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PROTOCOLS FOR CALCULATING VOC EMISSIONS
FROM LAND APPLICATIONS
USING EMISSION MODELS

TECHNICAL NOTE

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Work Assignment 17

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SECTION 1
INTRODUCTION

A number of emission models have been proposed for estimating volatile organics emissions from landfills and landfarming sites. This technical note discusses these models in detail and presents a protocol for their use. Equations for the models are presented, required input variables defined, sources of information for these variables suggested, and approximate precision levels for the variables presented. Physical property inputs are discussed and methods for their estimation are provided, as are selected values for some materials. Models are presented for covered landfills and for landtreatment (landfarming). For landfills, the recommended model is that of Farmer, as modified by Shen and Hwang, and for landtreatment, the Thibodeaux-Hwang model is recommended (1).

SECTION 2

LANDTREATMENT EMISSIONS

Two models which have been proposed for predicting emissions of volatile compounds from landtreatment operations are the Hartley and the Thibodeaux-Hwang models. These two models were presented and briefly discussed in an earlier report(1). Since the Hartley model is inadequate for describing evaporation of volatile waste material which has permeated below the soil surface, it is not recommended for consideration in the kinds of applications addressed by this protocol. Therefore, the Thibodeaux-Hwang model must be used.

This model is presented in Table 2-1. In the development of this model, the emission rate of a volatile chemical compound was assumed to be a function of:

- the evaporation rate of the compound from the interstitial soil surfaces, and
- the diffusion rate of the chemical compound through the air-filled pore spaces of the soil.

The emission rate is assumed to be controlled by the diffusion rate in the air pore space when the oil loading and soil particles are both small.

At soil loadings substantially greater than typical waste loadings, the mathematical description of the emission process is extremely complex. Thibodeaux and Hwang made a significant number of simplifying assumptions to develop a usable mathematical expression. The resulting model is a highly idealized and simplified description of a very complex process.

TABLE 2-1. THIBODEAUX-HWANG MODEL FOR VOLATILE ORGANIC EMISSIONS FROM LANDTREATMENT OPERATIONS

Basis: Emission rate is controlled by diffusion rate of vapor through the air-filled pores of the landtreated soil.

Form:

$$E_i = \frac{D_{ei} C_{ig}}{h_s^2 + \left(\frac{2 D_{ei} t A (h_p - h_s) C_{ig}}{M_{io}} \right)^{1/2}}$$

$$C_{ig} = \frac{H_c C_{io}}{\left(1 + \frac{H_c D_{ei} Z_o}{D_{wi} A_s f(y)} \right)}$$

and

$$f(y) = (h_p^2 + h_p h_s - 2h_s^2)/6$$

Symbol	Symbol/Parameter Definition	Typical Precision	Source of Input Parameter
A	surface area over which waste is applied, cm ²	± 2%	measured
A _s	interfacial area per unit volume of soil for the oily waste, cm ² /cm ³	-	calculated
C _{ig}	effective wet zone pore space concentration of component i, g/cm ³	-	calculated
C _{io}	concentration of component i in oil, g/cm ³	± 25%	calculated
D _{ei}	effective diffusivity of component i in the air-filled soil pore spaces, cm ² /s	± 25%	published data; estimation
d _p	soil clump diameter, cm	-	average calculated from measurements or estimated

(Continued)

TABLE 2-1. THIBODEAUX-HWANG MODEL FOR VOLATILE ORGANIC EMISSIONS FROM
 LANDTREATMENT OPERATIONS (Continued)

