volatile organic compounds (VOC). Wood temperature rises to approximately 275°C (527°F), and the VOC distillate yield increases. At this point, external application of heat is no longer required because the carbonization reactions become exothermic. At 350°C (662°F), exothermic pyrolysis ends, and heat is again applied to remove the less volatile tarry materials from the product charcoal.

Fabrication of briquettes from raw material may be either an integral part of a charcoal producing facility, or an independent operation, with charcoal being received as raw material. Figure 10.7-3 presents a flow diagram for charcoal briquette production. Raw charcoal is first crushed to pass through an approximately 3 millimeter (0.12 inch) screen aperture and then stored for briquetting. The charcoal is then mixed with a binder to form a 65 to 70 percent charcoal mixture. Typical binder solutions are 9 to 10 percent by weight solutions of cornstarch, milostarch, or wheatstarch. Sawdust or other materials may be added to obtain faster burning or higher temperatures. Briquettes are then formed in a press and dried at approximately 135°C (275°F) for 3 to 4 hours, resulting in a product with a 5 percent moisture content. This process generates a briquette of approximately 90 percent pyrolysis product.

10.7.2 Emissions And Controls³⁻¹²

There are five types of products and byproducts from charcoal production operations: charcoal, noncondensable gases (carbon monoxide [CO], carbon dioxide [CO₂], methane, and ethane), pyroacids (primarily acetic acid and methanol), tars and heavy oils, and water. With the exception of charcoal, all of these materials are emitted with the kiln exhaust. Product constituents and the distribution of these constituents vary, depending on raw materials and carbonization parameters. Organics and CO are naturally combusted to CO₂ and water before leaving the retort. Because the extent of this combustion varies from plant to plant, emission levels are quite variable. Some of the

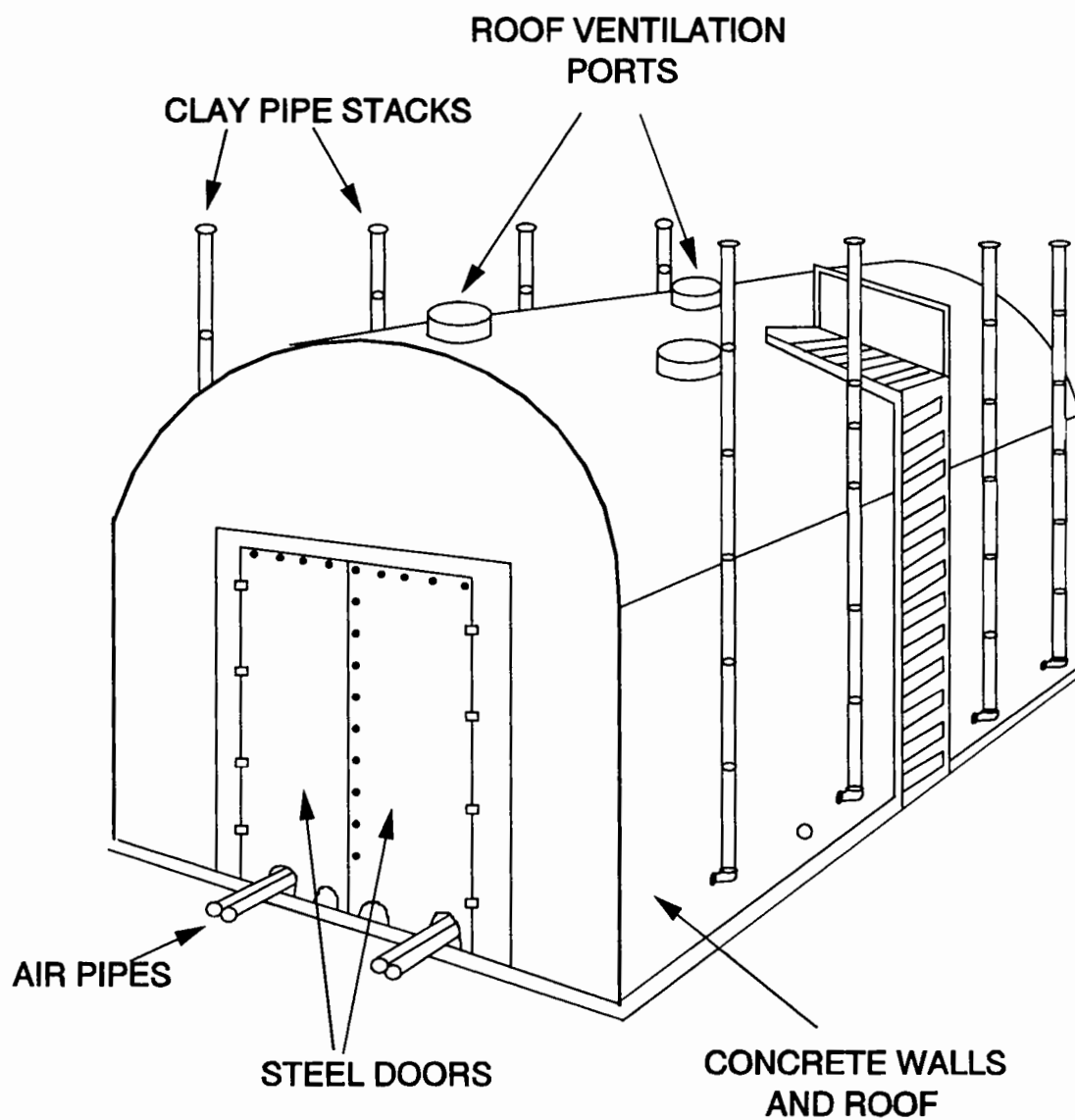


Figure 10.7-1. The Missouri-type charcoal kiln.⁷
(Source Classification Code: 3-01-006-03.)

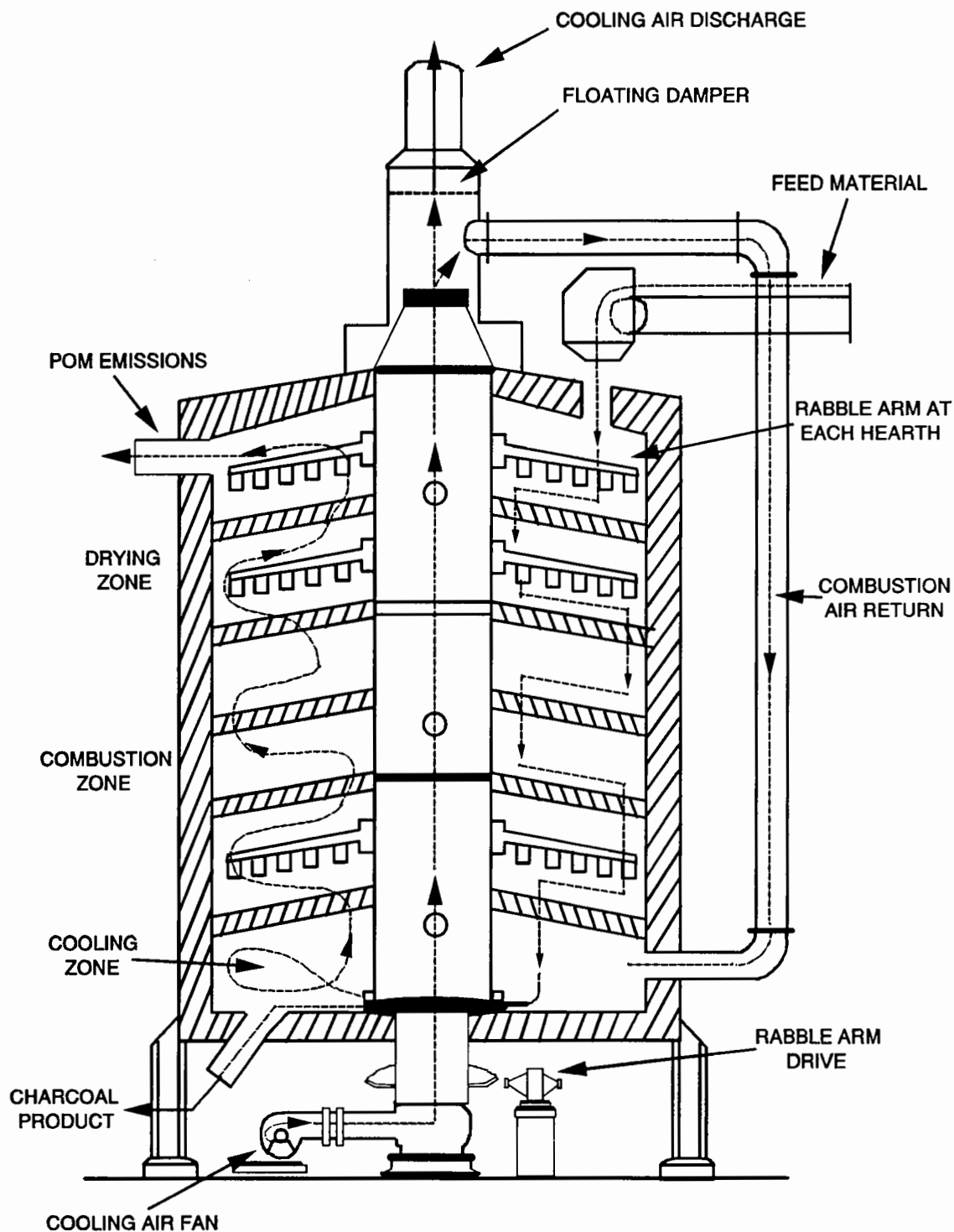


Figure 10.7-2. The continuous multiple hearth kiln for charcoal production.⁴
 (Source Classification Code: 3-01-006-04.)

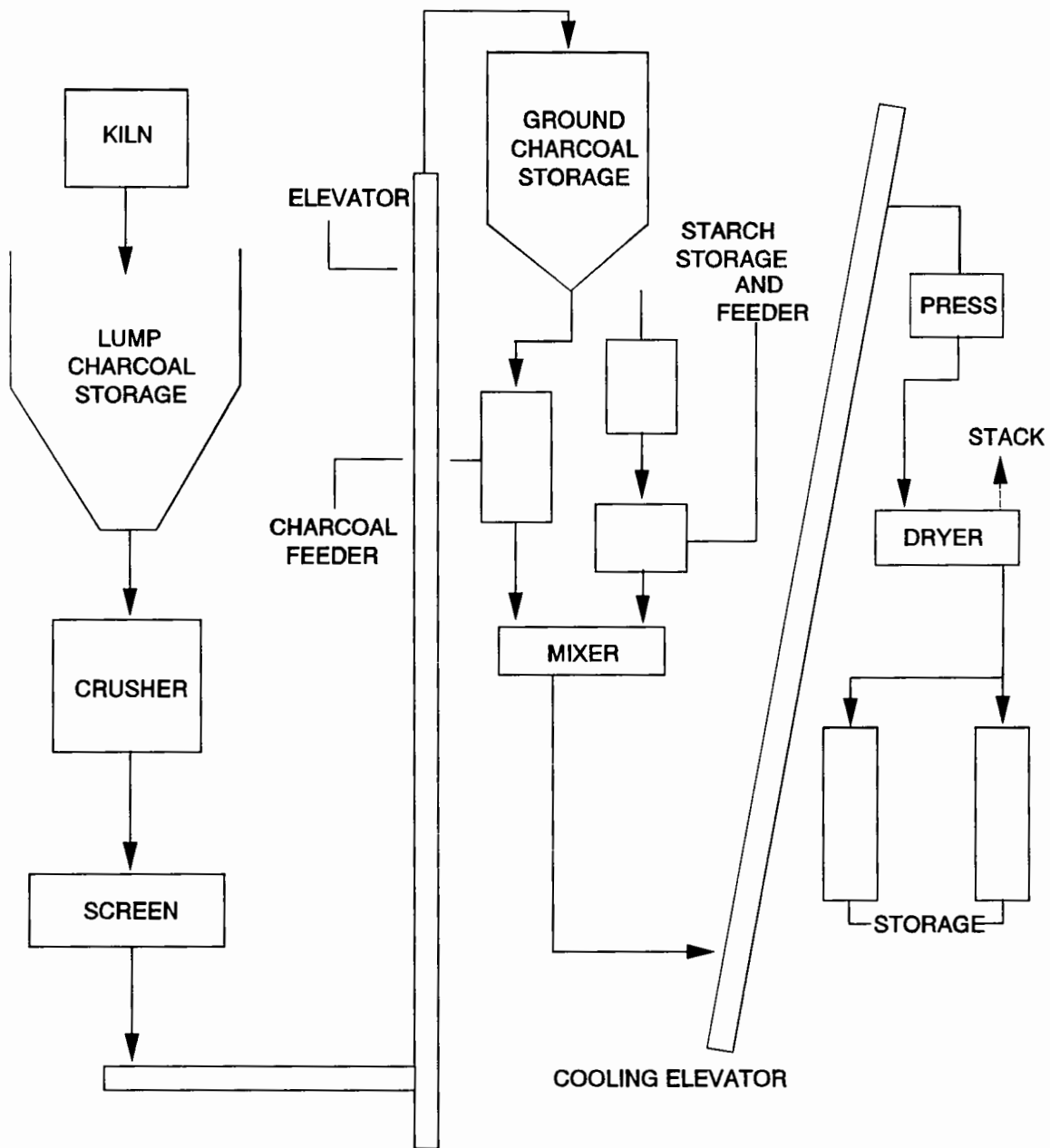


Figure 10.7-3. Flow diagram for charcoal briquette production.³
(Source Classification Code: 3-01-006-05.)

specific organic compounds that may be found in charcoal kiln emissions include ethane, methane, ethanol, and polycyclic organic matter (POM). If uncombusted, tars may solidify to form PM emissions, and pyroacids may form aerosol emissions.

The charcoal briquetting process is also a potential source of emissions. The crushing, screening, and handling of the dry raw charcoal may produce PM and PM-10 emissions. Briquette pressing and drying may be a source of VOC emissions, depending on the type of binder and other additives used.

Continuous production of charcoal is more amenable to emission control than batch production because emission composition and flow rate are relatively constant. Emissions from continuous multiple hearth charcoal kilns generally are controlled with afterburners. Cyclones, which commonly are used for product recovery, also reduce PM emissions from continuous kilns. Afterburning is estimated to reduce emissions of PM, CO, and VOC by at least 80 percent. Control of emissions from batch-type charcoal kilns is difficult because the process and, consequently, the emissions are cyclic. Throughout a cycle, both the emission composition and flow rate change. Batch kilns do not typically have emission control devices, but some may use after-burners.

Particulate matter emissions from briquetting operations can be controlled with a centrifugal collector (65 percent control) or fabric filter (99 percent control).

Emission factors for criteria pollutant emissions from the manufacture of charcoal are shown in Table 10.7-1. Table 10.7-2 presents factors for emission of organic pollutants from charcoal manufacturing.

Table 10.7-1 EMISSION FACTORS FOR CHARCOAL MANUFACTURING--
CRITERIA POLLUTANTS AND CO₂^a

EMISSION FACTOR RATING: E

Source	lb/ton				
	Total PM ^b	NO _x	CO	VOC	CO ₂
Charcoal kiln ^c (SCC 3-01-006-03, -04)	310 ^d	24 ^e	290 ^f	270 ^g	1,100 ^f
Briquetting ^h (SCC 3-01-006-05)	56 ^f	ND	ND	ND	ND

^a Factors represent uncontrolled emissions. SCC = Source Classification Code. ND = no data.

Emission factors units are lb/ton of product. One lb/ton = 0.5 kg/Mg.

^b Includes condensibles and consists primarily of tars and oils.

^c Applicable to both batch and continuous kilns.

^d References 2,6-7.

^e Reference 3. Based on 0.14 percent nitrogen content of wood.

^f References 2,6-7,11.

^g References 2-3,6.

^h For entire briquetting process.

Table 10.7-2. EMISSION FACTORS FOR CHARCOAL MANUFACTURING--
MISCELLANEOUS ORGANIC POLLUTANTS^a

EMISSION FACTOR RATING: E

Source	Pollutant	Emission factor, lb/ton
Charcoal kiln ^b (SCC 3-01-006-3, -04)	Methane ^c	110
	Ethane ^d	52
	Methanol ^e	150
	POM ^f	0.0095

^a Factors represent uncontrolled emissions. SCC = Source Classification Code. Emission factors units are lb/ton of product. One lb/ton = 0.5 kg/Mg.

^b Applicable to both batch and continuous kilns.

^c References 2,6.

^d References 3,6.

^e Reference 2.

^f Reference 7.

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11.10 Coal Cleaning

11.10.1 Process Description^{1-2,9}

Coal cleaning is a process by which impurities such as sulfur, ash, and rock are removed from coal to upgrade its value. Coal cleaning processes are categorized as either physical cleaning or chemical cleaning. Physical coal cleaning processes, the mechanical separation of coal from its contaminants using differences in density, are by far the major processes in use today. Chemical coal cleaning processes are currently being developed, but their performance and cost are undetermined at this time. Therefore, chemical processes are not included in this discussion.

The scheme used in physical coal cleaning processes varies among coal cleaning plants but can generally be divided into four basic phases: initial preparation, fine coal processing, coarse coal processing, and final preparation. A process flow diagram for a typical coal cleaning plant is presented in Figure 11.10-1.

In the initial preparation phase of coal cleaning, the raw coal is unloaded, stored, conveyed, crushed, and classified by screening into coarse and fine coal fractions. The size fractions are then conveyed to their respective cleaning processes.

Fine coal processing and coarse coal processing use similar operations and equipment to separate the contaminants. The primary difference is the severity of operating parameters. The majority of coal cleaning processes use upward currents or pulses of a fluid such as water to fluidize a bed of crushed coal and impurities. The lighter coal particles rise and are removed from the top of the bed. The heavier impurities are removed from the bottom. Coal cleaned in the wet processes then must be dried in the final preparation processes.

Final preparation processes are used to remove moisture from coal, thereby reducing freezing problems and weight and raising the heating value. The first processing step is dewatering, in which a major portion of the water is removed by the use of screens, thickeners, and cyclones. The second step is normally thermal drying, achieved by any one of three dryer types: fluidized bed, flash, and multilouvered. In the fluidized bed dryer, the coal is suspended and dried above a perforated plate by rising hot gases. In the flash dryer, coal is fed into a stream of hot gases for instantaneous drying. The dried coal and wet gases are both drawn up a drying column and into a cyclone for separation. In the multilouvered dryer, hot gases are passed through a falling curtain of coal, which is then raised by flights of a specially designed conveyor.

11.10.2 Emissions And Controls^{1-2,9-10}

Emissions from the initial coal preparation phase of either wet or dry processes consist primarily of fugitive particulate matter (PM) as coal dust from roadways, stock piles, refuse areas, loaded railroad cars, conveyor belt pouroffs, crushers, and classifiers. The major control technique used to reduce these emissions is water wetting. Another technique that applies to unloading, conveying, crushing, and screening operations involves enclosing the process area and circulating air from the area through fabric filters. Uncontrolled emission factors for various types of fugitive sources in coal cleaning facilities can be developed from the equations found in Section 13.2, "Fugitive Dust Sources".

