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ERRATUM

The corrected Table of Contents is shown on the following page:

API PUBLICATION 2518
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CONTENTS

Documentation File for API Manual of Petroleum Measurement Standards Chapter 19.1—Evaporative Loss From Fixed Roof Tanks [API Bulletin 2518]

API PUBLICATION CHAPTER 19.1D
FIRST EDITION, MARCH 1993

American Petroleum Institute
1220 L Street, Northwest
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Documentation File for API Manual of Petroleum Measurement Standards Chapter 19.1—Evaporative Loss From Fixed Roof Tanks [API Bulletin 2518]

Measurement Coordination

API PUBLICATION CHAPTER 19.1D
FIRST EDITION, MARCH 1993

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API PUBLICATION 2518
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INTRODUCTION

This document is the Documentation File to API Publication 2518, Second Edition [A7]*.

The purpose of the Documentation File is to present detailed technical information related to the development of API Publication 2518 that includes: (1) the development of theoretical equations; (2) comparisons with test data; (3) a sensitivity analysis of the loss equation; and (4) other pertinent information that was developed during the preparation of API Publication 2518.

The Documentation File is divided into two main parts: Sections A through H pertain to the standing storage loss, and Sections I through L pertain to the working loss.

The standing storage loss equation in the Second Edition [A7] is different then that in the First Edition [A6]. Sections A through H present the development of the new standing storage loss equation.

The working loss equation in the Second Edition [A7] is the same as that in the First Edition [A6]. Sections I through L contain development information that originally appeared in the First Edition.

Section R contains a list of important References that were reviewed in developing the Second Edition. These references are cited in various sections of the Documentation File.

* Numbers in brackets refer to the numbered references listed at the end of this Documentation File.

API PUBLICATION 2518
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SECTION A

DEVELOPMENT OF
VAPOR SPACE EXPANSION FACTOR, K_E

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SECTION A

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API PUBLICATION 2518
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SECTION A

NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
A	Vapor pressure function constant	dimensionless
B	Vapor pressure function constant	^oR
K_E	Vapor space expansion factor	dimensionless
n	Number of moles	mole
P	Pressure	psi
ΔP	Pressure change	psi
R	Ideal gas constant (10.731)	psia ft^3/lbmole ^oR
T	Temperature	^oR
ΔT	Temperature change	^oR
V	Volume	ft^3
ΔV	Volume change	ft^3
y	Mole fraction in the vapor phase	mole fraction

SUBSCRIPTS

A	Air
ATM	Atmospheric
B	Breather Vent
BP	Breather Vent Pressure Setting
BV	Breather Vent Vacuum Setting
L	Liquid
LA	Liquid Average
T	Total
V	Stock Vapor
VA	Vapor Average
1	Initial Condition or Minimum Condition
2	Final Condition or Maximum Condition

A1.0 INTRODUCTION

This section of the Documentation File to API Publication 2518, Second Edition, contains a derivation of the equation for the vapor space expansion factor, K_E. This equation is derived from the ideal gas law and from the pressure, temperature and volume conditions that exist in the vapor space of a fixed-roof tank containing a volatile liquid stock.

Section A2 presents a derivation of the vapor space volume change due to thermal breathing. This derivation closely follows that originally derived by Boardman [1]* and that presented at the API "Symposium on Evaporation Loss of Petroleum from Storage Tanks" November 10, 1952 [2].

Section A3 defines the vapor space expansion factor, K_E, and develops the equation that may be used to calculate this factor.

Section A4 describes various simplifications that can be made to the equation for the vapor space expansion factor to permit ease of calculation with little loss in accuracy.

A2.0 VAPOR SPACE VOLUME CHANGE

Figure A1 is a schematic illustrating the tank vapor space thermal breathing process in a fixed-roof tank that is partially filled with a volatile liquid stock and equipped with a pressure-vacuum vent.

During the thermal breathing process, the pressure, volume and temperature vary from minimum condition 1 to maximum condition 2. At conditions 1 and 2, the total absolute pressure in the vapor space is P_1 and P_2, respectively, where:

$$P_1 = P_{ATM} + P_{BV} \tag{A-1}$$

$$P_2 = P_{ATM} + P_{BP} \tag{A-2}$$

* Numbers in brackets refer to the numbered references listed at the end of this Documentation File.