D_{wi}	effective diffusivity of compound i in the oil, cm^2/s	$\pm 5\%$	published data; estimation
E_i	flux of component i from the soil surface, $\text{g}/\text{cm}^2\text{-sec}$	-	calculated
$f(y)$	$(h_p^2 + h_p h_s - 2h_s^2)/6$ accounts for the lengthening dry zone	-	calculated
H_c	Henry's Law constant in concentration form, $\text{cm}^3 \text{ oil}/\text{cm}^3 \text{ air}$	$\pm 15\%$	published data or measurement
h_p	depth of soil contaminated or wetted with landtreated waste, cm	$\pm 10\%$	measured
M_{io}	initial mass of component i incorporated into the zone $(h_p - h_s)$, g	$\pm 5\%$	measured
t	time after application, sec		measured
y	height of wetted soil remaining after partial drying, cm	-	measured
w_f	weight fraction oil in film form in soil	-	calculated
Z_o	oil layer diffusion length, cm	-	calculated or estimated
f	fraction of oil in film form	-	estimated
ρ_p	soil clump density, g/cm^3	$\pm 10\%$	measured or estimated
$\bar{\rho}_w$	waste-oil density, g/cm^3	$\pm 10\%$	measured or estimated

Much of the material that is typically landtreated consists of oily sludges. These sludges are usually mixtures of solids, water, and a complex solution of a very large number of organic compounds. The sludges may consist of two- or three-phase solutions or even emulsions. They are applied to the landtreatment area at high soil loadings. At this time, the Thibodeaux-Hwang model has not been validated and/or calibrated under experimental and field conditions in the range of typical landtreatment operating conditions. Without such validation, no estimate of the accuracy of the model predicted emission rates can be determined.

There is very little available data which can be used to validate this model under any conditions. Thibodeaux and Hwang (2) used two sets of data to compare measured emission rates with rates predicted by the model. The initial results of a joint API/EPA study were used as one data set. Partial agreement of the data with predicted results was obtained. However, the conditions during the short period (<30 minutes after sludge application) of time in which data were reported deviated substantially from those described by the model. Much of the applied sludge was still in the process of soaking into the soil, and substantial amounts were still present as liquid pools on the soil surface.

Thibodeaux and Hwang also used experimentally determined emission rates of Spencer and Cliath (3) and Farmer and Letey (4) to compare with emission rates predicted with the model. There appears to be good agreement between the predicted and measured emission rates of the pesticide dieldrin. However, the dieldrin soil loadings were two orders of magnitude lower than those typically encountered in landtreatment operations. Dieldrin is also a solid in the normal ambient temperature range. Therefore, the experimental conditions are very different from those encountered during typical landtreatment operations, and this comparison is not a verification of the model under typical landtreatment conditions.

The computational procedure for using the Thibodeaux-Hwang model is:

1. Calculate Z_o .

If oil is in film form $Z_o = d_p \rho_p f / 6 \bar{\rho}_w$

if oil is in lump form $Z_o = d_p / 2$

2. Calculate A_s , the interfacial area per unit volume of soil.

If oil is in film form $A_s = 6/d_p$

If oil is in lump form $A_s = 2.70/d_p$

3. Calculate $f(y) = (h_p^2 + h_p h_s - 2h_s^2)/6$.

4. Calculate wet zone pore space concentration.

$$C_{ig} = \frac{H_c C_{io}}{1 + \left(\frac{H_c D_{ei} Z_o}{D_{wi} A_s f(y)} \right)}$$

5. Calculate emission rate for component i.

$$E_i = \frac{D_{ei} C_{ig}}{h_s^2 + \left(\frac{2 D_{ei} t A (h_p - h_s) C_{ig}}{M_{io}} \right)^{1/2}}$$

6. Calculate total emission rate of all components.

$$E_t = \sum_{i=1}^N E_i$$

In practice, it is often not practical to calculate individual component emissions in order to estimate total emissions. In such cases, an estimate of total emissions may be made by summing the emissions estimated for several classes of compounds using a representative individual component for each class.

The selection of a representative individual component is somewhat arbitrary. Some compounds are more likely to be encountered than others, and compounds in the mid-molecular weight ranges (4-8 carbons) are likely to dominate in frequency of occurrence. Therefore, at this time, the following classes and compounds have been selected as representative for making emissions estimates:

Class	Compound
Paraffins	Hexane
Olefins	Butene
Aromatics	Toluene
Halogenated hydrocarbons	Methylene chloride
Oxygenated hydrocarbons	Acetone

Key properties of some compounds are found in Table 5-1 of Section 5.