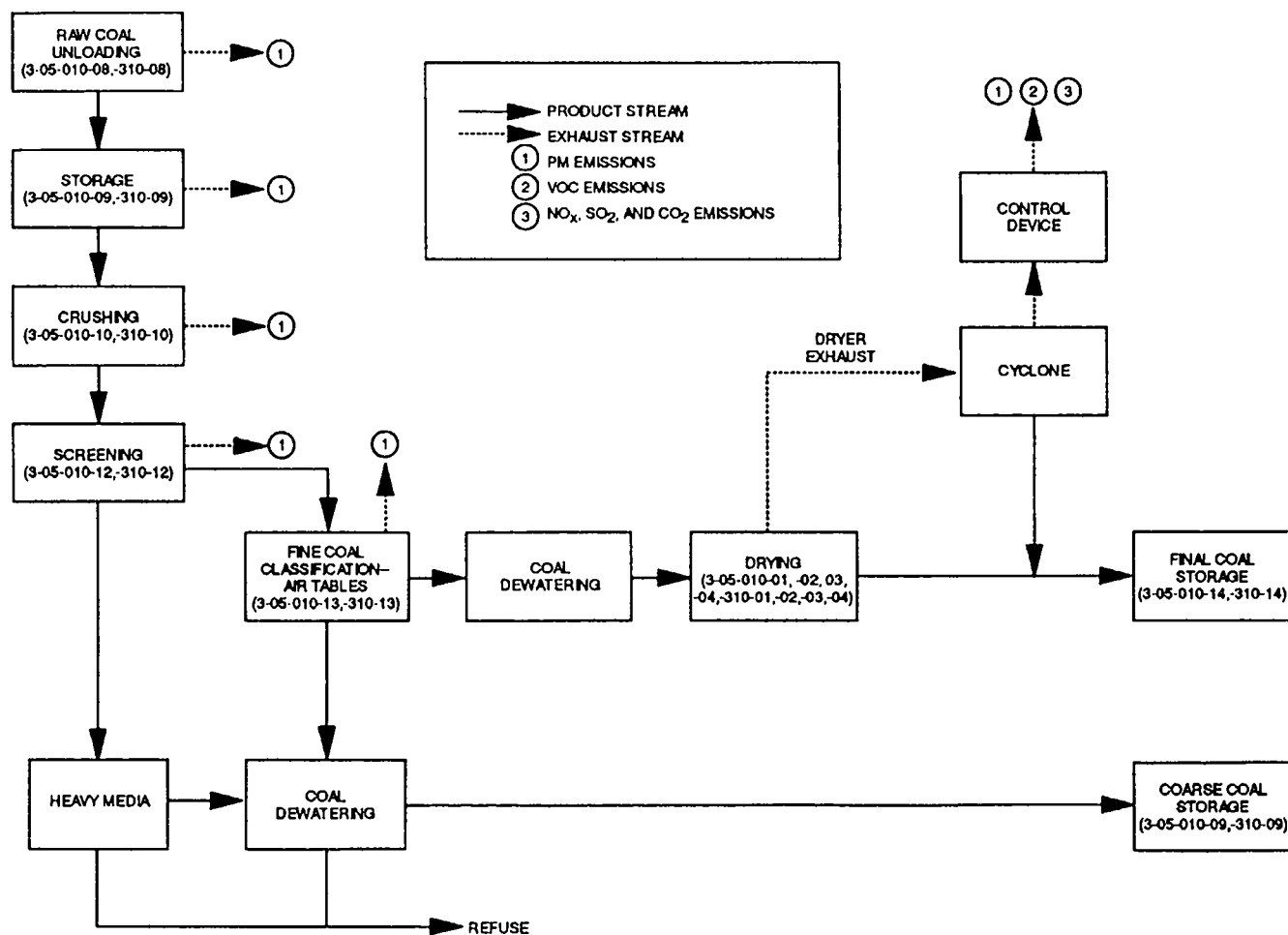


Figure 11.10-1. Typical coal cleaning plant process flow diagram.
(Source Classification Codes in parenthesis.)

The major emission source in the fine or coarse coal processing phases is the air exhaust from the air separation processes (air tables). For the dry cleaning process, these emissions are generated when the coal is stratified by pulses of air. Particulate matter emissions from this source are normally controlled with cyclones followed by fabric filters. Potential emissions from wet cleaning processes are very low.

The major source of emissions from the final preparation phase is the thermal dryer exhaust. This emission stream contains coal particles entrained in the drying gases and volatile organic compounds (VOC) released from the coal, in addition to the standard products of coal combustion resulting from burning coal to generate the hot gases (including carbon monoxide [CO], carbon dioxide [CO₂], VOC, sulfur dioxide [SO₂], and nitrogen oxides [NO_x]). Table 11.10-1 shows emission factors for PM. Emission factors for SO₂, NO_x, VOC, and CO₂ are presented in Table 11.10-2. The most common technology used to control dryer emissions is venturi scrubbers and mist eliminators downstream from the product recovery cyclones. The control efficiency of these techniques for filterable PM ranges from 98 to 99.9 percent. Scrubbers also may achieve between 0 and 95 percent control of SO₂ emissions. The use of a neutralizing agent (such as NaOH) in the scrubber water increases the SO₂ removal efficiency of the scrubber.

A number of inorganic hazardous air pollutants are found in trace quantities in coal. These include arsenic, beryllium, cadmium, chromium, copper, mercury, manganese, nickel, lead, thorium, and uranium. It is likely that many of these are emitted in trace amounts from crushing, grinding, and drying operations.

The new source performance standards (NSPS) for coal preparation plants were promulgated in January 1976 (40 CFR Subpart Y). These standards specify emission limits for PM from coal cleaning thermal dryers and pneumatic cleaning equipment sources, and opacity limits for fugitive emissions from coal processing and conveying equipment, coal storage systems, and coal transfer and loading systems.

Table 11.10-1. PM EMISSION FACTORS FOR COAL CLEANING^a

EMISSION FACTOR RATING: D (except as noted)

Process	Filterable PM ^b			Condensible PM ^c	
	PM	PM-2.5	PM-1.0	Inorganic	Organic
Multilouvered dryer ^d (SCC 3-05-010-03)	3.7	ND	ND	0.057	0.018
Fluidized bed dryer ^e (SCC 3-05-010-01)	26 ^f	3.8 ^g	1.1 ^g	0.034 ^h	0.0075 ^h
Fluidized bed dryer with venturi scrubber ^j (SCC 3-05-010-01)	0.17	ND	ND	0.043	0.0048
Fluidized bed dryer with venturi scrubber and tray scrubber ^k (SCC 3-05-010-01)	0.025	ND	ND	ND	ND
Air tables with fabric filter ^m (SCC 3-05-010-13)	0.032 ⁿ	ND	ND	0.033 ^p	0.0026 ^q

^a Emission factor units are lb/ton of coal feed, unless noted. 1 lb/ton = 2 kg/Mg. SCC = Source Classification Code. ND = no data.

^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.

^d Reference 11. Alternate SCC is 3-05-310-03, which corresponds to units of lb/thousand tons of coal feed. To determine the emission factor for this alternate SCC, multiply the factor in this table by 1,000.

^e Alternate SCC is 3-05-310-01, which corresponds to units of lb/thousand tons of coal feed. To determine the emission factor for this alternate SCC, multiply the factor in this table by 1,000.

^f References 12,15.

^g References 12,15. EMISSION FACTOR RATING: E. Particle size data from Reference 15 used in conjunction with filterable PM data from References 12 and 15. Actual cut size of PM-2.5 data was 2.7 microns.

^h Reference 12.

^j References 12-13,15-16,20. See footnote "e" above for alternate SCC.

^k Reference 21. Tray scrubber using NaOH as the scrubbing liquid. See footnote "e" above for alternate SCC.

^m Alternate SCC is 3-05-310-13, which corresponds to units of lb/thousand tons of coal feed. To determine the emission factor for this alternate SCC, multiply the factor in this table by 1,000.

ⁿ References 18-19.

^p Reference 19.

^q Reference 18.

**Table 11.10-2. GASEOUS POLLUTANT EMISSION FACTORS
FOR COAL CLEANING^a**

EMISSION FACTOR RATING: D (except as noted)

Process	VOC ^b	SO ₂	NO _x	CO ₂
Multilouvered dryer ^c (SCC 3-05-010-03)	ND	ND	ND	160
Fluidized bed dryer ^d (SCC 3-05-010-01)	ND	1.4 ^e	0.16 ^f	30 ^g
Fluidized bed dryer with venturi scrubber ^h (SCC 3-05-010-01)	0.098 ^j	^k	0.16 ^f	30 ^g
Fluidized bed dryer with venturi scrubber and tray scrubber ^m (SCC 3-05-010-01)	ND	0.072 ⁿ	0.16 ^f	30 ^g

- ^a Emission factor units are lb/ton of coal feed, unless noted. 1 lb/ton = 2 kg/Mg.
SCC = Source Classification Code. ND = no data.
- ^b VOC as methane, measured with an EPA Method 25A sampling train. Measurement may include compounds designated as nonreactive.
- ^c Reference 11. EMISSION FACTOR RATING: E. Alternate SCC is 3-05-310-03, which corresponds to units of lb/thousand tons of coal feed. To determine the emission factor for this alternate SCC, multiply the factor in this table by 1,000.
- ^d Alternate SCC is 3-05-310-01, which corresponds to units of lb/thousand tons of coal feed. To determine the emission factor for this alternate, SCC, multiply the factor in this table by 1,000.
- ^e References 12,14,17. EMISSION FACTOR RATING: E.
- ^f References 12,14,21. Includes NO_x measurements before and after control devices that are not expected to provide control of NO_x emissions.
- ^g References 12-16,20. Includes CO₂ measurements before and after control devices that are not expected to provide control of CO₂ emissions.
- ^h See footnote "d" above for alternate SCC.
- ^j References 13-14.
- ^k Venturi scrubbers may achieve between 0 and 95% control of SO₂ emissions. The use of a neutralizing agent in the scrubber water increases the SO₂ control efficiency.
- ^m Venturi scrubber followed by tray scrubber using a NaOH solution as the scrubbing liquid. See footnote "d" above for alternate SCC.
- ⁿ Reference 21.

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11.14 Frit Manufacturing

11.14-1 Process Description¹⁻⁶

Frit is a homogeneous melted mixture of inorganic materials that is used in enameling iron and steel and in glazing porcelain and pottery. Frit renders soluble and hazardous compounds inert by combining them with silica and other oxides. Frit also is used in bonding grinding wheels, to lower vitrification temperatures, and as a lubricant in steel casting and metal extrusion. The six digit Source Classification Code (SCC) for frit manufacturing is 3-05-013.

Frit is prepared by fusing a variety of minerals in a furnace and then rapidly quenching the molten material. The constituents of the feed material depend on whether the frit is to be used as a ground coat or as a cover coat. For cover coats, the primary constituents of the raw material charge include silica, fluorspar, soda ash, borax, feldspar, zircon, aluminum oxide, lithium carbonate, magnesium carbonate, and titanium oxide. The constituents of the charge for a ground coat include the same compounds plus smaller amounts of metal oxides such as cobalt oxide, nickel oxide, copper oxide, and manganese oxide.

To begin the process, raw materials are shipped to the manufacturing facility by truck or rail and are stored in bins. Next, the raw materials are carefully weighed in the correct proportions. The raw batch then is dry mixed and transferred to a hopper prior to being fed into the smelting furnace. Although pot furnaces, hearth furnaces, and rotary furnaces have been used to produce frit in batch operations, most frit is now produced in continuous smelting furnaces. Depending on the application, frit smelting furnaces operate at temperatures of 930° to 1480°C (1700° to 2700°F). If a continuous furnace is used, the mixed charge is fed by screw conveyor directly into the furnace. Continuous furnaces operate at temperatures of 1090° to 1430°C (2000° to 2600°F). When smelting is complete, the molten material is passed between water-cooled metal rollers that limit the thickness of the material, and then it is quenched with a water spray that shatters the material into small glass particles called frit.

After quenching, the frit is milled by either wet or dry grinding. If the latter, the frit is dried before grinding. Frit produced in continuous furnaces generally can be ground without drying, and it is sometimes packaged for shipping without further processing. Wet milling of frit is no longer common. However, if the frit is wet-milled, it can be charged directly to the grinding mill without drying. Rotary dryers are the devices most commonly used for drying frit. Drying tables and stationary dryers also have been used. After drying, magnetic separation may be used to remove iron-bearing material. The frit is finely ground in a ball mill, into which clays and other electrolytes may be added, and then the product is screened and stored. The frit product then is transported to on-site ceramic manufacturing processes or is prepared for shipping. In recent years, the electrostatic deposition spray method has become the preferred method of applying frit glaze to surfaces. Frit that is to be applied in that manner is mixed during the grinding step with an organic silicon encapsulating agent, rather than with clay and electrolytes. Figure 11.14-1 presents a process flow diagram for frit manufacturing.

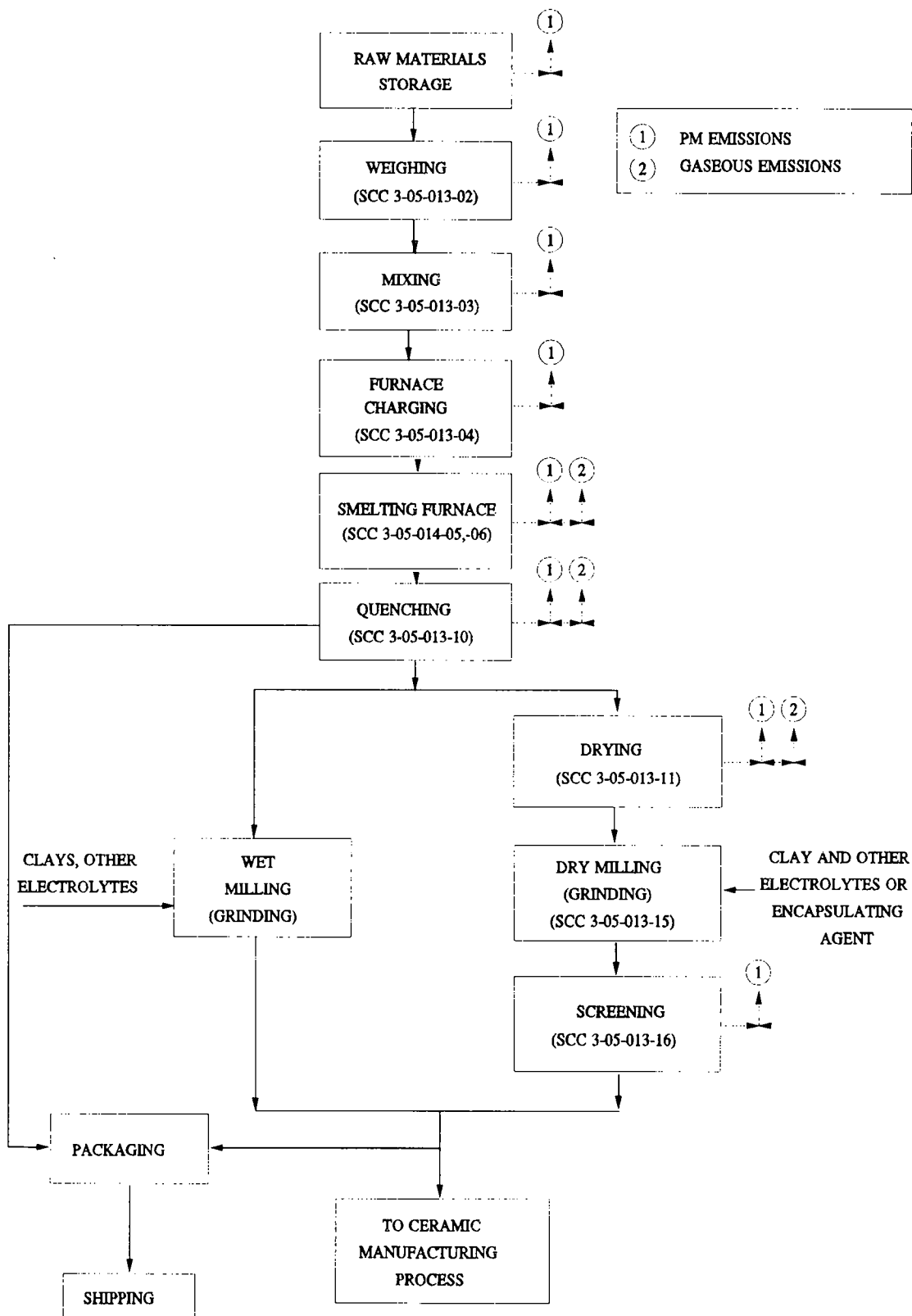


Figure 11.14-1. Process flow diagram for frit manufacturing.
(Source Classification Code in parentheses.)

11.14-2 Emissions And Controls^{1,7-10}

Significant emissions of particulate matter (PM) and PM less than 10 micrometers (PM-10) are created by the frit smelting operation in the form of dust and fumes. These emissions consist primarily of condensed metallic oxide fumes that have volatilized from the molten charge. The emissions also contain mineral dust and sometimes hydrogen fluoride. Emissions from furnaces also include products of combustion, such as carbon monoxide (CO), carbon dioxide (CO₂), and nitrogen oxides (NO_x). Sulfur oxides (SO_x) also may be emitted, but they generally are absorbed by the molten material to form an immiscible sulphate that is eliminated in the quenching operation. Particulate matter also is emitted from drying, grinding, and materials handling and transfer operations.

Emissions from the furnace can be minimized by careful control of the rate and duration of raw material heating, to prevent volatilization of the more fusible charge materials. Emissions from rotary furnaces also can be reduced with careful control of the rotation speed, to prevent excessive dust carryover. Venturi scrubbers and fabric filters are the devices most commonly used to control emissions from frit smelting furnaces, and fabric filters are commonly used to control emissions from grinding operations. No information is available on the type of emission controls used on quenching, drying, and materials handling and transfer operations.

Tables 11.14-1 (metric units) and 11.14-2 (English units) present emission factors for filterable PM, CO, NO_x, and CO₂, emissions from frit manufacturing. Table 11.14-3 (metric and English units) presents emission factors for other pollutant emissions from frit manufacturing.

Table 11.14-1 (Metric Units).
EMISSION FACTORS FOR FRIT MANUFACTURING^a

EMISSION FACTOR RATING: E

Source	Filterable PM ^b	CO	NO _x	CO ₂
Smelting furnace (SCC 3-05-013-05,-06)	8.1 ^c	2.4 ^c	49 ^d	1,100 ^e
Smelting furnace with venturi scrubber (SCC 3-05-013-05,-06)	0.90 ^f	g	g	g
Smelting furnace with fabric filter (SCC 3-05-013-05,-06)	0.061 ^h	g	g	g

^a Factors represent uncontrolled emissions unless noted. Emission factor units are kg/Mg of feed material. 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 Reference 1.

^d Reference 10. EMISSION FACTOR RATING: D.

^e References 7-10.

^f References 7-9. EMISSION FACTOR RATING: D.

^g See factor for uncontrolled emissions.

^h Reference 10.

Table 11.14-2 (English Units).
EMISSION FACTORS FOR FRIT MANUFACTURING^a

EMISSION FACTOR RATING: E

Source	Filterable PM ^b	CO	NO _x	CO ₂
Smelting furnace (SCC 3-05-013-05,-06)	16 ^c	4.8 ^c	99	2,100 ^e
Smelting furnace with venturi scrubber (SCC 3-05-013-05,-06)	1.8 ^d	g	g	g
Smelting furnace with fabric filter (SCC 3-05-013-05,-06)	0.12 ^h	g	g	g

^a Factors represent uncontrolled emissions unless otherwise noted. Emission factor units are lb/ton of feed material. 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 Reference 1.

^d Reference 10. EMISSION FACTOR RATING: D.

^e References 7-10.

^f References 7-9. EMISSION FACTOR RATING: D.

^g See factor for uncontrolled emissions.

^h Reference 10.

Table 11.14-3 (Metric And English Units).
EMISSION FACTORS FOR FRIT MANUFACTURING--ORGANIC POLLUTANTS^a

EMISSION FACTOR RATING: E

	Pollutant	Emission factor,	
		kg/Mg	lb/ton
Smelting furnace with fabric filter (SCC 3-05-013-05,-06)	fluorides	2.6	5.2
	barium	8.4 x 10 ⁻⁵	0.00017
	chromium	4.2 x 10 ⁻⁵	8.3 x 10 ⁻⁵
	cobalt	1.3 x 10 ⁻⁵	2.5 x 10 ⁻⁵
	copper	5.6 x 10 ⁻⁵	0.00011
	lead	2.9 x 10 ⁻⁵	5.7 x 10 ⁻⁵
	manganese	4.3 x 10 ⁻⁵	8.5 x 10 ⁻⁵
	nickel	5.0 x 10 ⁻⁵	0.00010
	zinc	0.00038	0.00075

^a Reference 10. Factor units are kg/Mg and lb/ton of material feed.
SCC = Source Classification Code.

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11.19.1 Sand And Gravel Processing

11.19.1.1 Process Description¹⁻⁶

Deposits of sand and gravel, the unconsolidated granular materials resulting from the natural disintegration of rock or stone, are generally found in near-surface alluvial deposits and in subterranean and subaqueous beds. Sand and gravel are siliceous and calcareous products of the weathering of rocks and unconsolidated or poorly consolidated materials. Such deposits are common throughout the country. The six-digit Source Classification Code (SCC) for construction sand and gravel processing is 3-05-025, and the six-digit SCC for industrial sand and gravel is 3-05-027.