During the thermal breathing process, the pressure, volume and temperature vary from a certain combination of values at the minimum condition to be certain combination of values at the maximum condition. At the minimum condition 1, it is assumed that all of the variables are simultaneously at their minimum values; and at the maximum condition 2, it is assumed that all of the variables are simultaneously at their maximum values. The value of the variables at the minimum condition 1 and maximum condition 2 are listed in Table A1.

Table A1 - Value of the Variables at the Minimum and Maximum Conditions

Variable	Units	Minimum Condition 1	Maximum Condition 2
Gas space total pressure	psia	P_1	P_2
Atmospheric pressure	psia	P_{ATM}	P_{ATM}
Gas space gage pressure	psig	P_{BV}	P_{BP}
Stock vapor pressure	psia	P_{V1}	P_{V2}
Air partial pressure	psi	P_{A1}	P_{A2}
Gas volume	ft^3	V_1	V_2
Gas temperature	^oR	T_1	T_2
Liquid surface temperature	^oR	T_{L1}	T_{L2}

From the ideal gas law, the total number of moles of gas, n_T, in an enclosed volume, V, at temperature, T, and pressure, P, is given by:

$$n_T = \frac{P\ V}{R\ T} \quad \text{(A-3)}$$

Assume that the gas mixture in the tank vapor space is a two-component mixture consisting air and stock vapor. The mole fraction of air, y_A, and the mole fraction of stock vapor, y_V, may be determined by Eqs (A-4) through (A-7):

$$y_A = \frac{n_A}{n_T} \quad \text{(A-4)}$$

$$y_A = \frac{P_A}{P} \quad \text{(A-5)}$$

$$y_V = \frac{n_V}{n_T} \quad \text{(A-6)}$$

$$y_V = \frac{P_V}{P} \quad \text{(A-7)}$$

The mole fraction of air, y_A, may be expressed in terms of the mole fraction of vapor, y_V, as follows:

$$y_A = 1 - y_V \quad \text{(A-8)}$$

During the thermal breathing process of the tank vapor space, the number of moles of air, n_A, in the volumes, V_1 and V_2, is assumed to remain the same. This assumption may be expressed as follows:

$$n_{A1} = n_{A2} \quad \text{(A-9)}$$

We may substitute Eq (A-4) into Eq (A-9) to yield:

$$y_{A1}\, n_{T1} = y_{A2}\, n_{T2} \quad \text{(A-10)}$$

We may substitute Eq (A-3) into Eq (A-10) to yield:

$$y_{A1} \left[\frac{P_1 V_1}{R\ T_1}\right] = y_{A2} \left[\frac{P_2 V_2}{R\ T_2}\right] \quad \text{(A-11)}$$

Solving for V_2 and using Eq (A-8), we may write:

$$V_2 = V_1 \left(\frac{y_{A1}}{y_{A2}}\right) \left(\frac{P_1}{P_2}\right) \left(\frac{T_2}{T_1}\right) \quad \text{(A-12)}$$

$$V_2 = V_1 \left(\frac{1 - y_{V1}}{1 - y_{V2}}\right) \left(\frac{P_1}{P_2}\right) \left(\frac{T_2}{T_1}\right) \quad \text{(A-13)}$$

We may substitute Eq (A-7) into Eq (A-13) to yield:

$$V_2 = V_1 \left(\frac{1 - \frac{P_{V1}}{P_1}}{1 - \frac{P_{V2}}{P_2}}\right) \left(\frac{P_1}{P_2}\right) \left(\frac{T_2}{T_1}\right)$$

$$V_2 = V_1 \left(\frac{P_1 - P_{V1}}{P_2 - P_{V2}}\right) \left(\frac{T_2}{T_1}\right) \quad \text{(A-14)}$$

Using Eq (A-14), the volume change due to thermal breathing, ΔV, may be determined as follows:

$$\Delta V = V_2 - V_1 \quad \text{(A-15)}$$

$$\Delta V = V_1 \left[\left(\frac{P_1 - P_{V1}}{P_2 - P_{V2}}\right) \left(\frac{T_2}{T_1}\right) - 1\right] \quad \text{(A-16)}$$