SECTION 3

LANDFILL EMISSIONS

The most generally accepted model for the prediction of emission rates from covered landfills is the mathematical expression proposed by Farmer, et. al. (5). In this model, shown in Table 3-1, the emission rate from a covered landfill is assumed to be controlled by the diffusion rate of pollutant gases through the soil cover. Two forms of the model were developed; a rigorous form and a simplified form. The model in its rigorous form was validated by Farmer using laboratory simulation data for hexachlorobenzene. The model was simplified by Farmer for use in the predictive mode, and modified slightly by Shen (6). A multiplicative factor of 6.0 was added to account for convective effects due to gases generated by the codisposal of biologically degradable wastes (7).

The limited validation performed by Farmer supports the basic technical integrity of the rigorous model. It should not be considered as verification of the simplified model with the added codisposal factor. Furthermore, the validity of the model for predicting emissions from complex, multicomponent waste mixtures has not been tested.

The computational procedure for the Farmer model is as follows:

1. From field measurements or a given value, calculate A, the landfill surface area.
2. Calculate the saturation vapor concentration.

$$C_s = P_i M / RT$$

TABLE 3-1. FARMER MODEL FOR VOLATILE ORGANIC EMISSIONS FROM COVERED LANDFILLS

Basis: Emission rate is assumed to be mass transfer controlled by diffusion of gases through the air-filled soil pores.

Form:

$$E_i = K_D D_i C_s A \frac{(P_a)^{10/3}}{(P_t)^2} \left(\frac{1}{L} \right) \left(\frac{W_i}{W} \right)$$

$$C_s = \frac{P_i M_i}{RT}$$

$$P_t = 1 - \left(\frac{B}{\rho_s} \right)$$

$$\theta = \left(\frac{W_w}{W} \right) \left(\frac{B}{\rho_w} \right)$$

$$P_a = P_c - \theta$$

Symbol	Symbol/Parameter Definition	Precision	Input Parameter
A	Surface area of the landfill (cm ₂)	+0.1%	File data or direct measurement
B	Soil bulk density (g/cm ₃)	+8%	Varies from 1 to 2 g/cc. Need direct measurement for accuracy.
C _s	Saturation vapor concentration (g/m ₃)	.05%	Calculated from gas law and species vapor pressure.

(Continued)

TABLE 3-1. FARMER MODEL FOR VOLATILE ORGANIC EMISSIONS FROM
 COVERED LANDFILLS (Continued)

$D_{i,air}$	Diffusion coefficient of the species of interest in air (cm^2/sec)	$\pm 5\%$	Calculated value from literature or ratio to a compound with a known D by molecular weight.
E_i	Mass emission rate (g/sec)	-	--
K_D	Codisposal factor. Use 1.0 for isolated toxic waste disposal and 6.0 for toxic waste codisposed with biologically degradable wastes.	$+10\%$ -2%	Literature
L	Depth of soil cover (cm)	$\pm 17\%$	File data or measurement
M_i	Molecular weight of the species (g/mole)	-	Literature
P_a	Air-filled porosity (dimensionless)	$\pm 30\%$	Calculated
P_i	Vapor pressure of the species in interest (mm Hg)	5%	Literature or direct measurement.
ρ_s	Soil particle density (g/cm^3)	$\pm 8\%$	Recommends 2.65 g/cm^3 for most mineral material.
P_t	Soil porosity (dimensionless)	$\pm 13\%$	Can be estimated based on soil bulk density and soil particle density.
ρ_w	Density of water (g/cm^3)	$\pm 2\%$	Literature
R	Gas constant $62,300 \frac{mm\ Hg - cm^3}{^\circ K - mole}$	-	Given

(Continued)

TABLE 3-1. FARMER MODEL FOR VOLATILE ORGANIC EMISSIONS FROM
COVERED LANDFILLS (Continued)

W_i/W	Weight fraction of the species of interest in the disposed waste (g/g)	$\pm 20\%$	Direct measure- ment.
W_w/W	Weight fraction of water in the soil cover	$\pm 5\%$	Direct measure- ment.
T	Temperature ($^{\circ}\text{K}$)	$\pm 1^{\circ}\text{K}$	Direct measure- ment.
θ	Volume fraction of water in the soil cover (g/g)	$\pm 17\%$	Direct measure- ment.