Construction Sand And Gravel -

Sand and gravel typically are mined in a moist or wet condition by open pit excavation or by dredging. Open pit excavation is carried out with power shovels, draglines, front end loaders, and bucket wheel excavators. In rare situations, light charge blasting is done to loosen the deposit. Mining by dredging involves mounting the equipment on boats or barges and removing the sand and gravel from the bottom of the body of water by suction or bucket-type dredges. After mining, the materials are transported to the processing plant by suction pump, earth mover, barge, truck, belt conveyors, or other means.

Although significant amounts of sand and gravel are used for fill, bedding, subbase, and basecourse without processing, most domestic sand and gravel are processed prior to use. The processing of sand and gravel for a specific market involves the use of different combinations of washers, screens, and classifiers to segregate particle sizes; crushers to reduce oversized material; and storage and loading facilities. A process flow diagram for construction sand and gravel processing is presented in Figure 11.19.1-1. The following paragraphs describe the process in more detail.

After being transported to the processing plant, the wet sand and gravel raw feed is stockpiled or emptied directly into a hopper, which typically is covered with a "grizzly" of parallel bars to screen out large cobbles and boulders. From the hopper, the material is transported to fixed or vibrating scalping screens by gravity, belt conveyors, hydraulic pump, or bucket elevators. The scalping screens separate the oversize material from the smaller, marketable sizes. Oversize material may be used for erosion control, reclamation, or other uses, or it may be directed to a crusher for size reduction, to produce crushed aggregate, or to produce manufactured sands. Crushing generally is carried out in one or two stages, although three-stage crushing may also be performed. Following crushing, the material is returned to the screening operation for sizing.

The material that passes through the scalping screen is fed into a battery of sizing screens, which generally consists of either horizontal or sloped, and either single or multideck, vibrating screens. Rotating trommel screens with water sprays are also used to process and wash wet sand and gravel. Screening separates the sand and gravel into different size ranges. Water is sprayed onto the material throughout the screening process. After screening, the sized gravel is transported to stockpiles, storage bins, or, in some cases, to crushers by belt conveyors, bucket elevators, or screw conveyors.

The sand is freed from clay and organic impurities by log washers or rotary scrubbers. After scrubbing, the sand typically is sized by water classification. Wet and dry screening is rarely used to size the sand. After classification, the sand is dewatered using screws, separatory cones, or

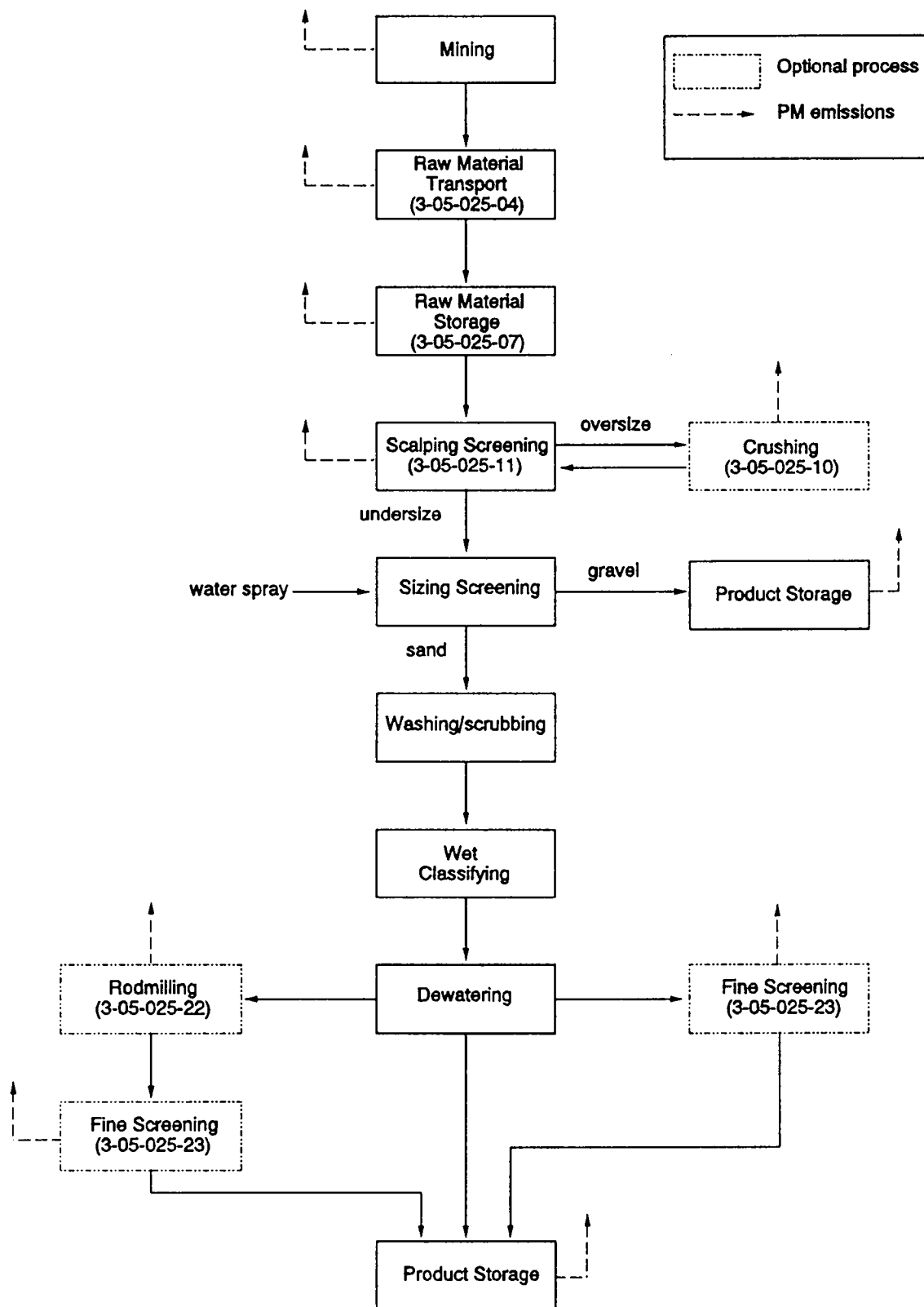


Figure 11.19.1-1. Process flow diagram for construction sand and gravel processing.
(Source Classification Codes in parentheses.)

hydroseparators. Material may also be rod-milled to produce smaller sized fractions, although this practice is not common in the industry. After processing, the sand is transported to storage bins or stockpiles by belt conveyors, bucket elevators, or screw conveyors.

Industrial Sand And Gravel -

Industrial sand and gravel typically are mined from open pits of naturally occurring quartz-rich sand and sandstone. Mining methods depend primarily on the degree of cementation of the rock. In some deposits, blasting is required to loosen the material prior to processing. The material may undergo primary crushing at the mine site before being transported to the processing plant.

Figure 11.19.1-2 is a flow diagram for industrial sand and gravel processing.

The mined rock is transported to the processing site and stockpiled. The material then is crushed. Depending on the degree of cementation, several stages of crushing may be required to achieve the desired size reduction. Gyratory crushers, jaw crushers, roll crushers, and impact mills are used for primary and secondary crushing. After crushing, the size of the material is further reduced to 50 micrometers (μm) or smaller by grinding, using smooth rolls, media mills, autogenous mills, hammer mills, or jet mills. The ground material then is classified by wet screening, dry screening, or air classification. At some plants, after initial crushing and screening, a portion of the sand may be diverted to construction sand use.

After initial crushing and screening, industrial sand and gravel are washed to remove unwanted dust and debris and are then screened and classified again. The sand (now containing 25 to 30 percent moisture) or gravel then goes to an attrition scrubbing system that removes surface stains from the material by rubbing in an agitated, high-density pulp. The scrubbed sand or gravel is diluted with water to 25 to 30 percent solids and is pumped to a set of cyclones for further desliming. If the deslimed sand or gravel contains mica, feldspar, and iron bearing minerals, it enters a froth flotation process to which sodium silicate and sulfuric acid are added. The mixture then enters a series of spiral classifiers where the impurities are floated in a froth and diverted to waste. The purified sand, which has a moisture content of 15 to 25 percent, is conveyed to drainage bins where the moisture content is reduced to about 6 percent. The material is then dried in rotary or fluidized bed dryers to a moisture content of less than 0.5 percent. The dryers generally are fired with natural gas or oil, although other fuels such as propane or diesel also may be used. After drying, the material is cooled and then undergoes final screening and classification prior to being stored and packaged for shipment.

11.19.1.2 Emissions And Controls⁶⁻¹⁴

Emissions from the production of sand and gravel consist primarily of particulate matter (PM) and particulate matter less than 10 micrometers (PM-10) in aerodynamic diameter, which are emitted by many operations at sand and gravel processing plants, such as conveying, screening, crushing, and storing operations. Generally, these materials are wet or moist when handled, and process emissions are often negligible. A substantial portion of these emissions may consist of heavy particles that settle out within the plant. Other potentially significant sources of PM and PM-10 emissions are haul roads. Emissions from dryers include PM and PM-10, as well as typical combustion products including CO, CO₂, and NO_x. In addition, dryers may be sources of volatile organic compounds (VOC) or sulfur oxides (SO_x) emissions, depending on the type of fuel used to fire the dryer.

With the exception of drying, emissions from sand and gravel operations primarily are in the form of fugitive dust, and control techniques applicable to fugitive dust sources are appropriate. Some successful control techniques used for haul roads are dust suppressant application, paving, route

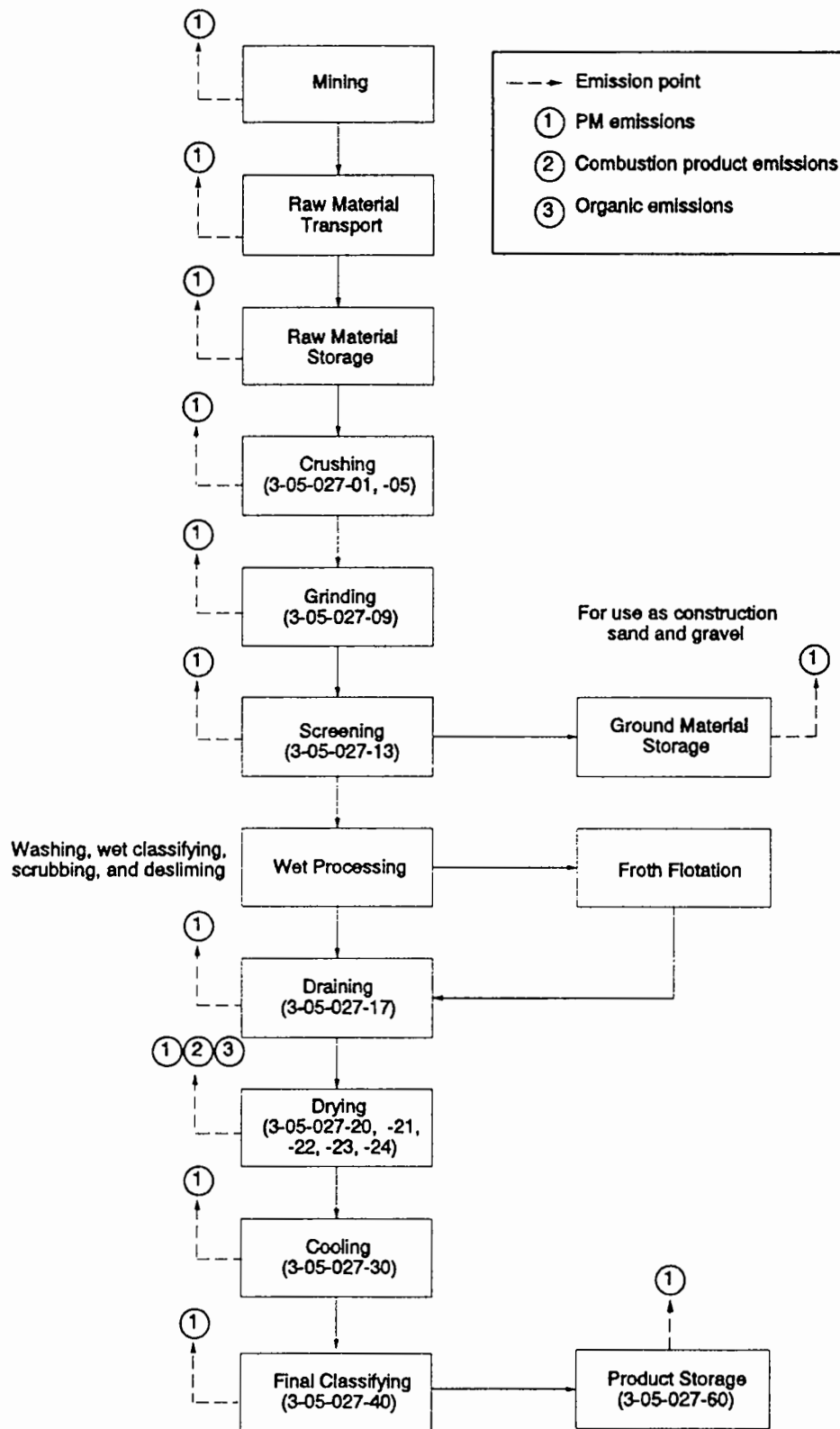


Figure 11.19.1-2. Process flow diagram for industrial sand and gravel processing.
(Source Classification Codes in parentheses.)

modifications, and soil stabilization; for conveyors, covering and wet suppression; for storage piles, wet suppression, windbreaks, enclosure, and soil stabilizers; for conveyor and batch transfer points, wet suppression and various methods to reduce freefall distances (e. g., telescopic chutes, stone ladders, and hinged boom stacker conveyors); and for screening and other size classification, covering and wet suppression.

Wet suppression techniques include application of water, chemicals and/or foam, usually at crusher or conveyor feed and/or discharge points. Such spray systems at transfer points and on material handling operations have been estimated to reduce emissions 70 to 95 percent. Spray systems can also reduce loading and wind erosion emissions from storage piles of various materials 80 to 90 percent. Control efficiencies depend upon local climatic conditions, source properties and duration of control effectiveness. Wet suppression has a carryover effect downstream of the point of application of water or other wetting agents, as long as the surface moisture content is high enough to cause the fines to adhere to the larger rock particles.

In addition to fugitive dust control techniques, some facilities use add-on control devices to reduce emissions of PM and PM-10 from sand and gravel processing operations. Controls in use include cyclones, wet scrubbers, venturi scrubbers, and fabric filters. These types of controls are rarely used at construction sand and gravel plants, but are more common at industrial sand and gravel processing facilities.

Emission factors for criteria pollutant emissions from industrial sand and gravel processing are presented in Table 11.19.1-1 (metric and English units), and emission factors for organic pollutant emissions from industrial sand and gravel processing are presented in Table 11.19.1-2 (metric and English units). Although no emission factors are presented for construction sand and gravel processing, emission factors for the crushing, screening, and handling and transfer operations associated with stone crushing can be found in Section 11.19.2, "Crushed Stone Processing." In the absence of other data, the emission factors presented in Section 11.19.2 can be used to estimate emissions from corresponding sand and gravel processing sources. The background report for this AP-42 section also presents factors for the combined emissions of total suspended particulate from construction gravel storage pile wind erosion, material handling, and vehicle traffic. However, because the applicability of those emission factors to other storage piles is questionable, they are not presented here. To estimate emissions from fugitive sources, refer to AP-42 Chapter 13, "Miscellaneous Sources". The emission factors for industrial sand storage and screening presented in Table 11.19.1-1 are not recommended as surrogates for construction sand and gravel processing, because they are based on emissions from dried sand and may result in overestimates of emissions from those sources. Construction sand and gravel are processed at much higher moisture contents.

Table 11.19.1-1 (Metric And English Units).
EMISSION FACTORS FOR INDUSTRIAL SAND AND GRAVEL PROCESSING^a

EMISSION FACTOR RATING: D

Source	Total PM		NO _x		CO ₂	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Sand dryer (SCC 3-05-027-20)	0.98 ^{b,c}	2.0 ^{b,c}	0.016 ^d	0.031 ^d	14 ^e	27 ^e
Sand dryer with wet scrubber (SCC 3-05-027-20)	0.019 ^{b,f}	0.039 ^{b,f}	g	g	g	g
Sand dryer with fabric filter (SCC 3-05-027-20)	0.0053 ^{b,h}	0.010 ^{b,h}	g	g	g	g
Sand handling, transfer, and storage with wet scrubber (SCC 3-05-027-60)	0.00064 ^j	0.0013 ^j	ND	ND	ND	ND
Sand screening with venturi scrubber (SCC 3-05-027-13)	0.0042 ^k	0.0083 ^k	ND	ND	ND	ND

^a Factors represent uncontrolled emissions unless noted. Dryer emission factors in units of kg/Mg and lb/ton of dried material produced; other factors in units of kg/Mg and lb/ton of material stored or screened. SCC = Source Classification Code.

^b Factors are for filterable PM only. Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train. Condensible organic and inorganic PM emission factors are not available. Factors presented can be considered a conservative underestimate of total PM.

^c Reference 12. EMISSION FACTOR RATING: E.

^d Reference 10.

^e References 10,13.

^f References 5,13. EMISSION FACTOR RATING: C.

^g Control device has no effect on emissions. See factor for uncontrolled emissions.

^h References 7,11.

^j Reference 9. For dried sand.

^k Reference 14. Screening of dried sand.

Table 11.19.1-2 (Metric And English Units).
EMISSION FACTORS FOR INDUSTRIAL SAND AND GRAVEL PROCESSING--
ORGANIC POLLUTANTS^a

EMISSION FACTOR RATING: D

Source	Pollutant		Emission factor	
	CASRN ^b	Name	kg/Mg	lb/ton
Diesel-fired rotary sand dryer with fabric filter (SCC 3-05-027-22)	50-00-0	Formaldehyde	0.0021	0.0043
	206-44-0	Fluoranthene	3.0×10^{-6}	6.0×10^{-6}
	91-20-3	Naphthalene	2.9×10^{-5}	5.9×10^{-5}
	85-01-8	Phenanthrene	7.5×10^{-6}	1.5×10^{-5}

^a Reference 8. Factors represent uncontrolled emissions unless noted. Dryer emission factors in units of kg/Mg and lb/ton of material dried. SCC = Source Classification Code.

^b Chemical Abstract Service Registry Number.

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11.22 Diatomite Processing

11.22.1 Process Description¹⁻²

Diatomite is a chalky, sedimentary rock consisting mainly of an accumulation of skeletons remaining from prehistoric diatoms, which are single-celled, microscopic aquatic plants. The skeletons are essentially amorphous hydrated or opaline silica occasionally with some alumina. Diatomite is primarily used to filter food processing products such as beer, whiskey, and fruit juice, and to filter organic liquids such as solvents and oils. Diatomite also is often used as a filler in paint, paper, asphalt products, and plastic. The six-digit Source Classification Code (SCC) for diatomite processing is 3-05-026.

Most diatomite deposits are found at or near the earth's surface and can be mined by open pit methods or quarrying. Diatomite mining in the United States is all open pit, normally using some combination of bulldozers, scraper-carriers, power shovels, and trucks to remove overburden and the crude material. In most cases, fragmentation by drilling and blasting is not necessary. The crude diatomite is loaded on trucks and transported to the mill or to stockpiles. Figure 11.22-1 shows a typical process flow diagram for diatomite processing.

The processing of uncalcined or natural-grade diatomite consists of crushing and drying. Crude diatomite commonly contains as much as 40 percent moisture, in many cases over 60 percent. Primary crushing to aggregate size (normally done by a hammermill) is followed by simultaneous milling-drying, in which suspended particles of diatomite are carried in a stream of hot gases. Flash and rotary dryers are used to dry the material to a powder of approximately 15 percent moisture. Typical flash dryer operating temperatures range from 70° to 430°C (150° to 800°F). The suspended particles exiting the dryer pass through a series of fans, cyclones, and separators to a baghouse. These sequential operations separate the powder into various sizes, remove waste impurities, and expel the absorbed water. These natural-milled diatomite products are then bagged or handled in bulk without additional processing.