We may substitute Eqs (A-1) and (A-2) into Eq (A-16) to yield:

$$\Delta V = V_1 \left[\left(\frac{P_{ATM} + P_{BV} - P_{V1}}{P_{ATM} + P_{BP} - P_{V2}} \right) \left(\frac{T_2}{T_1} \right) - 1 \right] \quad \text{(A-17)}$$

$$\Delta V = V_1 \left[\left(1 + \frac{(P_{V2} - P_{V1}) - (P_{BP} - P_{BV})}{P_{ATM} + P_{BP} - P_{V2}} \right) \left(1 + \frac{(T_2 - T_1)}{T_1} \right) - 1 \right] \quad \text{(A-18)}$$

It is a convenient to define the terms ΔP_V, ΔP_B and ΔT_V as follows:

$$\Delta P_V = P_{V2} - P_{V1} \quad \text{(A-19)}$$

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

$$\Delta T_V = T_2 - T_1 = T_{V2} - T_{V1} \quad \text{(A-21)}$$

We may substitute Eqs (A-19), (A-20) and (A-21) into Eq (A-18) and expand the terms to yield:

$$\Delta V = V_1 \left[\left(1 + \frac{\Delta P_V - \Delta P_B}{P_{ATM} + P_{BP} - P_{V2}} \right) \left(1 + \frac{\Delta T_V}{T_{V1}} \right) - 1 \right] \quad \text{(A-22)}$$

$$\Delta V = V_1 \left[1 + \left(\frac{\Delta T_V}{T_{V1}} \right) + \left(\frac{\Delta P_V - \Delta P_B}{P_{ATM} + P_{BP} - P_{V2}} \right) + \left(\frac{(\Delta P_V - \Delta P_B)\, \Delta T_V}{P_{ATM} + P_{BP} - P_{V2}} \right) - 1 \right] \quad \text{(A-23)}$$

Since the terms $(\Delta T_V/T_{V1})$ and $(\Delta P_V - \Delta P_B)/(P_{ATM} + P_{BP} - P_{V2})$ are small, their product can be considered negligable. Thus, the product term in Eq (A-23) can be neglected. Eq (A-23) then simplifies to the following:

$$\Delta V = V_1 \left[\frac{\Delta T_V}{T_{V1}} + \frac{\Delta P_V - \Delta P_B}{P_{ATM} + P_{BP} - P_{V2}} \right] \quad \text{(A-24)}$$

A3.0 VAPOR SPACE EXPANSION FACTOR

The vapor space expansion factor, K_E, is defined as the ratio of the volume change, ΔV, to the initial volume, V_1, as follows:

$$K_E \equiv \frac{\Delta V}{V_1} \qquad \text{(A-25)}$$

Substituting Eq (A-24) into (A-25) we obtain:

$$\boxed{K_E = \frac{\Delta T_V}{T_{V1}} + \frac{\Delta P_V - \Delta P_B}{P_{ATM} + P_{BP} - P_{V2}}} \qquad \text{(A-26)}$$

A4.0 SIMPLIFIED EQUATIONS FOR THE VAPOR SPACE EXPANSION FACTOR

Eq (A-26) may be simplified for ease of calculation. Sections A4.1 through A4.4 present various simplifications that can be made.

A4.1 Neglecting the Term P_{BP}

It should be noted that P_{BP} is small (about 0.03 psi) compared to P_{ATM} (about 14.7 psia) and can be neglected in the denomination of Eq (A-26) to yield:

$$K_E = \frac{\Delta T_V}{T_{V1}} + \frac{\Delta P_V - \Delta P_B}{P_{ATM} - P_{V2}} \qquad \text{(A-27)}$$

A4.2 Replacement of T_{V1} With T_{LA}

In the first term of Eq (A-27), the minimum vapor space temperature, T_{V1}, is close to the daily average liquid surface temperature, T_{LA}, since both are absolute temperatures. Thus, for ease of calculation, we can replace T_{V1} with T_{LA} in Eq (A-27) to yield:

$$K_E = \frac{\Delta T_V}{T_{LA}} + \frac{\Delta P_V - \Delta P_B}{P_{ATM} - P_{V2}} \qquad \text{(A-28)}$$

A4.3 Replacement of P_{V2} With P_{VA}

For low vapor pressure stocks, the stock vapor pressure, P_V, is small compared to atmospheric pressure, P_{ATM}. Thus, we may replace the stock vapor pressure at the minimum liquid surface temperature, P_{V2}, with the stock vapor pressure at the daily average liquid surface temperature, P_{VA}, in Eq (A-28) to yield:

$$\boxed{K_E = \frac{\Delta T_V}{T_{LA}} + \frac{\Delta P_V - \Delta P_B}{P_{ATM} - P_{VA}}} \qquad \text{(A-29)}$$

Eq (A-29) appears as Eq 4 in Ref. A7.