3. Calculate soil porosity.

$$P_t = 1 - B/P_s$$

4. Calculate volume fraction water in soil.

$$\theta = (W_w/W)(B/P_w)$$

5. Calculate mass emission rate of component i.

$$E_i = K_D D C_s A \frac{(P_a)^{10/3}}{(P_t)^2} \left(\frac{1}{L} \right) \left(\frac{W_i}{W} \right)$$

6. Calculate total emissions.

$$E_t = \sum_{i=1}^N E_i$$

In practice, it is often not practical to calculate individual component emissions in order to estimate total emissions. In such cases, an estimate of total emissions may be made by summing the emissions estimated for several classes of compounds using a representative individual component for each class.

The selection of a representative individual component is somewhat arbitrary. Some compounds are more likely to be encountered than others, and compounds in the mid-molecular weight ranges (4-8 carbons) are likely to dominate in frequency of occurrence. Therefore, at this time, the following classes and compounds have been selected as representative for making emissions estimates:

Class	Compound
Paraffins	Hexane
Olefins	Butene
Aromatics	Toluene
Halogenated hydrocarbons	Methylene chloride
Oxygenated hydrocarbons	Acetone

Key properties of some compounds are found in Table 5-1 of Section 5.

SECTION 4

SOURCES OF PHYSICAL PROPERTY DATA

Physical property data for air, water, and some chemical species are available in various literature sources. Where data are not available, it is possible to use methods to estimate the properties. Properties required for the models discussed in this report are listed in Table 4-1.

4.1 GASEOUS DIFFUSION COEFFICIENTS

A recommended equation for estimating the diffusivity of a nonpolar specie "i" in air is the method of Fuller, Schettler, and Giddings (8):

$$D_{i,air} = \frac{10^{-3} T^{1.75} [(M_i + M_{air})/M_i M_{air}]^{1/2}}{P [(\sum v_i)^{1/3} + (\sum v_{air})^{1/3}]^2}$$

where, P = pressure, (atm)

T = temperature, (°K)

M_i = molecular weight of "i"

M_{air} = molecular weight of air

v = diffusion volume increments for components of species "i"
 molecular structure tabulated in Table 4-2.

$$\sum v_{air} = 20.1$$

Errors are in the range of 5 to 10%.

For a polar specie, the method of Brokaw is recommended (6):

$$D_{i,air} = 1.858 \times 10^{-3} T^{3/2} \frac{[(M_i + M_{air})/M_i M_{air}]^{1/2}}{P \sigma_{i,air}^2 \Omega_D}$$

TABLE 4-1. PHYSICAL PROPERTIES REQUIRED FOR EMISSIONS ESTIMATE MODELS

$D_{i,air}$	Diffusivity of compound i in air (cm^2/sec)
$D_{i,w}$	Diffusivity of compound i in water (cm^2/sec)
μ_g	Viscosity of air (cp)
μ_w	Viscosity of water (cp)
ρ_g	Density of air (g/cm^3)
ρ_w	Density of water (g/cm^3)

TABLE 4-2. ATOMIC DIFFUSION VOLUMES FOR NON-POLAR DIFFUSIVITY
ESTIMATES

Structural Increment	Diffusion Volume Increment, v
C	16.5
H	1.98
O	5.48
N	5.69
Cl	19.5
S	17.0
Aromatic ring	-20.2
Heterocyclic ring	-20.2

Source: Adapted from Reference 8.

where, P = pressure (atm)

T = temperature (°K)

$\sigma_{i,air}$ = characteristic length (Å)