For filtration uses, natural grade diatomite is calcined by heat treatment in gas- or fuel oil-fired rotary calciners, with or without a fluxing agent. Typical calciner operating temperatures range from 650° to 1200°C (1200° to 2200°F). For straight-calcined grades, the powder is heated in large rotary calciners to the point of incipient fusion, and thus, in the strict technical sense, the process is one of sintering rather than calcining. The material exiting the kiln then is further milled and classified. Straight calcining is used for adjusting the particle size distribution for use as a medium flow rate filter aid. The product of straight calcining has a pink color from the oxidation of iron in the raw material, which is more intense with increasing iron oxide content.

Further particle size adjustment is brought about by the addition of a flux, usually soda ash, before the calcining step. Added fluxing agent sinters the diatomite particles and increases the particle size, thereby allowing increased flow rate during liquid filtration. The resulting products are called "flux-calcined". Flux-calcining produces a white product, believed to be colored by the

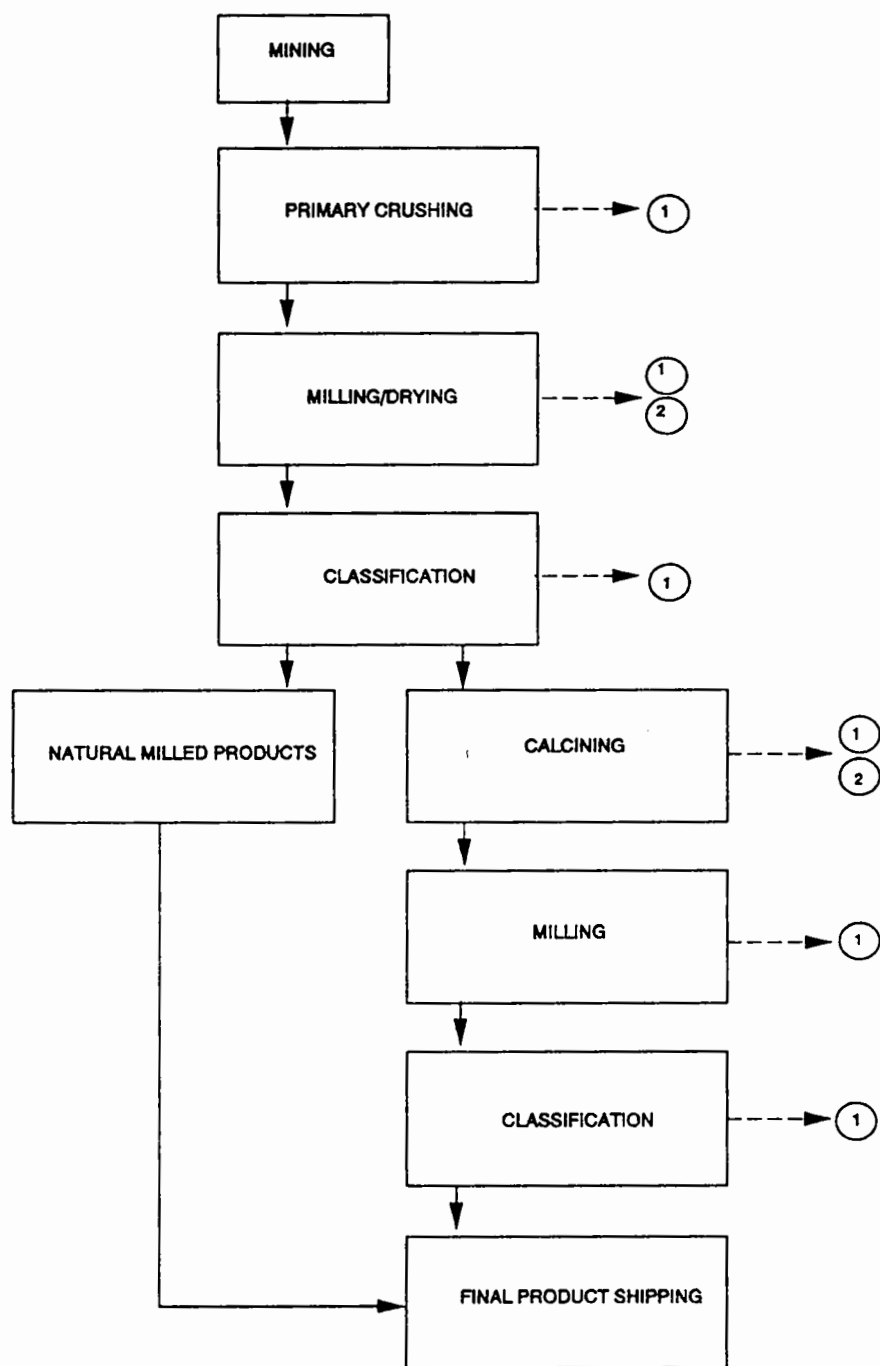


Figure 11.22-1. Typical process flow diagram for diatomite processing.

conversion of iron to complex sodium-aluminum-iron silicates rather than to the oxide. Further milling and classifying follow calcining.

11.22.2 Emissions And Controls¹⁻²

The primary pollutant of concern in diatomite processing is particulate matter (PM) and PM less than 10 micrometers (PM-10). Particulate matter is emitted from crushing, drying, calcining, classifying, and materials handling and transfer operations. Emissions from dryers and calciners include products of combustion, such as carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), and sulfur oxides (SO_x), in addition to filterable and condensable PM. Table 11.22-1 summarizes the results of a trace element analysis for one type of finished diatomite. These elements may constitute a portion of the PM emitted by the sources listed above.

Wet scrubbers and fabric filters are the most commonly used devices to control emissions from diatomite dryers and calciners. No information is available on the type of emission controls used on crushing, classifying, and materials handling and transfer operations.

Because of a lack of available data, no emission factors for diatomite processing are presented.

TABLE 11.22-1. TRACE ELEMENT CONTENT OF FINISHED DIATOMITE²

Element ^a	ppm ^b	Element	ppm
Antimony*	2	Mercury*	0.3
Arsenic*	5	Molybdenum	5
Barium	30	Neodymium	20
Beryllium*	1	Nickel*	120
Bismuth	<0.5	Niobium	5
Boron	100	Osmium	<0.5
Bromine	20	Palladium	<1
Cadmium*	2	Platinum	<2
Cerium	10	Praseodymium	2
Cesium	5	Rhenium	<0.5
Chlorine	400	Rhodium	<0.5
Chromium*	100	Rubidium	10
Cobalt*	5	Ruthenium	<1
Copper	40	Samarium	2
Dysprosium	<1	Scandium	20
Erbium	<0.5	Selenium*	10
Europium	1	Silver	<0.5
Fluorine	50	Strontium	20
Gadolinium	<1	Tantalum	20
Gallium	5	Tellurium	<2
Germanium	<10	Terbium	<0.2
Gold	<0.5	Thallium	<0.5
Hafnium	<0.5	Thorium	5
Holmium	<0.2	Thulium	0.2
Indium	<0.5	Tin	<1
Iodine	1	Tungsten	<0.5
Iridium	<0.5	Uranium	5
Lanthanum	10	Vanadium	200
Lead*	2	Ytterbium	<0.5
Lithium	1	Yttrium	100
Lutetium	<0.2	Zinc	<10
Manganese*	60	Zirconium	20

^a Listed hazardous air pollutants indicated by an asterisk (*).

^b < indicates below detection limit.

References For Section 11.22

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11.26 Talc Processing

11.26.1 Process Description¹⁻⁹

Talc, which is a soft, hydrous magnesium silicate ($3\text{MgO}\cdot 4\text{SiO}_2\cdot \text{H}_2\text{O}$), is used in a wide range of industries including the manufacture of ceramics, paints, paper, and asphalt roofing. The end-uses for talc are determined by variables such as chemical and mineralogical composition, particle size and shape, specific gravity, hardness, and color. There is no Source Classification Code (SCC) for the source category.

Over 95 percent of the talc ore produced in the United States comes from open-pit mines. Mining operations usually consist of conventional drilling and blasting methods.

Figure 11.26-1 is a process flow diagram for a typical domestic talc plant. Talc ore generally is hauled to the plant by truck from a nearby mine. The ore is crushed, typically in a jaw crusher, and screened. The coarse (oversize) material then is returned to the crusher. Rotary dryers may be used to dry the material. Secondary grinding is achieved with pebble mills or roller mills, producing a product that is 44 to 149 micrometers (μm) (325 to 100 mesh) in size. Some roller mills are designed to use heated air to dry the material as it is being ground. Hammer mills or steam- or compressed air-powered jet mills may be used to produce additional final products. Air classifiers (separators), generally in closed circuit with the mills, separate the material into coarse, coarse-plus-fine, and fine fractions. The coarse and coarse-plus-fine fractions then are stored as products. The fines may be concentrated using a shaking table (tabling process) to separate product containing small quantities of nickel, iron, cobalt, or other minerals and then may undergo a one-step flotation process. The resultant talc slurry is dewatered and filtered prior to passing through a flash dryer. The flash-dried product is then stored for shipment, unless it needs further grinding to meet customer specifications. The classified material also may be pelletized prior to packaging for specific applications. In the pelletizing step, processed talc is mixed with water to form a paste and then is extruded as pellets.

Talc deposits mined in the southwestern United States contain organic impurities and must be calcined prior to additional processing to yield a product with uniform chemical and physical properties. Generally, a separate product will be used to produce the calcined talc. Prior to calcining, the mined ore passes through a crusher and is ground to a specified screen size. After calcining in a rotary kiln, the material passes through a rotary cooler. The cooled calcine (0 percent free water) is then either stored for shipment or further processed. Calcined talc may be mixed with dried talc from other product lines and passed through a roller mill prior to bulk shipping.

11.26.2 Emissions And Controls^{1-2,4-5,7-8,10-13}

The primary pollutants of concern in talc processing are particulate matter (PM) and PM less than $10\ \mu\text{m}$ (PM-10). Particulate matter is emitted from drilling, blasting, crushing, screening, grinding, drying, calcining, classifying, materials handling and transfer operations, packaging, and storage. Although pelletizing is a wet process, PM may be emitted from the transfer and feeding of processed talc to the pelletizer. Depending on the purity of the talc ore body, PM emissions may include trace amounts of several inorganic compounds that are listed hazardous air pollutants (HAP), including arsenic, cadmium, chromium, cobalt, manganese, nickel, and phosphorus.

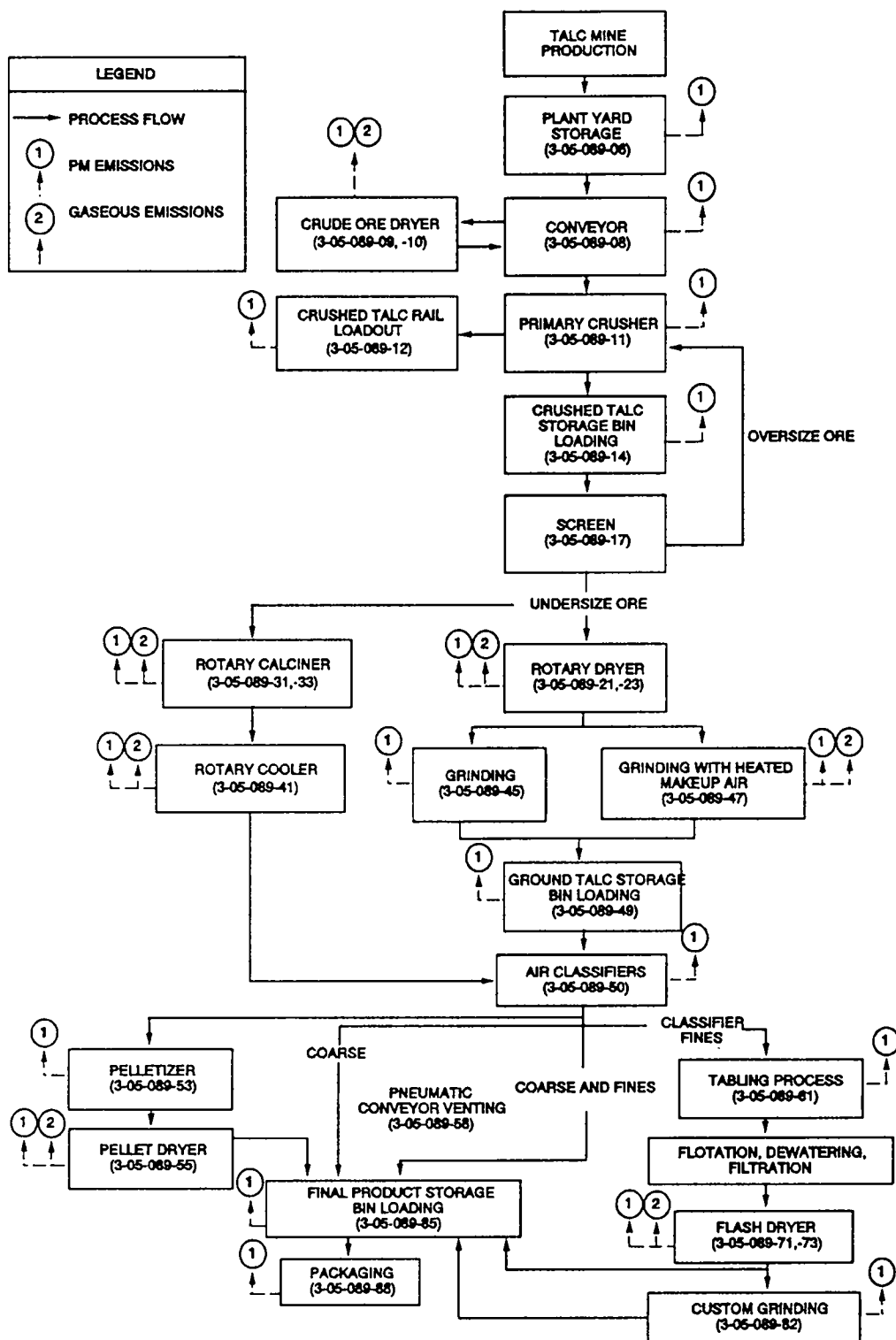


Figure 11.26-1. Process flow diagram for talc processing.^{1,4,6}
(Source Classification Codes in parentheses.)

The emissions from dryers and calciners include products of combustion, such as carbon monoxide, carbon dioxide, nitrogen oxides, and sulfur oxides, in addition to filterable and condensable PM. Volatile organic compounds also are emitted from the drying and calcining of southwestern United States talc deposits, which generally contain organic impurities. Products of combustion and VOC may also be emitted from roller mills that use heated air and from the furnaces that provide the heated air to the mill.

Emissions from talc dryers and calciners are typically controlled with fabric filters. Fabric filters also are used at some facilities to control emissions from mechanical processes such as crushing and grinding. Emission factors for emissions from talc processing are presented in Table 11.26-1. Particle size distributions for talc processing are summarized in Table 11.26-2 and are depicted graphically in Figure 11.26-2.

Table 11.26-1. EMISSION FACTORS FOR TALC PROCESSING^a

EMISSION FACTOR RATING: D

Process	Total PM ^b	CO ₂
	lb/1,000 lb	lb/1,000 lb
Natural gas-fired crude ore drying with fabric filter ^c (SCC 3-05-089-09)	0.0020	ND
Primary crushing, with fabric filter ^d (SCC 3-05-089-11)	0.00074	NA
Crushed talc railcar loading ^e (SCC 3-05-089-12)	0.00049	NA
Screening, with fabric filter ^f (SCC 3-05-089-17)	0.0043	NA
Grinding, with fabric filter ^g (SCC 3-05-089-45)	0.022	NA
Grinding with heated makeup air, with fabric filter (SCC 3-05-089-47)	0.022 ^g	9.3 ^h
Classifying, with fabric filter ^j (SCC 3-05-089-50)	0.00077	NA
Pellet drying, with fabric filter ^k (SCC 3-05-089-55)	0.032	ND
Pneumatic conveyor venting, with fabric filter ^m (SCC 3-05-089-58)	0.0018	NA
Packaging, with fabric filter ⁿ (SCC 3-05-089-88)	0.0090	NA
Crushed talc storage bin loading, with fabric filter ^p (SCC 3-05-089-14)	0.0036	NA
Ground talc storage bin loading, with fabric filter ^q (SCC 3-05-089-49)	0.0016	NA
Final product storage bin loading, with fabric filter ^p (SCC 3-05-089-85)	0.0035	NA

^a Units are lb/1,000 lb of production unless noted. One lb/1,000 lb is equal to 1 kg/Mg.

SCC = Source Classification Code. NA = not applicable. ND = no data.

^b Total PM includes the PM collected in the front half and the inorganic PM caught in the back half (impingers) of a Method 5 sampling train.^c Reference 15. Filterable PM fraction is 60%, and condensible inorganic fraction is 40%.^d References 10,13,15.^e Reference 14.^f References 10,13. For crushed talc ore.^g References 11,13.^h References 10-11. For roller mill using heated makeup air. EMISSION FACTOR RATING: E.^j Reference 13. For ground talc.^k Reference 13. Filterable PM fraction is 56%, and condensible inorganic fraction is 44%. EMISSION FACTOR RATING: E.^m Reference 13. For final product. Units are lb/1,000 lb of material conveyed.ⁿ Reference 10,13.^p Reference 13. Units are lb/1,000 lb of material loaded into storage bin.^q Reference 12. Units are lb/1,000 lb of material loaded into storage bin.

Table 11.26-2. SUMMARY OF PARTICLE SIZE DISTRIBUTIONS FOR
TALC PROCESSING^a

Process	Diameter, μm	Cumulative Percent Less Than Diameter
Primary crushing (SCC 3-05-089-11)	55.4	91.3
	34.9	78.2
	22.0	56.7
	17.4	47.2
	11.0	38.8
	6.9	21.4
	3.0	3.0
	2.0	0.94
	1.0	0.11
Grinding (SCC 3-05-089-45)	29.0	100.0
	18.8	99.7
	14.9	99.4
	11.9	97.1
	9.4	80.8
	7.5	43.3
	4.7	7.5
	3.0	2.1
	1.9	0.28
	1.0	0.04
Storage, bagging, air classification (SCC 3-05-089-85,-88,-50)	43.9	99.9
	27.7	97.9
	17.4	86.6
	13.8	73.2
	11.0	56.8
	6.9	24.5
	4.4	7.4
	3.0	3.1
	2.0	0.92
	1.0	0.10

^a Reference 5. Optical procedures used to determine particle size distribution, rather than inertial separators. Data are suspect. SCC = Source Classification Code.