A4.4 Use of a Simplified Equation for the Vapor Pressure Range, ΔP_V

The vapor pressure of the stock may be determined from Eq (A-30), where the vapor pressure function constants A and B must be selected for the particular stock [see Tables 4 and 5 in Ref. A7].

$$P_V = \exp\left[A - (B/T_L)\right] \qquad \text{(A-30)}$$

We can determine the slope of the vapor space pressure function by taking its derivative with respect to the liquid surface temperature, T_L, as follows:

$$\frac{dP_V}{dT_L} = \frac{B\,P_V}{T_L^2} \qquad \text{(A-31)}$$

Eq (A-31) can be written in differential form as follows:

$$\Delta P_V = \frac{B\ P_V}{T_L^{\ 2}}\ \Delta T_L \qquad \text{(A-32)}$$

Eq (A-32) gives the vapor pressure range, ΔP_V, in terms of the liquid surface temperature range, ΔT_L.

For most hydrocarbon liquids, the liquid surface temperature range, ΔT_L, may be related to the vapor temperature range, ΔT_V, as follows (see Eq (F-16) in Section F):

$$\Delta T_L = 0.50\ \Delta T_V \qquad \text{(A-33)}$$

Substituting Eq (A-33) into Eq (A-32), we obtain the following simplified equation for the vapor pressure range:

$$\boxed{\Delta P_V = \left[\frac{0.50\ B\ P_V}{T_L^{\ 2}}\right] \Delta T_V} \qquad \text{(A-34)}$$

Eq (A-34) may be substituted into Eq (A-29) to yield:

$$\boxed{K_E = \left[\frac{\Delta T_V}{T_{LA}}\right] \left[1 + \left[\frac{0.50\ B}{T_{LA}}\right]\left[\frac{P_{VA}}{P_{ATM} - P_{VA}}\right]\right] - \frac{\Delta P_B}{(P_{ATM} - P_{VA})}} \qquad \text{(A-35)}$$

A4.5 Neglecting the Term ΔP_B

For most atmospheric storage tanks, the breather vent pressure and vacuum settings are typically +0.03 psi and -0.03 psi, respectively. Thus, the term $\Delta P_B/(P_{ATM} - P_{VA})$ is small (about 0.002 for low vapor pressure stock) compared to the term $\Delta T_V/T_{LA}$ (about 0.040 for $\Delta T_V = 20^{o}F$ and $T_{LA} = 520^{o}R$). For these cases, the last term in Eq (A-35) may be neglected to yield:

$$K_E = \left(\frac{\Delta T_V}{T_{LA}}\right)\left[1 + \left(\frac{0.50\ B}{T_{LA}}\right)\left(\frac{P_{VA}}{P_{ATM} - P_{VA}}\right)\right] \quad \text{(A-36)}$$

In comparing Eq (A-36) to Eq (A-26), we can see that the calculation process is greatly simplified because it is not necessary to determine all of the variables, T_{L1}, T_{L2}, T_{LA}, P_{V1}, P_{V2} and P_{VA}, but only the variables T_{LA} and P_{VA}.

A5.0 CONCLUSION

Equation (A-29) was selected for use in calculating the vapor space expansion factor, K_E, in API Publication 2518, Second Edition [A7]. This equation was derived from the ideal gas law and from the pressure, temperature, and volume conditions that exist in the vapor space of a fixed-roof tank containing a volatile liquid stock. Equation (A-29) was developed from a more complete expression, Eq (A-26), by incorporating several simplifications that make the calculations more user friendly, with little loss in accuracy.