Ω_D = dimensionless collision integral

and Ω_D are calculated from additional equations as follows:

$$\Omega_D = \left[\frac{A}{T^{*B}} + \frac{C}{\exp DT^*} + \frac{E}{\exp FT^*} + \frac{G}{\exp HT^*} \right] + \frac{(0.19)\delta_{i,air}^2}{T^*}$$

where, $T^* = kT / \epsilon_{i,air}$

k = Boltzman's constant

T = temperature, °K

$\epsilon_{i,air} = (\epsilon_i, \epsilon_{air})^{1/2}$

$\epsilon_i = 1.18k (1 + 1.3\delta_i^2)T_{bi}$

$\delta_i = 1.94 \times 10^3 \mu_{pi} / V_{bi}T_{bi}$

$\mu_{p,i}$ = dipole moment, debyes

V_{bi} = liquid molar volume at boiling point, cm³/g-mol

T_{bi} = normal boiling point, °K

$$\sigma_i = \left(\frac{1.585V_{b,i}}{1+1.3\delta_i^2} \right)^{1/3}$$

$\sigma_{i,air} = (\sigma_i \sigma_{air})^{1/2}$

A = 1.06036
~~F~~

E = 1.03587

B = 0.15610

F = 1.52996

C = 0.19300

G = 1.76474

D = 0.47635

H = 3.89411

A discussion of these equations and terms and sources of values for various terms for some compounds are given in Reference 8.

4.2 LIQUID DIFFUSION COEFFICIENTS

The diffusion coefficient in water at infinite dilution can be estimated from the Wilke-Chang method (8) which when expressed specifically for a specie "i" in water is:

$$D_{i,w}^{\circ} = 50.6 \times 10^{-8} T / (\mu_w V_i^{0.6})$$

where, $D_{i,w}^{\circ}$ = diffusion coefficient of i in water at infinite dilution,
(cm²/sec)

μ_w = viscosity of water at temperature of interest, (cp)

V_i = molal volume of solute at its normal boiling point,
(cm³/g-mole)

T = temperature (°K)

Diffusion in multicomponent mixtures can be approximated by taking the molal average value of the diffusion coefficient of i in each of the possible binary combinations in the system (9). The molal volume of a solute can be estimated from the following equation (8): $V_i = 0.285 V_{c,i}^{1.048}$ where $V_{c,i}$ = the critical volume of specie "i" (cm³/g-mol). Values of V_c are available in various literature sources.

Values of aqueous phase diffusion coefficients for various compounds are given in Section 5.

4.3 VISCOSITY

Viscosities of air and water are readily available from handbooks (10). In Section 5, Table 5-2 presents the viscosity of air and Table 5-4 the viscosity of water as functions of temperature.

4.4 DENSITY

Densities of air and water are readily available from handbooks (10). In Section 5, Table 5-3 presents the density of air and Table 5-5 the density of water as functions of temperature.

4.5 HENRY'S LAW CONSTANT

Henry's law constant is central to expressing the vapor-liquid equilibrium relationship between the liquid and gaseous phases. This relationship is:

$$P_i = H_i C_i$$

where, P_i = partial pressure of specie "i" in the air

C_i = concentration of specie "i" in the water

H_i = Henry's law constant

Compilations of Henry's law constant for various materials are available in literature sources. Values for selected compounds are given in Table 5-1 of Section 5 along with other properties. In the absence of experimentally determined values, methods exist for estimating Henry's law constants by calculation (9).

The calculational method is based on the foregoing equation written as:

$$H \text{ (m}^3\text{-atm/g-mole)} = 18 \times 10^{-6} \gamma p^v$$

where, Y = the liquid phase activity coefficient, and P_i is the pure component vapor pressure.

Y can be estimated as a function of molecular properties as discussed in Reference 9. Another method of estimating H_i is :

$$H_i = P_i / S_{i,sat}$$

where $S_{i,sat}$ = max solubility in water at system temperature.

SECTION 5

TABULATIONS OF DATA FOR USE IN EMISSION'S MODEL CALCULATIONS

This section presents constants, conversion factors, and property data to be used in the emission models. The following tables are included:

- Table 5-1 Property Data for Use in Emissions Estimates of Selected Organic Compounds
- Table 5-2 Viscosity of Air at Various Temperatures
- Table 5-3 Density of Air at Various Temperatures
- Table 5-4 Viscosity of Water at Various Temperatures
- Table 5-5 Density of Water at Various Temperatures
- Table 5-6 Units Conversion Factors