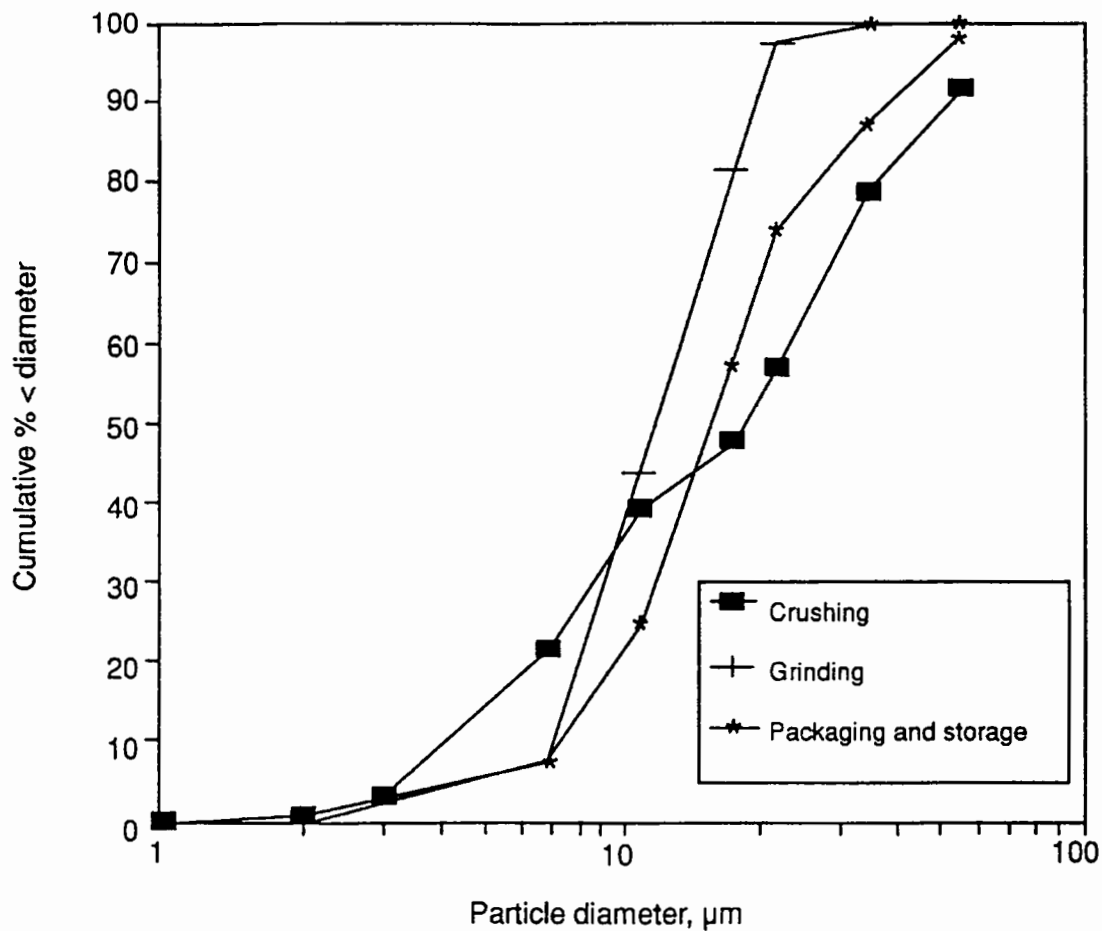


Figure 11.26-2. Particle size distribution for talc processing.⁵

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11.28 Vermiculite Processing

11.28.1 Process Description¹⁻⁹

Vermiculite is the geological name given to a group of hydrated laminar minerals that are aluminum-iron-magnesium silicates and that resemble mica in appearance. The chemical formula for vermiculite is $(\text{Mg}, \text{Ca}, \text{K}, \text{Fe}^{+2})_3(\text{Si}, \text{Al}, \text{Fe}^{+3})_4\text{O}_{10}(\text{OH})_2 \cdot 4\text{H}_2\text{O}$. When subjected to heat, vermiculite has the unusual property of exfoliating, or expanding, due to the interlaminar generation of steam. Uses of unexpanded vermiculite include muds for oil-well drilling and fillers in fire-resistant wallboard. The six-digit source classification code (SCC) for vermiculite processing is 3-05-033.

Vermiculite ore is mined using open-pit methods. Beneficiation includes screening, flotation, drying in rotary or fluid bed dryers, and expansion by exposure to high heat. All mined vermiculite is dried and sized at the mine site prior to exfoliation.

Crude Ore Processing -

Figure 11.28-1 is a process flow diagram for vermiculite processing. Crude ore from open-pit mines is brought to the mill by truck and is loaded onto outdoor stockpiles. Primary processing consists of screening the raw material to remove the waste rock greater than 1.6 centimeters (cm) (5/8 inch [in.]) and returning the raw ore to stockpiles. Blending is accomplished as material is removed from stockpiles and conveyed to the mill feed bin. The blended ore is fed to the mill, where it is separated into fractions by wet screening and then concentrated by gravity. All concentrates are collected, dewatered, and dried in either a fluidized bed or rotary dryer. Drying reduces the moisture content of the vermiculite concentrate from approximately 15 to 20 percent to approximately 2 to 6 percent. At least one facility uses a hammermill to crush the material exiting the dryer. However, at most facilities, the dryer products are transported by bucket elevators to vibrating screens, where the material is classified. The dryer exhaust generally is ducted to a cyclone for recovering the finer grades of vermiculite concentrate. The classified concentrate then is stored in bins or silos for later shipment or exfoliation.

The rotary dryer is the more common dryer type used in the industry, although fluidized bed dryers also are used. Drying temperatures are 120° to 480°C (250° to 900°F), and fuel oil is the most commonly used fuel. Natural gas and propane also are used to fuel dryers.

Exfoliation -

After being transported to the exfoliation plant, the vermiculite concentrate is stored. The ore concentrate then is conveyed by bucket elevator or other means and is dropped continuously through a gas- or oil-fired vertical furnace. Exfoliation occurs after a residence time of less than 8 seconds in the furnace, and immediate removal of the expanded material from the furnace prevents damage to the structure of the vermiculite particle. Flame temperatures of more than 540°C (1000°F) are used for exfoliation. Proper exfoliation requires both a high rate of heat transfer and a rapid generation of steam within the vermiculite particles. The expanded product falls through the furnace and is air conveyed to a classifier system, which collects the vermiculite product and removes excessive fines. The furnace exhaust generally is ducted through a product recovery cyclone, followed by an emission control device. At some facilities, the exfoliated material is ground in a pulverizer prior to being classified. Finally, the material is packaged and stored for shipment.

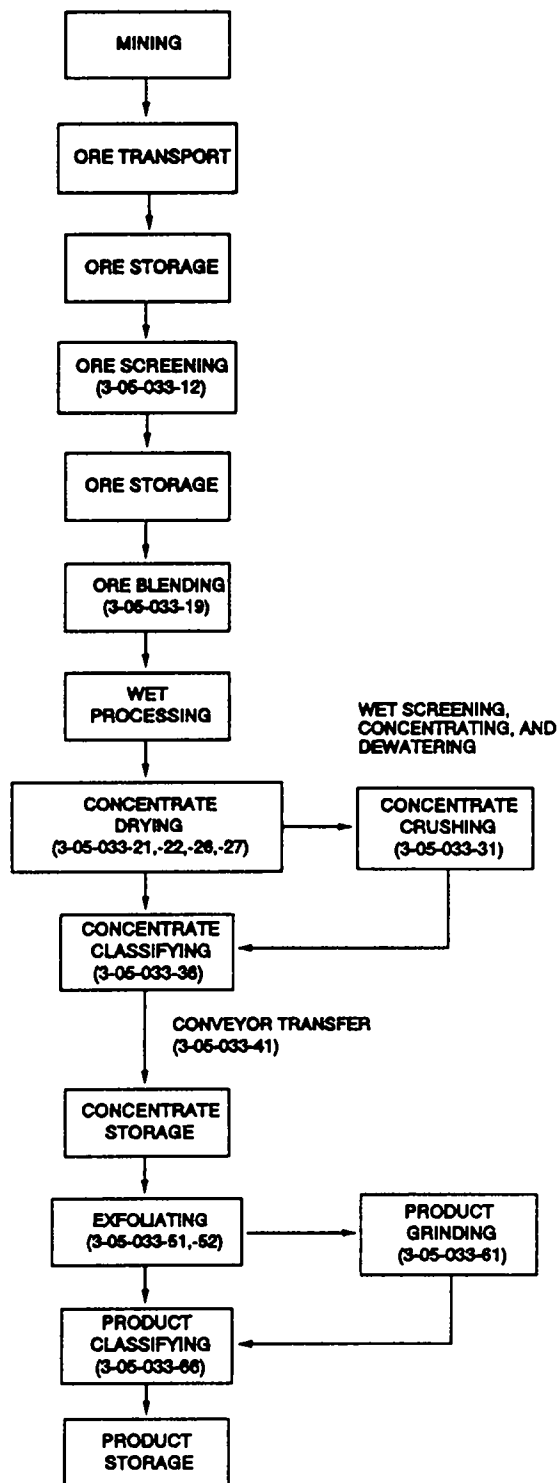


Figure 11.28-1. Process flow diagram for vermiculite processing.
(Source Classification Codes in parentheses.)

11.28.2 Emissions And Controls^{1,4-11}

The primary pollutants of concern in vermiculite processing are particulate matter (PM) and PM less than 10 micrometers (PM-10). Particulate matter is emitted from screening, drying, exfoliating, and materials handling and transfer operations. Emissions from dryers and exfoliating furnaces, in addition to filterable and condensible PM and PM-10, include products of combustion, such as carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), and sulfur oxides (SO_x).

Wet scrubbers are typically used to control dryer emissions. The majority of expansion furnaces are ducted to fabric filters for emission control. However, wet scrubbers also are used to control the furnace emissions. Cyclones and fabric filters also are used to control emissions from screening, milling, and materials handling and transfer operations.

Table 11.28-1 summarizes the emission factors for vermiculite processing.

Table 11.28-1 EMISSION FACTORS FOR VERMICULITE PROCESSING^a

EMISSION FACTOR RATING: D

Process	Filterable PM ^b	Condensible organic PM ^c	Total PM ^d	CO ₂
	kg/Mg	kg/Mg	kg/Mg	kg/Mg
Rotary dryer, with wet collector (SCC 3-05-033-21,-22)	0.29 ^e	ND	ND	50 ^f
Concentrate screening, with cyclone (SCC 3-05-033-36)	0.30 ^g	NA	0.30 ^g	NA
Concentrate conveyor transfer, with cyclone (SCC 3-05-033-41)	0.013 ^g	NA	0.013 ^g	NA
Exfoliation - gas-fired vertical furnace, with fabric filter (SCC 3-05-033-51)	0.32 ^h	0.18 ^j	0.50 ^k	ND
Product grinding, with fabric filter (SCC 3-05-033-61)	0.18 ^m	NA	0.18 ^m	NA

^a Factors represent uncontrolled emissions unless noted. Emission factor units for drying are kg/Mg of material feed; emission factor units for other processes are kg/Mg of product. 1 kg/Mg is equivalent to 1 lb/1,000 lb. SCC = Source Classification Code. ND = no data. NA = not applicable.

^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. Condensible organic PM is the organic fraction of the condensible PM.

^d Total PM equals the sum of the filterable PM, condensible organic PM, and condensible inorganic PM.

^e Reference 8. EMISSION FACTOR RATING: E.

^f References 8,11. Factor represents uncontrolled emissions of CO₂.

^g Reference 11. For dried ore concentrate.

^h Reference 10.

^j Reference 10. Emissions may be largely from volatilization of oil used in ore beneficiation.

^k Sum of factors for filterable PM and condensible organic PM; does not include condensible inorganic PM.

^m Reference 9.

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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. 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.

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.

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

k = base emission factor for particle size range and units of interest (see below)

sL = road surface silt loading (grams per square meter) (g/m^2)

W = average weight (tons) of the vehicles traveling the road

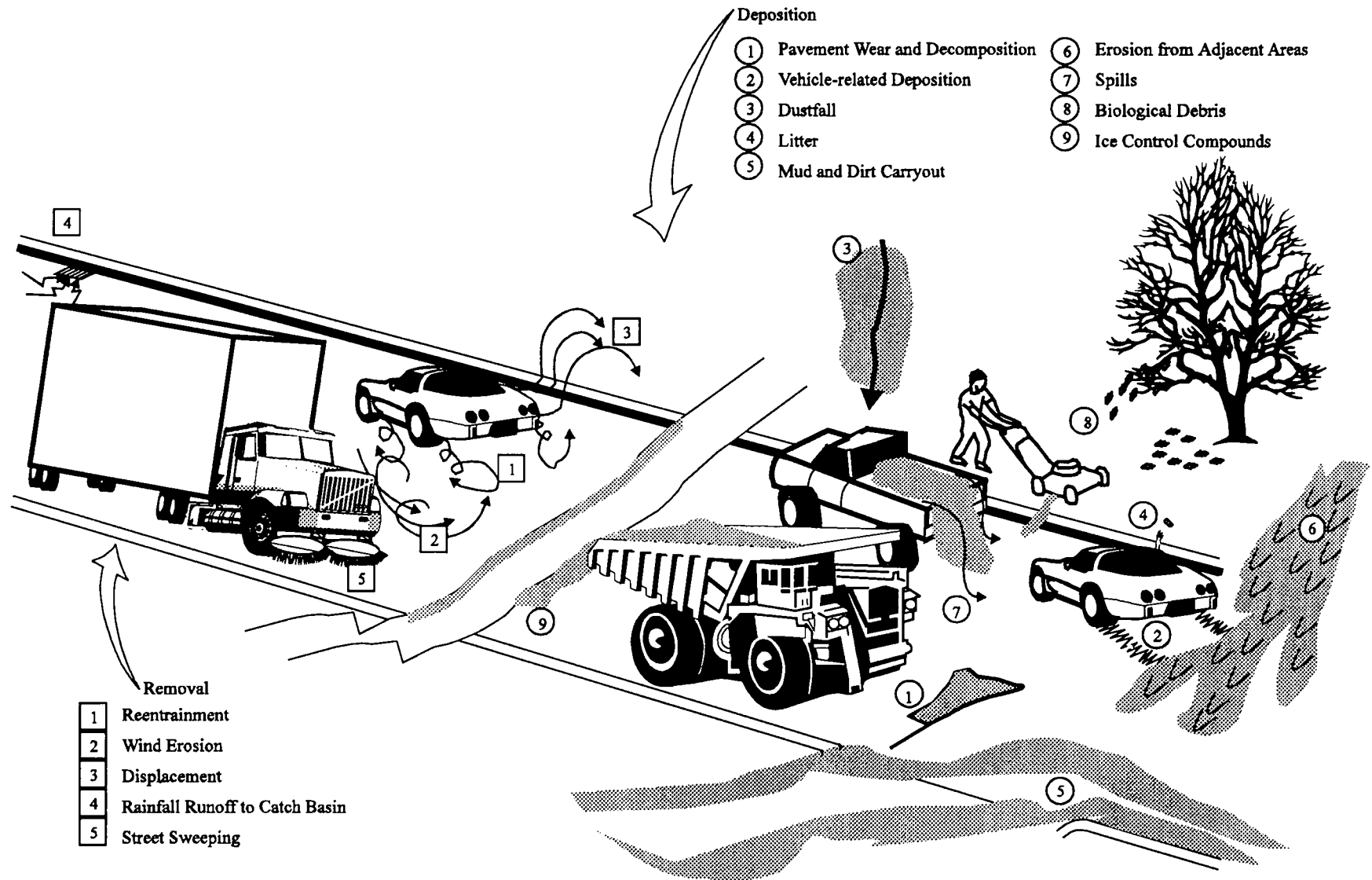


Figure 13.2.1-1. Deposition and removal processes.

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 1 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 follows:

Particle Size Multipliers For Paved Road Equation

Size Range ^a	Multiplier k ^b		
	g/VKT	g/VMT	lb/VMT
PM-2.5	2.1	3.3	0.0073
PM-10	4.6	7.3	0.016
PM-15	5.5	9.0	0.020
PM-30 ^c	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).

^c PM-30 is sometimes termed "suspendable particulate" (SP) and is often used as a surrogate for TSP.

To determine particulate emissions for a specific particle size range, use the appropriate value of k above.

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. No tests of "stop-and-go" traffic 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. 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 an industrial road may be selected from the mean values given in Table 13.2.1-1, but the quality rating of the equation should be reduced by 1 level. **Also, recall that Equation 1 refers to emissions due to freely flowing (not stop-and-go) traffic.**

Table 13.2.1-1 (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 ^b	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 1-2,5-6,10-12. Values represent samples collected from *industrial* roads. Public road silt loading values are presented in Figure 13.2.1-2, Figure 13.2.1-3, Figure 13.2.1-4, Figure 13.2.1-5, Figure 13.2.1-6, and Figure 13.2.1-7, and Tables 13.2.1-2 and 13.2.1-3. 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).

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. Although hundreds of public paved road sL measurements have been made since 1980,^{8, 14-21} uniformity has been lacking in sampling equipment and analysis techniques, in roadway classification schemes, and in the types of data reported.¹⁰ The assembled data set (described below) does not yield any readily identifiable, coherent relationship between sL and road class, average daily traffic (ADT), etc., even though an inverse relationship between sL and ADT had been found for a subclass of curbed paved roads in urban areas.⁸ The absence of such a relationship in the composite data set is believed to be due to the blending of data (industrial and nonindustrial, uncontrolled, and controlled, and so on). Further complicating any 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. For example, repeated sampling of the same roads over a period of 3 calendar years at 4 Montana municipalities indicated a noticeable annual cycle. In those areas, silt loading declines during the first 2 calendar quarters and increases during the fourth quarter.

Figure 13.2.1-2 and Figure 13.2.1-3 present the cumulative frequency distribution for the public paved road sL data base assembled during the preparation of this AP-42 section.¹⁰ The data base includes samples taken from roads that were treated with sand and other snow/ice controls. Roadways are grouped into high- and low-ADT sets, with 5000 vehicles per day being the approximate cutpoint. Figure 13.2.1-2 and Figure 13.2.1-3, respectively, present the cumulative frequency distributions for high- and low-ADT roads.

In the absence of site-specific sL data to serve as input to a public paved road inventory, conservatively high emission estimates can be obtained by using the following values taken from the figures. For annual conditions, the median sL values of 0.4 g/m² can be used for high-ADT roads (excluding limited access roads that are discussed below) and 2.5 g/m² for low-ADT roads. Worst-case loadings can be estimated for high-ADT (excluding limited access roads) and low-ADT roads, respectively, with the 90th percentile values of 7 and 25 g/m². Figure 13.2.1-4, Figure 13.2.1-5, Figure 13.2.1-6, and Figure 13.2.1-7 present similar cumulative frequency distribution information for high- and low-ADT roads, except that the sets were divided based on whether the sample was collected during the first or second half of the year. Information on the 50th and 90th percentile values is summarized in Table 13.2.1-2.

Table 13.2.1-2 (Metric Units). PERCENTILES FOR NONINDUSTRIAL SILT LOADING (g/m²) DATA BASE

Averaging Period	High-ADT Roads		Low-ADT Roads	
	50th	90th	50th	90th
Annual	0.4	7	2.5	25
January-June	0.5	14	3	30
July-December	0.3	3	1.5	5

In the event that sL values are taken from any of the cumulative frequency distribution figures, the quality ratings for the emission estimates should be downgraded 2 levels.

As an alternative method of selecting sL values in the absence of site-specific data, users can review the public (i. e., nonindustrial) paved road sL data base presented in Table 13.2.1-3 and can select values that are appropriate for the roads and seasons of interest. Table 13.2.1-3 presents paved road surface loading values together with the city, state, road name, collection date (samples collected from the same road during the same month are averaged), road ADT if reported, classification of the roadway, etc. Recommendation of this approach recognizes that end users of AP-42 are capable of identifying roads in the data base that are similar to roads in the area being inventoried. In the event that sL values are developed in this way, and that the selection process is fully described, then the quality ratings for the emission estimates should be downgraded only 1 level.

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 1 part of the country to another. For annual conditions, a default value of 0.02 g/m^2 is recommended for limited access roadways. Even fewer of the available data correspond to worst-case situations, and elevated loadings are observed to be quickly depleted because of high ADT rates. A default value of 0.1 g/m^2 is recommended for short periods of time following application of snow/ice controls to limited access roads.

13.2.1.4 Controls^{6,22}

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.

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. 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.

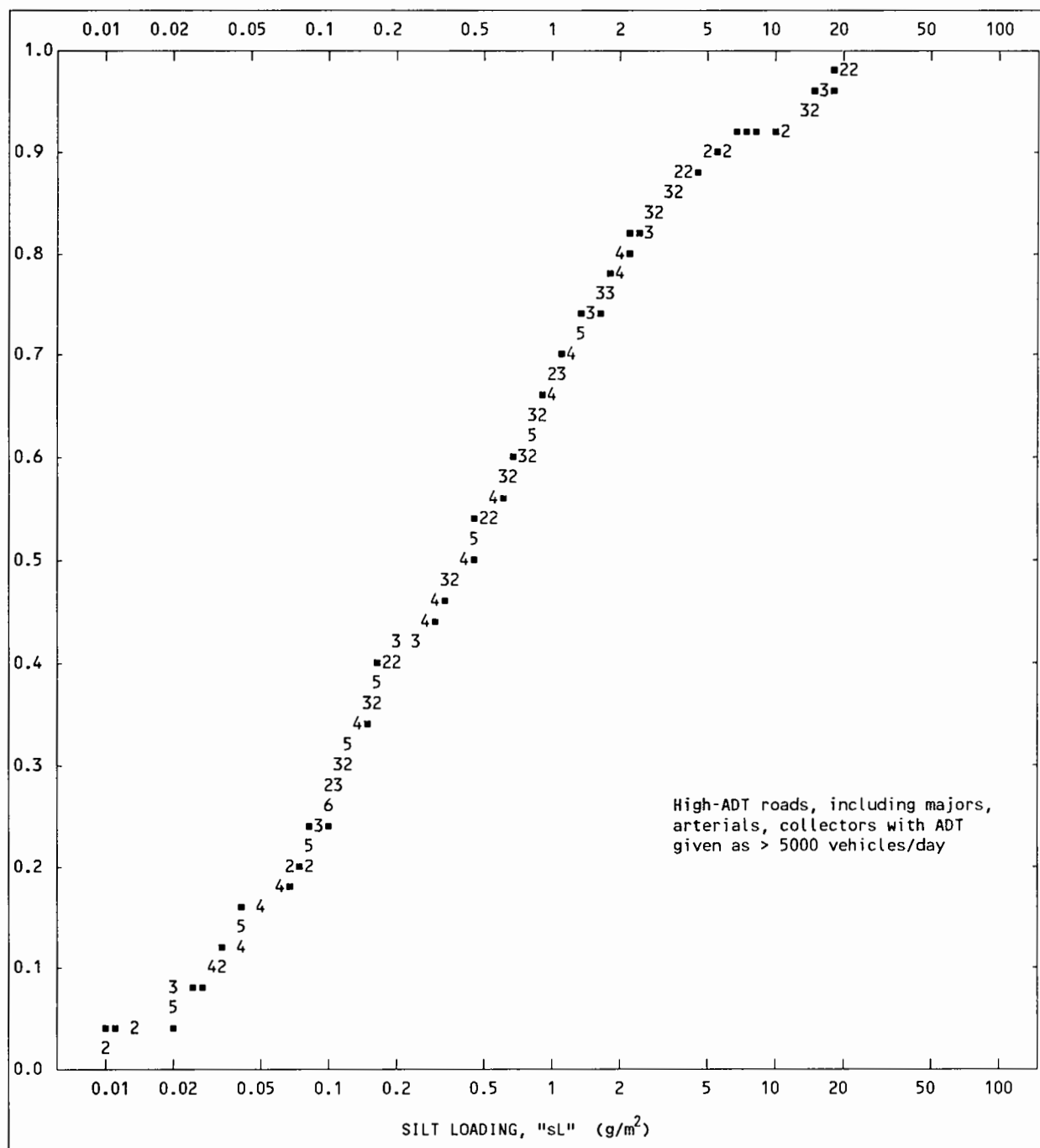


Figure 13.2.1-2. Cumulative frequency distribution for surface silt loading on high-ADT roadways.

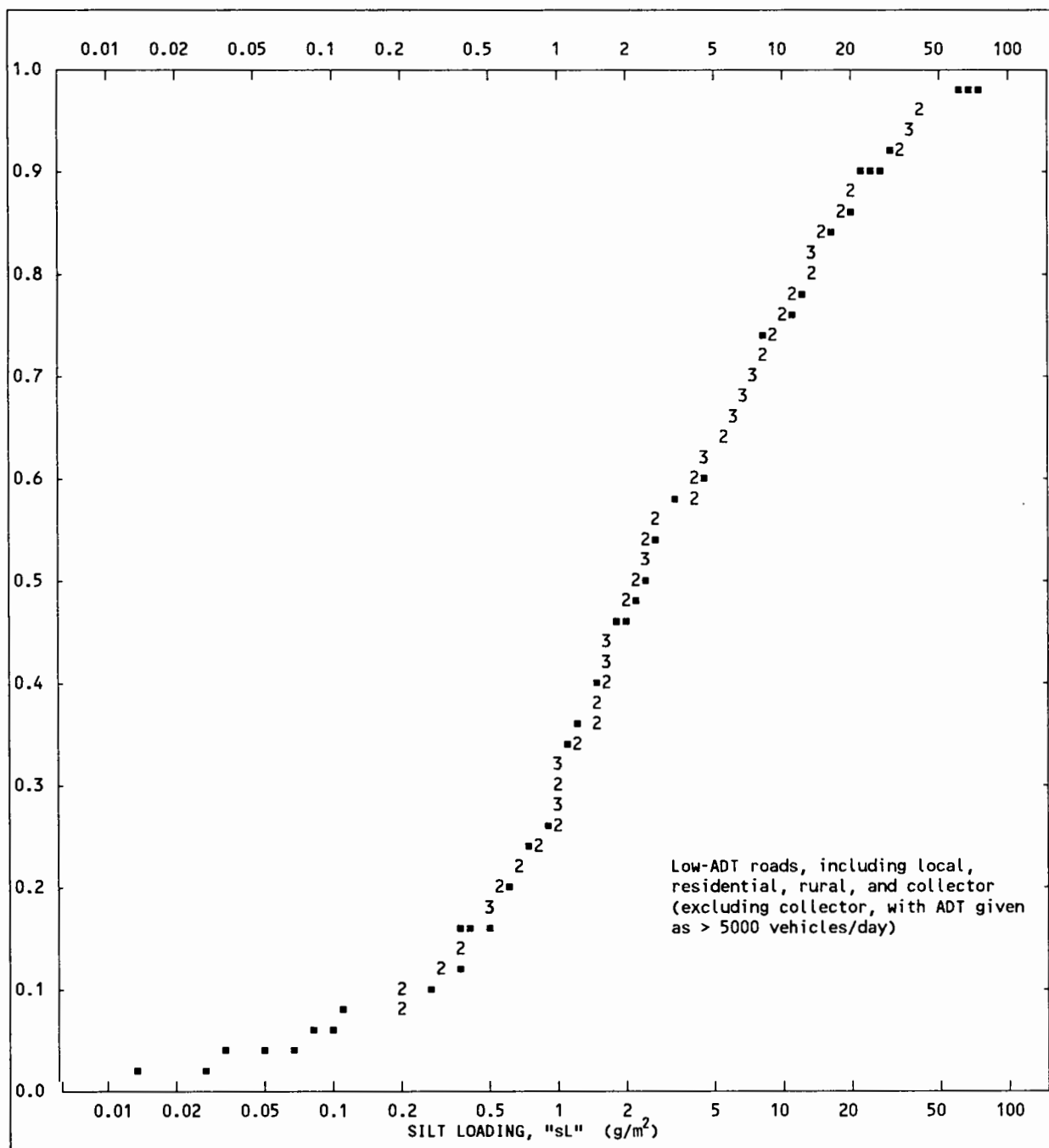


Figure 13.2.1-3. Cumulative frequency distribution for surface silt loading on low-ADT roadways.

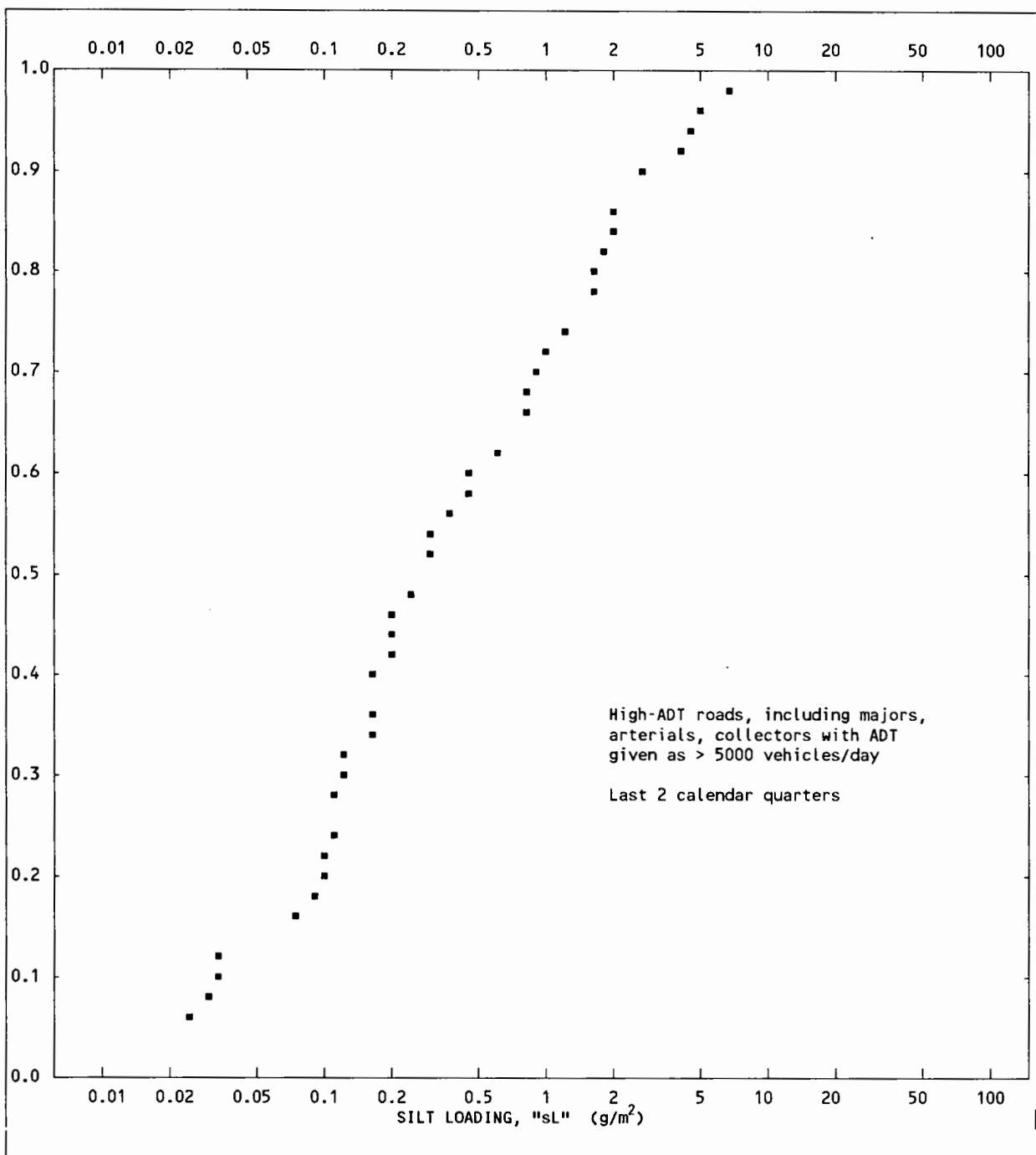


Figure 13.2.1-5. Cumulative frequency distribution for surface silt loading on high-ADT roadways, based on samples during second half of the calendar year.

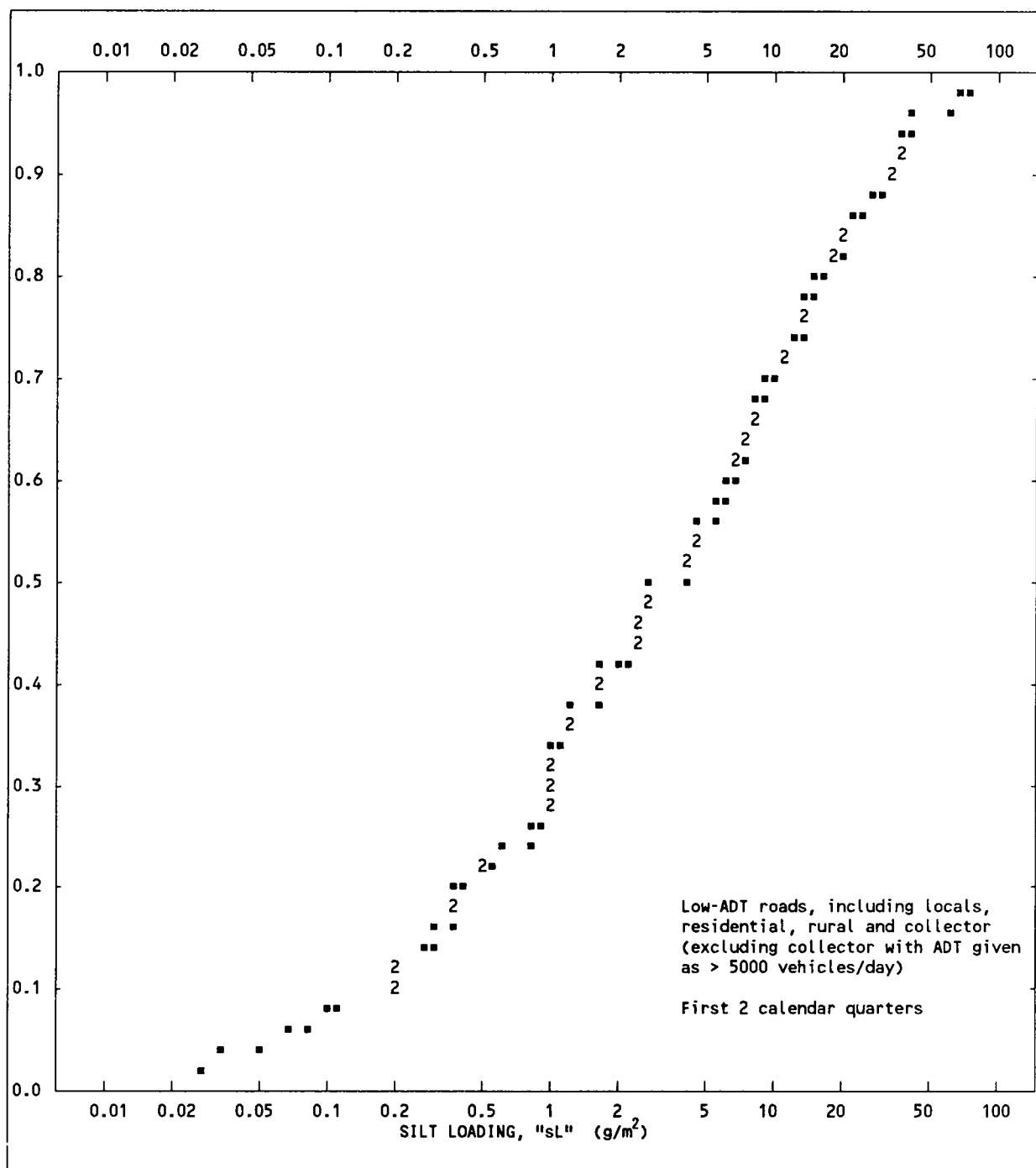


Figure 13.2.1-6. Cumulative frequency distribution for surface silt loading on low-ADT roadways, based on samples during first half of the calendar year.

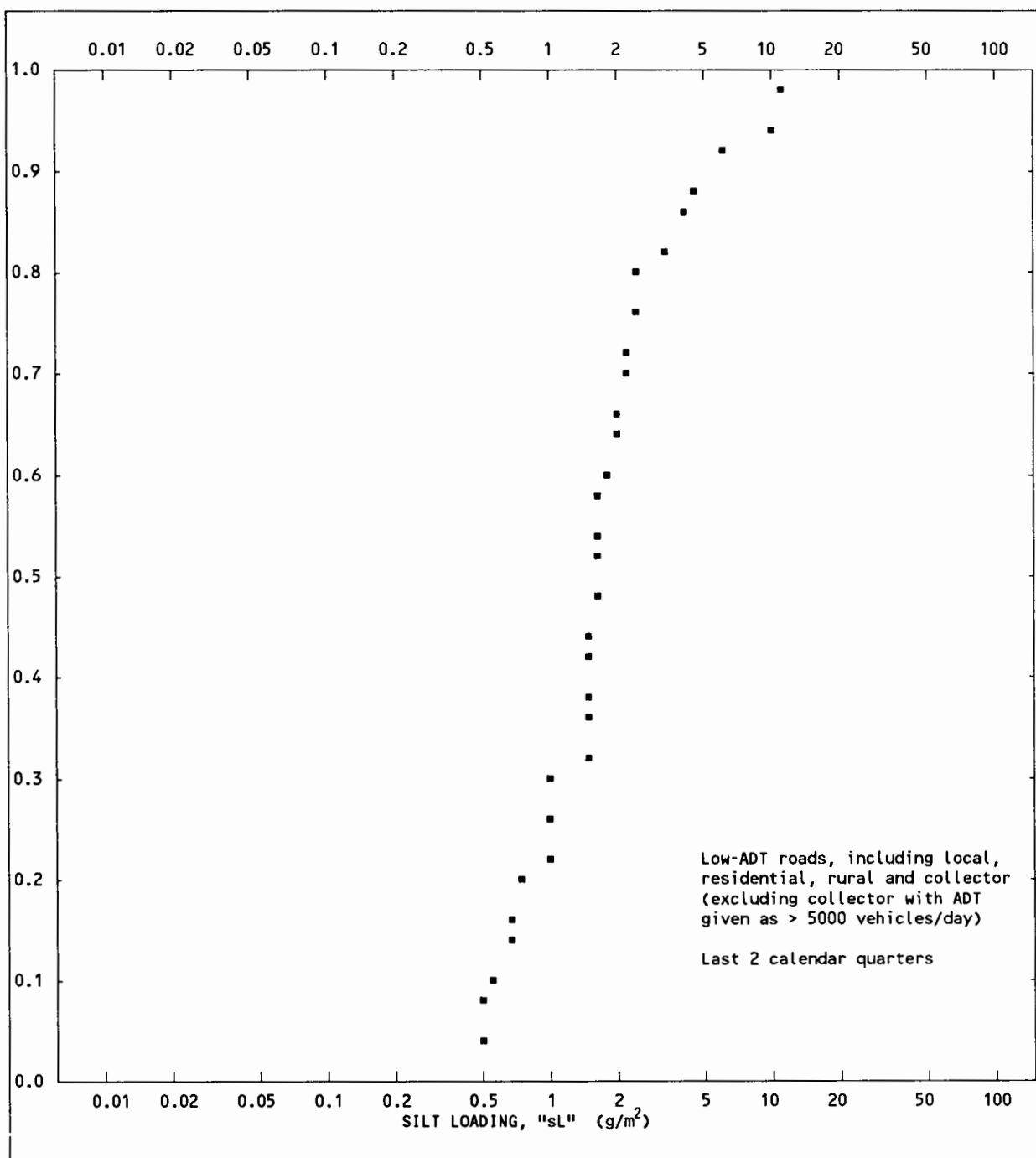


Figure 13.2.1-7. Cumulative frequency distribution for surface silt loading on low-ADT roadways, based on samples during second half of the calendar year.