TABLE 5-1. PROPERTY DATA FOR USE IN EMISSIONS ESTIMATES OF SELECTED ORGANIC COMPOUNDS^a

Compound	CAS Number	Molecular Weight (MW _i)	Normal Boiling Pt. (T _{b,i}), °C	Vapor Pressure @ 25°C (P _i), mm Hg	Henry's Law Constant @ 25°C (H _i), atm-m ³ /mol	Solubility in H ₂ O @ 25°C (mg/L)	Liquid Molal Volume at Normal B.P. (V _{b,i}), cm ³ /g-mol	Diffusivity in Air @ 25°C (D _{i,air}), cm ² /sec	Diffusivity in Water @ 25°C (D _{i,w}), 10 ⁻⁵ cm ² /sec
Acetaldehyde	75-07-0	44	20.8	922.57			55.9	0.124	1.41
Acrolein	107-02-8	56	53	258	6.79 x 10 ⁻⁵	280,000		0.105	1.216
Acrylonitrile	107-13-1	53	77.4	97.2	9.2 x 10 ⁻⁵	73,500	77.4	0.102	1.229
Benzene	71-43-2	78	80.1	101**	5.5 x 10 ⁻³	1,780	96.5	0.0932	0.994
Benzyl chloride	100-44-7	126	179	1.25	2.36 x 10 ⁻⁴	1,619			
1,3-Butadiene	106-99-0	54.09	-4.41				81.6		
Carbon tetrachloride	56-23-5	153.8	76.5	15.06			102	0.0632	0.884
Chlorobenzene	108-90-7	113	132	11.8	3.93 x 10 ⁻³	500	115.5	0.073	0.90
2-Chloro-1,3-butadiene (Chloroprene)	126-99-8	88.54	59.4						
Chloroform	67-66-3	119	61	172.1	3.93 x 10 ⁻³	9,300	88.6	0.0888	1.06
3-Chloro-1-propene (Allyl chloride)	107-05-1	76.53	45				86.6		
Cumene	98-82-8	120	153	4.507	1.46 x 10 ⁻²	50	163.1	0.065	0.71
1,2-Dibromoethane (Ethylene dibromide)	106-93-4	186	131-132 7m-9.3	11	6.25 x 10 ⁻⁴	4,310		0.075	0.909
p-Dichlorobenzene	106-46-7	147	174	0.67	2.37 x 10 ⁻³	69	140.8		
1,2-Dichloroethene (Ethylene dichloride)	107-06-2	96.94	60.3				18.3	0.0667	0.8915
Dichloromethane (Methylene chloride)	75-09-2	85	41	427.8	3.19 x 10 ⁻³	16,700	70.8	0.10	1.66
1,2-Dichloropropane (propylene dichloride)	78-87-5	113	96	50	2.8 x 10 ⁻³	2,700	83.5		1.070

(Continued)

TABLE 5-1. (Continued)

Compound	CAS Number	Molecular Weight (MW _i)	Normal Boiling Pt. (T _{b,i}), °C	Vapor Pressure @ 25°C (P _i), mm Hg	Henry's Law Constant @ 25°C (H _i), atm-m ³ /mol	Solubility in H ₂ O @ 25°C (mg/L)	Liquid Molal Volume at Normal B.P. (V _{b,i}), cm ³ /g-mol	Diffusivity in Air @ 25°C (D _{i,air}), cm ² /sec	Diffusivity in Water @ 25°C (D _{i,w}), 10 ⁻⁵ cm ² /sec
Epichlorohydrin	106-89-8	92.5	116.5	18.8	3.8 x 10 ⁻⁵	60,000		0.086	0.98
Ethylbenzene	100-41-4	106.2	136.2	1.27			141.6	0.075	0.78
Methyl acetate	79-20-9	74.08	57				84.3		
Methyl chloride (Chloromethane)	74-87-3	50	-24.2	5(20) 6.7(30)		4,000	50.6	0.126	0.65
Naphthalene	91-20-3	81	218	0.232**	4.8 x 10 ⁻⁴	30	156.0	0.0622	0.893
n-Propyl benzene	103-65-1	120	159.2				168.0		
Propylene oxide	75-56-9	58.08	34.3				68.1		
Styrene	100-42-5	104.16	145.2					0.071	0.80
1,1,2,2-Tetrachloroethane	79-34-5	168	146.2	4.2	4.7 x 10 ⁻⁴	3,000			
Tetrachloroethylene	127-18-4	166	121		2.8 x 10 ⁻²	100	108.5		0.79
Toluene	108-88-3	92	110.6	26.8	6.64 x 10 ⁻³	515	118.7	0.079	0.877
1,1,1-Trichloroethane	71-55-6	133	74.1	117**	4.92 x 10 ⁻³	950		0.0794	0.88
Trichloroethylene	79-01-6	131	87	71.6	8.92 x 10 ⁻³	1,100	95.2	0.0875	0.945
Vinyl chloride	75-01-4	62.5	-13.4	344(20*)			61.6	0.090	1.04
Vinylidene chloride (1,1-Dichloroethylene)	75-35-4	97	37	630.1	1.5 x 10 ⁻²	3,200	89.0		
o-Xylene	95-47-6	106	137-140	2.77	5.27 x 10 ⁻³	175	139.7	0.0628	
m-Xylene	108-38-3	106	139	3.20	2.55 x 10 ⁻³		142.4		
p-Xylene	106-42-3	106	138	3.15	2.51 x 10 ⁻³		143.6		