Table 13.2.1-3. NONINDUSTRIAL PAVED ROAD SAMPLING DATA^a

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
MT	Billings	ND	Rural	04/78	50	0.6	18.5	3.4	2 samples, range: 1.0 - 2.2
MT	Billings	Yellowstone	Residential	04/78	115	0.5	14.3	3.5	
MT	Missoula	Bancroft	Residential	04/78	4000	8.4	33.9	24.9	
MT	Butte	1st St	Residential	04/78	679	24.6	10.6	232.4	
MT	Butte	N Park Pl	Residential	04/78	60	103.7	7	1480.8	
MT	Billings	Grand Ave	Collector	04/78	6453	1.6	19.1	13.05	
MT	Billings	4th Ave E	Collector	04/78	3328	7.7	7.7	99.5	
MT	Missoula	6th St	Collector	04/78	3655	26	62.9	6	
MT	Butte	Harrison	Arterial	04/78	22849	1.9	5	37.3	
MT	Missoula	Highway 93	Arterial	04/78	18870	1.9	55.9	3.3	
MT	Butte	Montana	Arterial	04/78	13529	0.8	6.6	11.9	
MT	East Helena	Thurman	Residential	04/83	140	13.1	4.3	305.2	
MT	East Helena	1st St	Local	04/83	780	4	13.6	29	
MT	East Helena	Montana	Collector	04/83	2700	8.2	9.4	86.6	
MT	East Helena	Main St	Collector	04/83	1360	4.7	8.4	55.3	
MT	Libby	6th	Local	03/88	1310	ND	14.8	ND	
MT	Libby	5th	Local	03/88	331	ND	16.5	ND	
MT	Libby	Champion Int So gate	Collector	03/88	800	ND	27.5	ND	
MT	Libby	Mineral Ave	Collector	03/88	5900	7	16	43.5	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
MT	Libby	Main Ave btwn 6th &	Collector	03/88	536	61	20.4	299.2	
MT	Libby	California	Collector	03/88	4500	ND	12.1	ND	
MT	Libby	US 2	Arterial	03/88	10850	ND	12.3	ND	
MT	Butte	Garfield Ave	Residential	04/88	562	2.1	10.9	19.3	
MT	Butte	Continental Dr	Arterial	04/88	5272	0.9	10.1	8.8	
MT	Butte	Garfield Ave	Residential	06/89	562	1	8.7	11.2	
MT	Butte	So Park Ave	Residential	06/89	60	2.8	10.9	25.5	
MT	Butte	Continental Dr	Arterial	06/89	5272	7.2	3.6	197.6	
MT	East Helena	Morton St	Local	08/89	250	1.7	6.8	24.6	
MT	East Helena	Main St	Collector	08/89	2316	0.7	4.1	17	
MT	East Helena	US 12	Arterial	08/89	7900	2.1	12.5	16.5	
MT	Columbia Falls	7th St	Residential	03/90	390	ND	9.5	ND	
MT	Columbia Falls	4th St	Residential	03/90	400	18.8	14.3	131.5	
MT	Columbia Falls	3rd Ave	Residential	03/90	50	ND	14.3	ND	
MT	Columbia Falls	4th Ave	Residential	03/90	1720	ND	5.4	ND	
MT	Columbia Falls	CF Forest	Local	03/90	240	ND	16.3	ND	
MT	Columbia Falls	12th Ave	Collector	03/90	1510	ND	8.8	ND	
MT	Columbia Falls	3rd St	Collector	03/90	1945	ND	7	ND	
MT	Columbia Falls	Nucleus	Collector	03/90	4730	15.4	10	153.9	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
MT	Columbia Falls	Plum Creek	Collector	03/90	316	ND	6.2	ND	
MT	Columbia Falls	6th Ave	Collector	03/90	1764	ND	4.2	ND	
MT	Columbia Falls	US 2	Arterial	03/90	13110	2.7	18.7	14.6	
MT	East Helena	Morton	Residential	07/90	250	1.6	17	9.3	
MT	East Helena	Main St	Collector	07/90	2316	5.6	10.6	52.5	
MT	East Helena	US 12	Arterial	07/90	7900	3.2	15.4	20.9	
MT	Columbia Falls	4th Ave	Local	08/90	400	1.5	4	37.7	
MT	Libby	Main Ave 4th &	Collector	08/90	530	2.4	17.9	13.2	
MT	Columbia Falls	Nucleus	Collector	08/90	5730	0.8	5.3	16	
MT	Columbia Falls	US 2	Arterial	08/90	13039	0.2	7	2.9	
MT	East Helena	Morton	Local	10/90	250	3.4	10.2	33.6	
MT	East Helena	Main	Collector	10/90	2316	4.5	5.6	81.3	
MT	East Helena	US 12	Arterial	10/90	7900	0.6	13.9	4.3	
MT	Columbia Falls	Nucleus	Collector	11/06/90	5670	5.2	13.5	38	
MT	Columbia Falls	US 2	Arterial	11/06/90	15890	1.7	24.1	7.2	
MT	Libby	US 2	Arterial	12/08/90	10000	21.5	9.6	223.9	
MT	Libby	Main Ave 4th &	Collector	12/09/90	530	13.6	27.1	50.3	
MT	Butte	Texas	Collector	12/13/90	3070	1	15.4	6.4	
MT	East Helena	King	Local	01/91	75	1	3.4	30.6	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
MT	East Helena	Prickly Pear	Local	01/91	425	12	1.8	666.5	
MT	East Helena	Morton	Local	01/91	250	14.1	3.5	402.3	
MT	East Helena	Main St	Collector	01/91	2316	36.7	12.1	303.4	
MT	East Helena	US 12	Arterial	01/91	7900	0.8	14	5.6	
MT	Thompson Falls	Preston	Local	01/23/91	920	9.2	9.9	93	
MT	Thompson Falls	Highway 200	Collector	01/23/91	5000	33.3	27.2	122.2	
MT	East Helena	Seaver Park Rd	Local	02/91	150	21.6	7.1	304.7	
MT	East Helena	New Lake Helena Dr	Collector	02/91	2140	19.2	9	213.4	
MT	East Helena	Porter	Collector	02/91	850	74.4	7.7	966.8	
MT	Libby	Main Ave 4th &	Collector	02/14/91	530	33.3	18.7	178.2	
MT	Libby	US 2	Arterial	02/17/91	10000	69.3	21	330.3	
MT	Butte	Texas	Collector	02/21/91	3070	1.2	11	10.9	
MT	Butte	Harrison	Arterial	02/21/91	22849	2.9	7.9	36.6	
MT	Kalispell	3rd btwn Main & 1st	Collector	02/24/91	2653	30.5	24.8	122.9	
MT	Kalispell	Main	Arterial	02/24/91	14730	17.4	20.4	85.2	
MT	Thompson Falls	Preston	Local	02/25/91	920	35.7	17.9	199.6	
MT	Thompson Falls	Highway 200	Collector	02/25/91	5000	66.8	17.8	375.3	
MT	Helena	Montana	Arterial	03/91	21900	15.4	6.2	248.3	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
MT	Kalispell	3rd btwn Main & 1st	Collector	03/09/91	2653	39.1	29.1	134.5	
MT	Columbia Falls	Nucleus	Collector	03/91	5670	30.1	17	174.6	2 samples, range: 0.8 - 0.8
MT	Kalispell	Main	Arterial	03/09/91	14730	17.6	24.7	71.4	
MT	Thompson Falls	Preston	Local	03/91	920	4.4	8.3	51	2 samples, range: 2.8 - 5.9
MT	Thompson Falls	Highway 200	Collector	03/91	5000	4.3	15.5	28.9	2 samples, range: 1.0 - 7.5
MT	Libby	Main Ave 4th &	Collector	03/91	530	14.8	33.1	44.9	2 samples, range: 13.5 - 16.1
MT	Libby	US 2	Arterial	03/91	11963	20	19.5	111.9	3 samples, range: 11.4 - 32.4
MT	East Helena	Morton	Local	04/91	250	4.3	8.8	48.7	
MT	East Helena	US 12	Arterial	04/91	7900	0.5	8.7	5.7	
MT	Thompson Falls	Preston	Local	04/91	920	1.2	15.7	6.3	4 samples, range: 0.3 - 4.0
MT	Thompson Falls	Highway 200	Collector	04/04/91	5000	2	13.4	14.7	2 samples, range: 1.1 - 2.2
MT	Libby	Main Ave 4th &	Collector	04/91	530	3.5	44	7.8	2 samples, range: 2.5 - 4.4
MT	Libby	US 2	Arterial	04/91	12945	11.8	20.5	57.2	4 samples, range: 1.2 - 22.9
MT	Kalispell	3rd btwn Main & 1st	Collector	04/14/91	2653	15.1	37.1	40.9	
MT	Columbia Falls	Nucleus	Collector	04/91	5670	9	19.8	47.6	
MT	Kalispell	Main	Arterial	04/14/91	14730	13	44.5	29.4	
MT	Columbia Falls	Nucleus	Collector	05/91	5670	2.4	17.5	15.9	4 samples, range: 1.3 - 3.8
MT	Columbia Falls	US 2	Arterial	05/91	14712	5.5	20.7	24.8	5 samples, range: 1.5 - 14.2
MT	Libby	Main Ave 4th &	Collector	05/19/91	530	1.7	31	5.7	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
MT	Libby	Main Ave 4th &	Collector	06/27/91	530	1.7	24.3	7.1	
MT	Libby	US 2	Arterial	06/27/91	10000	3.8	12.6	30.6	
MT	East Helena	Morton	Local	07/91	250	1.7	11.4	15.3	
MT	East Helena	Main	Collector	07/91	2316	8.8	11	79.7	
MT	Thompson Falls	Preston	Local	07/09/91	920	10.9	11	98.7	
MT	Thompson Falls	Highway 200	Collector	07/09/91	5000	2.1	8.1	25.9	
MT	Helena	Montana	Arterial	07/17/91	21900	0.9	4.7	19.4	
MT	Butte	Texas	Collector	07/26/91	3070	2.5	28.2	8.9	
MT	Butte	Harrison	Arterial	07/26/91	22849	1.6	28.2	5.8	
MT	Kalispell	3rd btwn Main & 1st	Collector	08/03/91	2653	5.8	23	25.3	
MT	Kalispell	Main	Arterial	08/03/91	14730	4	21	19.3	
MT	Columbia Falls	US 2	Arterial	08/11/91	15890	0.1	5.6	2.3	
MT	Missoula	Russel btwn 4th & 5th	Road	08/30/91	5270	1.6	8.3	19.3	
MT	East Helena	US 12	Arterial	08/30/91	7900	7	20.5	34.3	
MT	Butte	Texas	Collector	10/03/91	3070	1	17.7	5.4	
MT	Butte	Harrison	Arterial	10/03/91	22849	2.1	23.1	9.1	
MT	Kalispell	3rd btwn Main & 1st	Collector	10/06/91	2653	10	31.3	31.9	
MT	Kalispell	Main	Arterial	10/06/91	14730	4.3	27.7	15.7	
MT	East Helena	Morton	Local	10/16/91	250	1.8	31	5.9	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
MT	East Helena	Main St	Collector	10/16/91	2316	1.6	20.5	7.7	2 samples, range: 13.0 - 89.5
MT	East Helena	US 12	Arterial	10/16/91	7900	1	6.7	14.9	
MT	Columbia Falls	Nucleus	Collector	10/20/91	5670	1.9	13.9	13.3	
MT	Columbia Falls	US 2	Arterial	10/20/91	15890	1.2	11.3	10.2	
MT	Kalispell	3rd btwn Main & 1st	Collector	11/06/91	2653	2.2	12.3	17.8	
MT	Kalispell	Main	Arterial	11/28/91	14730	2.7	8.6	30.8	
MT	Thompson Falls	Preston	Local	12/17/91	920	4	18.1	22.5	
MT	Thompson Falls	Highway 200	Collector	12/17/91	5000	1.5	13.2	11.6	
MT	Butte	Texas	Collector	02/02/92	3070	19.1	11.6	164.5	
MT	Butte	Harrison	Arterial	02/02/92	22849	8.3	12	69.3	
MT	East Helena	Morton	Local	02/03/92	250	78.3	9.5	824.7	
MT	Libby	W 4th St	Local	02/03/92	350	36.3	56.3	64.5	
MT	Libby	Main Ave 4th &	Collector	02/03/92	530	10.7	49.9	21.4	
MT	East Helena	Main St	Collector	02/03/92	2316	57.9	14.8	391	
MT	Columbia Falls	Nucleus	Collector	02/03/92	5670	29.2	20.1	145.4	
MT	Columbia Falls	US 2	Arterial	02/92	12945	51.3	32.2	143.1	
MT	East Helena	US 12	Arterial	02/03/92	7900	2.9	14.3	20.7	
MT	Thompson Falls	Preston	Local	02/22/92	920	0.5	18	2.6	
MT	Thompson Falls	Highway 200	Collector	02/22/92	5000	1.2	14.6	8.1	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
MT	Kalispell	3rd btwn Main & 1st	Collector	03/15/92	2653	81.1	37.3	217.3	3 samples, range: 0.4 - 1.0
MT	Kalispell	Main	Arterial	03/15/92	14730	16.5	32.1	51.3	
MT	Thompson Falls	Preston	Local	04/92	920	0.43	14.9	3.2	
MT	Thompson Falls	Highway 200	Collector	04/92	5000	0.8	18.2	4.7	
MT	Kalispell	3rd btwn 2nd & 3rd	Local	04/26/92	450	20.9	45.8	45.5	
MT	Kalispell	3rd btwn Main & 1st	Collector	04/26/92	2653	19.2	50.9	37.7	3 samples, range: 6.6 - 10.3
MT	Kalispell	Main	Arterial	04/26/92	14730	10.7	33.5	32.1	
MT	Kalispell	3rd btwn 2nd & 3rd	Local	05/92	450	8.3	35.6	23.5	
MT	Kalispell	3rd btwn Main & 1st	Collector	05/92	2653	8.5	32.4	25.8	3 samples, range: 6.3 - 11.4
MT	Kalispell	Main	Arterial	05/92	14730	5.1	23.6	21.7	3 samples, range: 3.8 - 5.9
MT	Libby	W 4th St	Local	05/11/92	350	13.4	56.5	23.7	
MT	Libby	Main Ave 4th &	Collector	05/11/92	530	5.6	58.9	9.4	
MT	Libby	US 2	Arterial	05/92	12945	10.4	25.6	29.4	
MT	East Helena	Morton	Local	05/15/92	250	6.9	6.7	103	
MT	East Helena	Main St	Collector	05/15/92	2316	6.4	10.2	62.8	
MT	East Helena	US 12	Arterial	05/15/92	7900	1.2	6.9	17	
MT	Columbia Falls	Nucleus	Collector	05/25/92	5670	1	21.7	4.5	
MT	Missoula	Inez btwn 4th & 5th	Local	06/04/92	500	1	17.4	5.6	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
MT	Missoula	Russel btwn 3rd & 4th	Collector	06/04/92	5270	15.2	14	108.4	
MT	Missoula	3rd btwn Prince & In	Arterial	06/04/92	12000	2	13.1	15.7	
CO	Denver	E. Colfax	Princ. Arterial ^b	03/89	1994 ^c	0.21	2	19.9	4 samples, range: 0.04 - 0.47
CO	Denver	E. Colfax	Princ. Arterial ^b	04/89	2228 ^c	0.73	1.7	106.7	18 samples, range: 0.08 - 1.76
CO	Denver	York St	Princ. Arterial ^b	04/89	780 ^c	0.86	1.2	74.8	2 samples, range: 0.83 - 0.89
CO	Denver	E. Belleview	Princ. Arterial ^b	04/89	ND	0.07	4.2	2	3 samples, range: 0.03 - 0.09
CO	Denver	I-225	Expressway ^b	04/89	4731 ^c	0.02	3.6	0.4	3 samples, range: 0.01 - 0.02
CO	Denver	W. Evans	Princ. Arterial ^b	05/89	1905 ^c	0.76	1.9	74	11 samples, range: 0.03 - 2.24
CO	Denver	W. Evans	Princ. Arterial ^b	06/89	1655 ^c	0.71	1.2	66.1	12 samples, range: 0.07 - 3.34
CO	Denver	E. Louisiana	Minor Arterial ^b	06/89	515 ^c	0.14	4.66	3.5	5 samples, range: 0.08 - 0.24
CO	Denver	E. Louisiana	Minor Arterial ^b	01/90	ND	1.44 ^d	ND	ND	6 samples, range: 0.12 - 2.8
CO	Denver	E. Jewell Ave	Collector ^b	01/24/90	ND	2.24 ^d	ND	ND	
CO	Denver	State Highway 36	Expressway ^b	01/30/90	ND	0.56 ^d	ND	ND	2 samples, range: 0.56 - 0.56

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
CO	Denver	State Highway 36	Expressway ^b	02/01/90	ND	1.92 ^d	ND	ND	4 samples, range: 1.92 - 1.92
CO	Denver	W. Evans Ave	Princ. Arterial ^b	02/03/90	ND	1.64 ^d	ND	ND	2 samples, range: 1.64 - 1.64
CO	Denver	E. Mexico St	Local ^b	02/07/90	ND	2.58 ^d	ND	ND	3 samples, range: 2.58 - 2.58
CO	Denver	E. Colfax Ave	Princ. Arterial ^b	02/90	ND	0.09 ^d	ND	ND	16 samples, range: 0.02 - 0.17
CO	Denver	State Highway 36	Expressway ^b	03/90	ND	ND	ND	ND	7 samples
CO	Denver	E. Louisiana Ave	Minor Arterial ^b	03/10/90	ND	ND	ND	ND	3 samples
CO	Denver	W. Evans Ave	Princ. Arterial ^b	03/90	ND	1.27 ^d	ND	ND	5 samples, range: 0.07 - 3.38
CO	Denver	W. Colfax Ave	Princ. Arterial ^b	03/90	ND	0.41 ^d	ND	ND	21 samples, range: 0.04 - 2.61
CO	Denver	Parker Rd	Local ^b	04/90	ND	0.05 ^d	ND	ND	6 samples, range: 0.01 - 0.11
CO	Denver	W. Byron Pl	Princ. Arterial ^b	04/90	ND	0.3 ^d	ND	ND	6 samples, range: 0.21 - 0.35
CO	Denver	E. Colfax Ave	Princ. Arterial ^b	04/18/90	ND	0.21 ^d	ND	ND	
UT	Salt Lake County	700 East	Arterial	— ^e	42340	0.137	11.5	1.187	4 samples, range: 0.107 - 0.162

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
UT	Salt Lake County	State St	Collector	— ^e	27140	0.288	17	1.692	4 samples, range: 0.212 - 0.357
UT	Salt Lake County	I-80	Freeway	— ^e	77040	0.023	21.4	0.1	5 samples, range: 0.011 - 0.034
UT	Salt Lake County	I-15	Freeway	— ^e	146180	0.096	23.5	0.419	6 samples, range: 0.078 - 0.126
UT	Salt Lake County	400 East	Local	— ^e	5000	1.967	4.07	46.043	14 samples, range: 0.177 - 5.772
NV	Las Vegas	Lake Mead	Major	07/15/87	ND	0.81	12.4	6.51	
NV	Las Vegas	Perlitter	Local	07/15/87	ND	2.23	31.2	7.14	
NV	Las Vegas	Bruce	Collector	07/15/87	ND	1.64	26.1	6.3	
NV	Las Vegas	Stewart	Major	09/29/87	ND	0.38	24	1.63	3 samples, range: 0.24 - 0.46
NV	Las Vegas	Ambler	Local	09/29/87	ND	1.38	23	6.32	3 samples, range: 0.64 - 2.00
NV	Las Vegas	28th St	Collector	09/29/87	ND	0.52	15.8	3.4	3 samples, range: 0.51 - 0.54
NV	Las Vegas	Lake Mead	Major	10/07/87	ND	0.19	14.9	1.26	2 samples, range: 0.17 - 0.20
NV	Las Vegas	Perlitter	Local	10/07/87	ND	1.5	31.9	4.76	2 samples, range: 1.48 - 1.52
NV	Las Vegas	Bruce	Collector	10/07/87	ND	0.9	24.1	3.74	2 samples, range: 0.76 - 1.03
AZ	Phoenix	Broadway	Arterial	— ^f	ND	0.127	12.2	1.071	
AZ	Phoenix	South Central	Arterial	— ^f	ND	0.085	5	1.726	
AZ	Phoenix	Indian School & 28th	Arterial	— ^f	ND	0.035	3.1	1.021	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
AZ	Glendale	43rd & Vista	Arterial	— ^f	ND	0.042	3.9	1.049	
AZ	Glendale	59th & Peoria	Arterial	— ^f	ND	0.099	8.2	1.183	
AZ	Mesa	Mesa Drive	Arterial	— ^f	ND	0.099	8.9	1.085	
AZ	Mesa	E. McKellips & Olive	Arterial	— ^f	ND	0.014	17	0.092	
AZ	Phoenix	17th & Highland	Collector	— ^f	ND	0.028	13.4	0.232	
AZ	Mesa	3rd & Miller	Collector	— ^f	ND	0.07	11.8	0.627	
AZ	Phoenix	Avalon & 25th	Collector	— ^f	ND	0.528	11.1	4.79	
AZ	Phoenix	Apache	Collector	— ^f	ND	0.282	6.4	4.367	
AZ	Phoenix	N. 28th St & E. Glenrosa	Collector	— ^f	ND	0.035	2.3	1.479	
AZ	Pima County	6th Ave	Collector	— ^f	ND	1.282	6.417	19.961	
AZ	Pima County	Speedway Blvd	Arterial	— ^f	ND	0.401	8.117	4.937	
AZ	Pima County	22nd St	Arterial	— ^f	ND	0.028	16.529	0.176	
AZ	Pima County	Amklam Rd	Collector	— ^f	ND	0.014	5.506	0.197	
AZ	Pima County	Fort Lowell Rd	Arterial	— ^f	ND	0.113	3.509	3.268	
AZ	Pima County	Oracle Rd	Arterial	— ^f	ND	0.014	1.556	0.725	
AZ	Pima County	Inn Rd	Arterial	— ^f	ND	0.021	18.756	0.127	
AZ	Pima County	Orange Grove	Arterial	— ^f	ND	0.162	21.989	0.725	
AZ	Pima County	La Canada	Arterial	— ^f	ND	0.106	3.975	2.571	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class ^a	Date	ADT ^a	Silt Loading (g/m ²)	Silt Content (%)	Total Loading (g/m ²)	Comments
KS	Kansas City	7th	Arterial	02/80	ND	0.29	6.8	4.2	3 samples, range: 0.15 - 0.46
MO	Kansas City	Volker	Arterial	02/80	ND	0.67	20.1	3.5	3 samples, range: 0.43 -1.00
MO	Kansas City	Rockhill	Arterial	02/80	ND	0.68	21.7	3.3	
KS	Tonganoxie	4th	Collector	03/80	ND	2.5	14.5	17.1	
KS	Kansas City	7th	Arterial	03/80	ND	0.29	12.2	2.4	
MO	St. Louis	I-44	Expressway	05/80	ND	0.02	ND	ND	4 samples
MO	St. Louis	Kingshighway	Collector	05/80	ND	0.08	10.9	0.7	3 samples, range: 0.05 - 0.11
IL	Granite City	24th	Arterial	05/80	ND	0.78	6.4	12.3	2 samples, range: 0.7 - 0.83
IL	Granite City	Benton	Collector	05/80	ND	0.93	8.6	10.8	
MN	Duluth	US 53 (northbound lanes)	Highway	03/19/92	5000	0.23	28	1.94	8 samples, range: 0.04 - 0.77
MN	Duluth	US 53 (southbound lanes)	Highway	02/26/92	5000	0.24	13.4	2.3	5 samples, range: 0.05 - 0.37

^a References 7,13-20. Classifications and values as given in reference, except as noted. ADT = average daily traffic. ND = no data.

^b Reference 16.

^c Value given is the hourly traffic rate observed during testing. ADT values not reported.

^d Samples are said to wet sieved. Wet sieving results are not directly comparable to those for the dry sieving described in AP-42 Appendix C.2.

^e No specific date given for sampling. Samples are said to be "post storm".

^f No specific date given for sampling.

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13.2.2 Unpaved Roads

13.2.2.1 General

Dust plumes trailing behind vehicles traveling on unpaved roads are a familiar sight in rural areas of the United States. When a vehicle travels an unpaved road, the force of the wheels on the road surface causes pulverization of surface material. Particles are lifted and dropped from the rolling wheels, and the road surface is exposed to strong air currents in turbulent shear with the surface. The turbulent wake behind the vehicle continues to act on the road surface after the vehicle has passed.

13.2.2.2 Emissions Calculation And Correction Parameters

The quantity of dust emissions from a given segment of unpaved road varies linearly with the volume of traffic. Field investigations also have shown that emissions depend on correction parameters (average vehicle speed, average vehicle weight, average number of wheels per vehicle, road surface texture, and road surface moisture) that characterize the condition of a particular road and the associated vehicle traffic.¹⁻⁴

Dust emissions from unpaved roads have been found to vary in direct proportion to the fraction of silt (particles smaller than 75 micrometers [μm] in diameter) in the road surface materials.¹ The silt fraction is determined by measuring the proportion of loose dry surface dust that passes a 200-mesh screen, using the ASTM-C-136 method. Table 13.2.2-1 summarizes measured silt values for industrial and rural unpaved roads.

Since the silt content of a rural dirt road will vary with location, it should be measured for use in projecting emissions. As a conservative approximation, the silt content of the parent soil in the area can be used. Tests, however, show that road silt content is normally lower than in the surrounding parent soil, because the fines are continually removed by the vehicle traffic, leaving a higher percentage of coarse particles.

Unpaved roads have a hard, generally nonporous surface that usually dries quickly after a rainfall. The temporary reduction in emissions caused by precipitation may be accounted for by not considering emissions on "wet" days (more than 0.254 millimeters [mm] [0.01 inches (in.)] of precipitation).

The following empirical expression may be used to estimate the quantity of size-specific particulate emissions from an unpaved road, per vehicle kilometer traveled (VKT) or vehicle mile traveled (VMT):

$$E = k(1.7) \left[\frac{s}{12} \right] \left[\frac{S}{48} \right] \left[\frac{W}{2.7} \right]^{0.7} \left[\frac{w}{4} \right]^{0.5} \left[\frac{365-p}{365} \right] \quad (\text{kilograms [kg]/VKT}) \quad (1)$$

$$E = k(5.9) \left[\frac{s}{12} \right] \left[\frac{S}{30} \right] \left[\frac{W}{3} \right]^{0.7} \left[\frac{w}{4} \right]^{0.5} \left[\frac{365-p}{365} \right] \quad (\text{pounds [lb]/VMT})$$

Table 13.2.2-1. TYPICAL SILT CONTENT VALUES OF SURFACE MATERIAL ON INDUSTRIAL AND RURAL UNPAVED ROADS^a

Industry	Road Use Or Surface Material	Plant Sites	No. Of Samples	Silt Content (%)	
				Range	Mean
Copper smelting	Plant road	1	3	16 - 19	17
Iron and steel production	Plant road	19	135	0.2 - 19	6.0
Sand and gravel processing	Plant road	1	3	4.1 - 6.0	4.8
Stone quarrying and processing	Plant road	2	10	2.4 - 16	10
	Haul road	1	10	5.0 - 15	9.6
Taconite mining and processing	Service road	1	8	2.4 - 7.1	4.3
	Haul road	1	12	3.9 - 9.7	5.8
Western surface coal mining	Haul road	3	21	2.8 - 18	8.4
	Access road	2	2	4.9 - 5.3	5.1
	Scraper route	3	10	7.2 - 25	17
	Haul road (freshly graded)	2	5	18 - 29	24
Rural roads	Gravel/crushed limestone	3	9	5.0 - 13	8.9
	Dirt	7	32	1.6 - 68	12
Municipal roads	Unspecified	3	26	0.4 - 13	5.7
Municipal solid waste landfills	Disposal routes	4	20	2.2 - 21	6.4

^a References 1,5-16.

where:

E = emission factor

k = particle size multiplier (dimensionless)

s = silt content of road surface material (%)

S = mean vehicle speed, kilometers per hour (km/hr) (miles per hour [mph])

W = mean vehicle weight, megagrams (Mg) (ton)

w = mean number of wheels

p = number of days with at least 0.254 mm (0.01 in.) of precipitation per year (see discussion below about the effect of precipitation.)

The particle size multiplier in the equation, k, varies with aerodynamic particle size range as follows:

Aerodynamic Particle Size Multiplier (k) For Equation 1					
$\leq 30 \mu\text{m}^a$	$\leq 30 \mu\text{m}$	$\leq 15 \mu\text{m}$	$\leq 10 \mu\text{m}$	$\leq 5 \mu\text{m}$	$\leq 2.5 \mu\text{m}$
1.0	0.80	0.50	0.36	0.20	0.095

^a Stokes diameter.

It is important to note that Equation 1 calls for the average speed, weight, and number of wheels of all vehicles traveling the road. For example, if 98 percent of traffic on the road are 4-wheeled cars and trucks while the remaining 2 percent consists of 18-wheeled trucks, then the mean number of wheels "w" is 4.3. More specifically, Equation 1 is *not* intended to be used to calculate a separate emission factor for each vehicle class. Instead, only one emission factor should be calculated that represents the "fleet" average of all vehicles traveling the road.

The number of wet days per year, p, for the geographical area of interest should be determined from local climatic data. Figure 13.2.2-1 gives the geographical distribution of the mean annual number of wet days per year in the United States.¹⁷ The equation is rated "A" for dry conditions ($p = 0$) and "B" for annual or seasonal conditions ($p > 0$). The lower rating is applied because extrapolation to seasonal or annual conditions assumes that emissions occur at the estimated rate on days without measurable precipitation and, conversely, are absent on days with measurable precipitation. Clearly, natural mitigation depends not only on how much precipitation falls, but also on other factors affecting the evaporation rate, such as ambient air temperature, wind speed, and humidity. Persons in dry, arid portions of the country may wish to base p (the number of wet days) on a greater amount of precipitation than 0.254 mm (0.01 in.). In addition, Reference 18 contains procedures to estimate the emission reduction achieved by the application of water to an unpaved road surface.

The equation retains the assigned quality rating, if applied within the ranges of source conditions that were tested in developing the equation, as follows:

Ranges Of Source Conditions For Equation					
Road Silt Content (wt %)	Mean Vehicle Weight		Mean Vehicle Speed		Mean No. Of Wheels
	Mg	ton	km/hr	mph	
4.3 - 20	2.7 - 142	3 - 157	21 - 64	13 - 40	4 - 13

Moreover, to retain the quality rating of the equation when addressing a specific unpaved road, it is necessary that reliable correction parameter values be determined for the road in question. The field and laboratory procedures for determining road surface silt content are given in AP-42 Appendices C.1 and C.2. In the event that site-specific values for correction parameters cannot be obtained, the appropriate mean values from Table 13.2.2-1 may be used, but the quality rating of the equation is reduced by 1 letter.

For calculating annual average emissions, the equation is to be multiplied by annual vehicle distance traveled (VDT). Annual average values for each of the correction parameters are to be

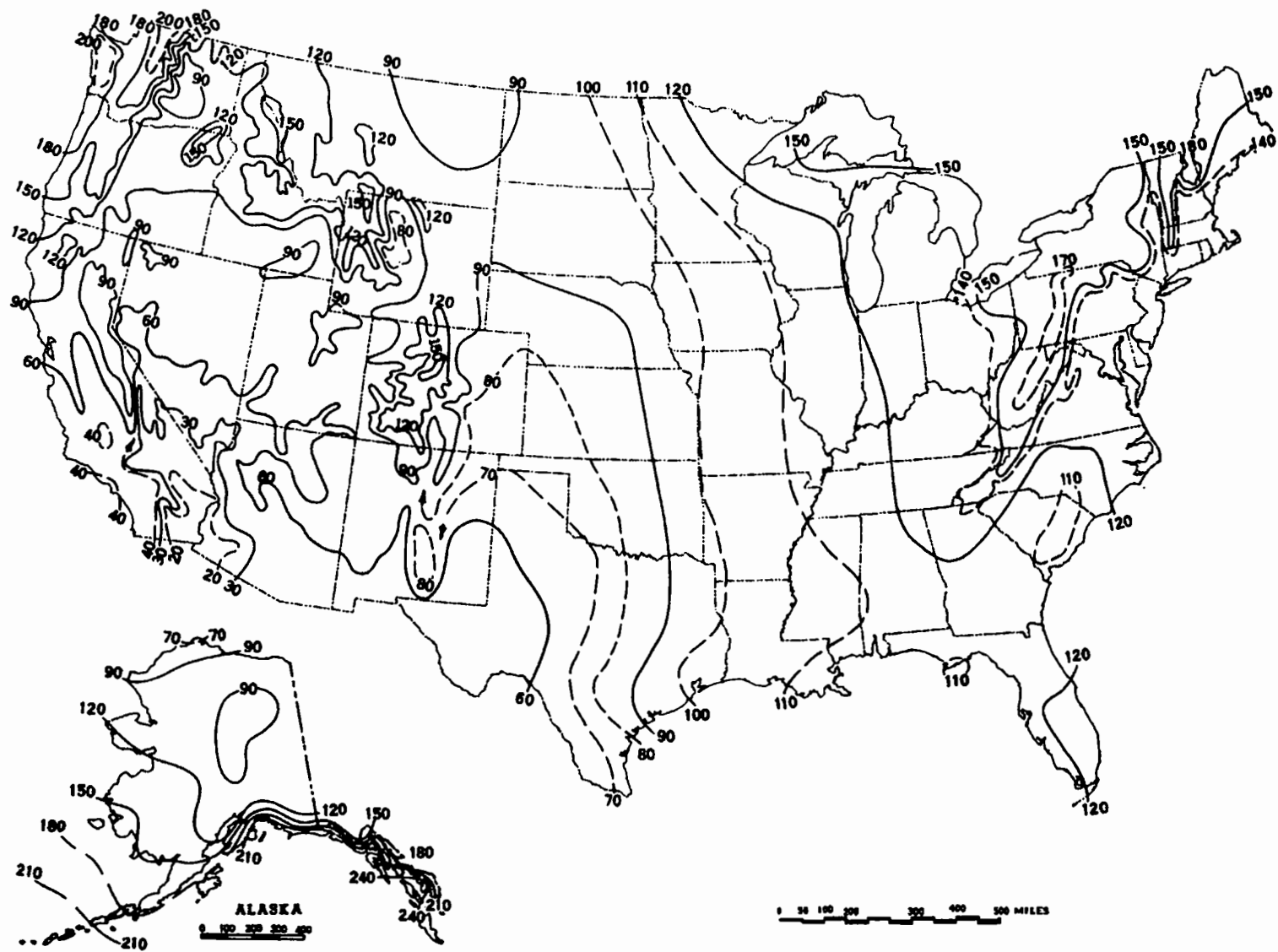


Figure 13.2.2-1. Mean number of days with 0.01 inch or more of precipitation in United States.

substituted for the equation. Worst-case emissions, corresponding to dry road conditions, may be calculated by setting $p = 0$ in the equation (equivalent to dropping the last term from the equation). A separate set of nonclimatic correction parameters and a higher than normal VDT value may also be justified for the worst-case average period (usually 24 hours). Similarly, in using the equation to calculate emissions for a 91-day season of the year, replace the term $(365-p)/365$ with the term $(91-p)/91$, and set p equal to the number of wet days in the 91-day period. Use appropriate seasonal values for the nonclimatic correction parameters and for VDT.

13.2.2.3 Controls¹⁸⁻²¹

Common control techniques for unpaved roads are paving, surface treating with penetration chemicals, working stabilization chemicals into the roadbed, watering, and traffic control regulations. Chemical stabilizers work either by binding the surface material or by enhancing moisture retention. Paving, as a control technique, is often not economically practical. Surface chemical treatment and watering can be accomplished at moderate to low costs, but frequent treatments are required. Traffic controls, such as speed limits and traffic volume restrictions, provide moderate emission reductions, but may be difficult to enforce. The control efficiency obtained by speed reduction can be calculated using the predictive emission factor equation given above.

The control efficiencies achievable by paving can be estimated by comparing emission factors for unpaved and paved road conditions, relative to airborne particle size range of interest. The predictive emission factor equation for paved roads, given in Section 13.2.4, requires estimation of the silt loading on the traveled portion of the paved surface, which in turn depends on whether the pavement is periodically cleaned. Unless curbing is to be installed, the effects of vehicle excursion onto shoulders (berms) also must be taken into account in estimating control efficiency.

The control efficiencies afforded by the periodic use of road stabilization chemicals are much more difficult to estimate. The application parameters that determine control efficiency include dilution ratio, application intensity, mass of diluted chemical per road area, and application frequency. Other factors that affect the performance of chemical stabilizers include vehicle characteristics (e. g., traffic volume, average weight) and road characteristics (e. g., bearing strength).

Besides water, petroleum resin products historically have been the dust suppressants most widely used on industrial unpaved roads. Figure 13.2.2-2 presents a method to estimate average control efficiencies associated with petroleum resins applied to unpaved roads.¹⁹ Several items should be noted:

1. The term "ground inventory" represents the total volume (per unit area) of petroleum resin concentrate (*not solution*) applied since the start of the dust control season.
2. Because petroleum resin products must be periodically reapplied to unpaved roads, the use of a time-averaged control efficiency value is appropriate. Figure 13.2.2-2 presents control efficiency values averaged over 2 common application intervals, 2 weeks and 1 month. Other application intervals will require interpolation.
3. Note that zero efficiency is assigned until the ground inventory reaches 0.2 liter per square meter (L/m^2) (0.05 gallon per square yard [gal/yd^2]).

As an example of the application of Figure 13.2.2-2, suppose that the equation was used to estimate an emission factor of 2.0 kg/VKT for PM-10 from a particular road. Also, suppose that,

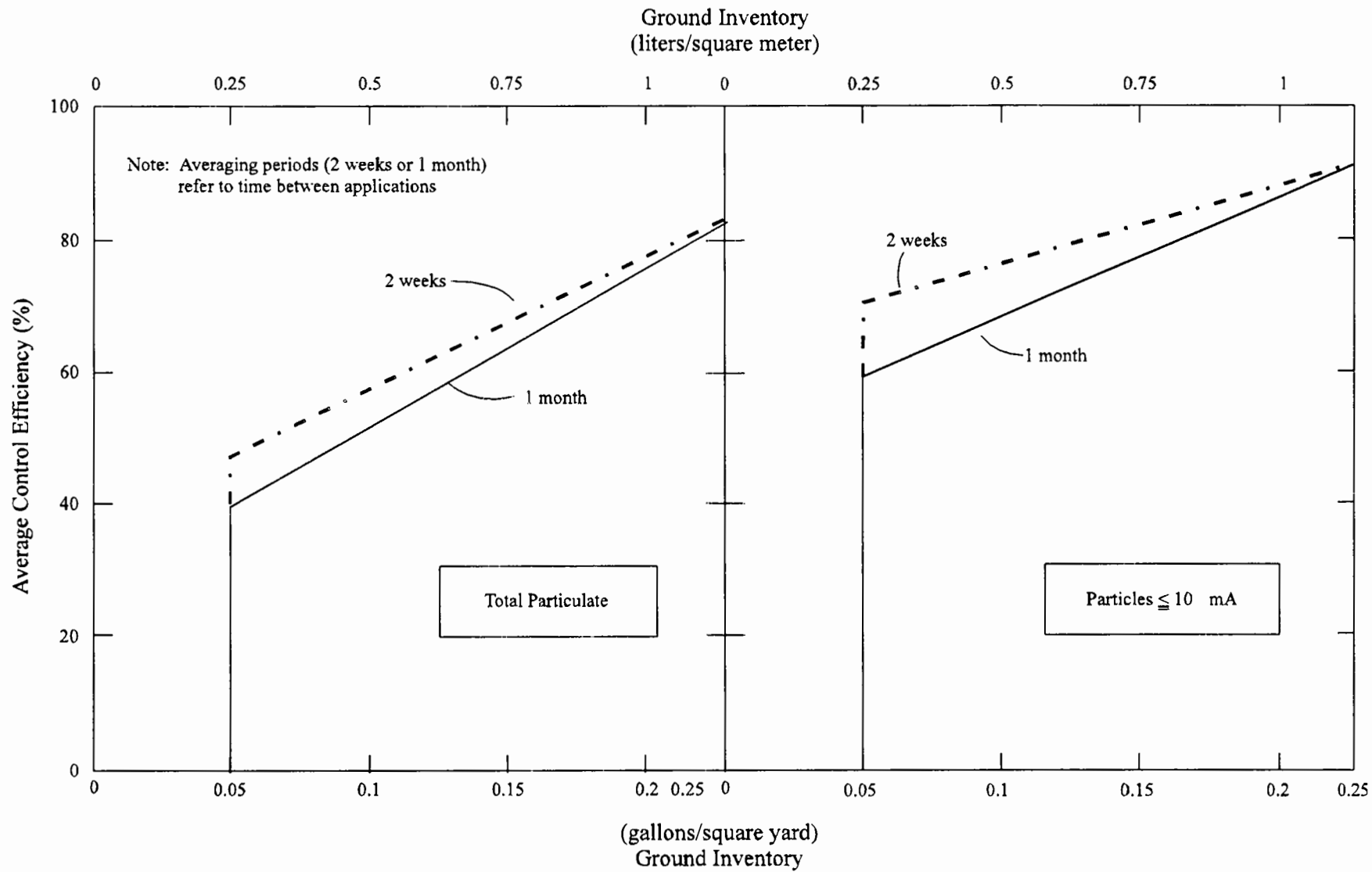


Figure 13.2.2-2. Average control efficiencies over common application intervals.

starting on May 1, the road is treated with 1 L/m² of a solution (1 part petroleum resin to 5 parts water) on the first of each month through September. Then, the following average controlled emission factors are found:

Period	Ground Inventory (L/m ²)	Average Control Efficiency ^a (%)	Average Controlled Emission Factor (kg/VKT)
May	0.17	0	2.0
June	0.33	62	0.76
July	0.50	68	0.64
August	0.67	74	0.52
September	0.83	80	0.40

^a From Figure 13.2.2-2, $\leq 10 \mu\text{m}$. Zero efficiency assigned if ground inventory is less than 0.2 L/m² (0.05 gal/yd²).

Newer dust suppressants are successful in controlling emissions from unpaved roads. Specific test results for those chemicals, as well as for petroleum resins and watering, are provided in References 18 through 21.

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