*Blanks indicate that data were not found in readily available sources.

TABLE 5-2. VISCOSITY OF AIR AT VARIOUS TEMPERATURES AT PRESSURE = 1 ATM

Temperature, °C	Viscosity, cp
38	0.0185
27	0.0181
16	0.0178
4	0.0170

Source: Reference 10.

TABLE 5-3. DENSITY OF AIR AT VARIOUS TEMPERATURES AT PRESSURE - 1 ATM

Temperature, °C	Density ^a g/L
40	1.1034
30	1.1507
20	1.1981
10	1.2454
0	1.2928

^aFrom Reference 10 at 0°C. Other values calculated from ideal gas law absolute temperature ratio dependence.

TABLE 5-4. VISCOSITY OF WATER AT VARIOUS TEMPERATURES AT
PRESSURE = 1 ATM

Temperature, °C	Viscosity, cp
38	0.73
32	0.82
27	0.90
21	1.02
16	1.13
10	1.27
4	1.40

Source: Reference 10

TABLE 5-5. DENSITY OF WATER AT VARIOUS TEMPERATURES AT
PRESSURE - 1 ATM

Temperature, °C	Density g/cm ³
40	0.9922
35	0.9941
30	0.9957
25	0.9971
20	0.9982
15	0.9991
10	0.9997

Source: Reference 10

TABLE 5-6. UNITS CONVERSION FACTORS

To Convert From:	To:	Multiply By:
liter (L)	meter ³ (m ³)	1 x 10 ⁻³
grams (g)	pounds (lb)	2.2046 x 10 ⁻³
foot (ft)	meter (m)	3.048 x 10 ⁻¹
foot (ft)	centimeter (cm)	30.48
foot ³ (ft ³)	centimeter (cm)	2.832 x 10 ⁴
lb/ft ³	g/cm ³	1.6017 x 10 ⁻²
Btu/hour	horsepower*	3.933 x 10 ⁻⁴
ft-lb/sec	horsepower*	1.818 x 10 ⁻³
Ergs/sec	horsepower*	1.341 x 10 ⁻¹⁰
Kilowatts	horsepower*	1.341
watts	horsepower*	1.341 x 10 ⁻³
lb/ft-sec	centipoises (cp)	1.488 x 10 ³
g/cm-sec (poise)	centipoises (cp)	1 x 10 ²
lb/ft ² -hr	g/cm ² -s	1.3566 x 10 ⁻⁴
mm Hg	atmospheres (atm)	1.3158 x 10 ⁻³
Temperature Conversion		
°C = 5/9 (°F - 32)		
°K = 273.15 + °C		
Constants		
acceleration of gravity (g)	32.17 ft/sec ²	9.807 x 10 ² cm/sec ²

*Mechanical horsepower, equal to 550 ft-lb/sec

SECTION 6

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