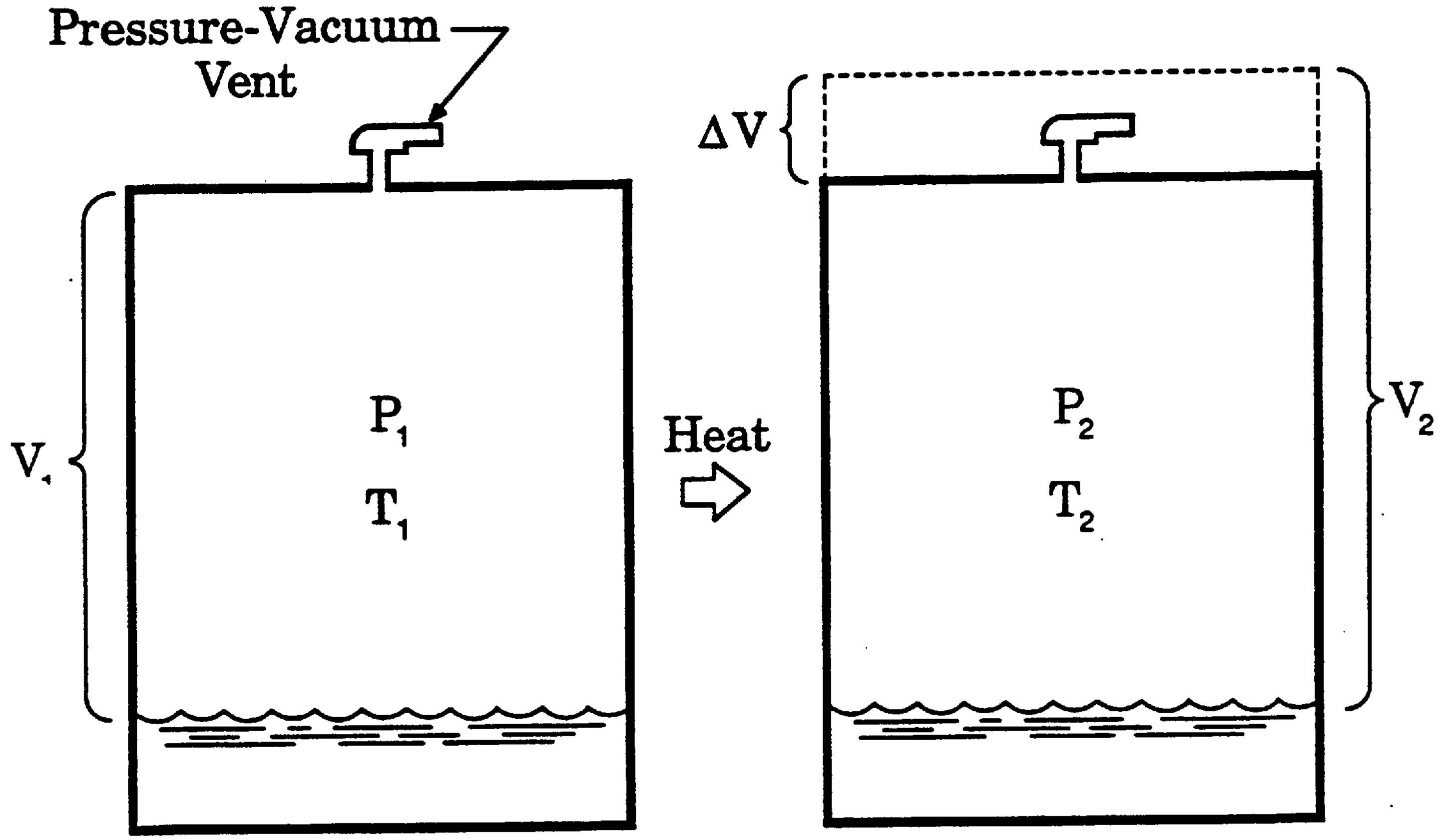

Figure A1 - Schematic of the Tank Vapor Space Heating Process and the Resulting Volume Expansion Due to Thermal Breathing

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SECTION B

DEVELOPMENT OF VENTED VAPOR SATURATION FACTOR, K_S

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SECTION B

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SECTION B

NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
A	Constant in the vapor pressure equation	psia
A_L	Area of the stock liquid surface	ft^2
a	Defined by Eq (B-15)	dimensionless
B	Constant in the vapor pressure equation	^oR
b	Defined by Eq (B-16)	dimensionless
C_V	Average vapor concentration in the vented gas	lbm/sft^3
D	Tank diameter	ft
E	Evaporation loss	lbm/day
E_C	Evaporation loss calculated	lbm/day
E_M	Evaporation loss measured	lbm/day
H_V	Tank vapor space outage	ft
K	Overall mass transfer coefficient between the liquid surface and the vented vapor	$\left(\frac{lbmole}{ft^2\ hr\ mole\ frac.}\right)$
K_E	Vapor space expansion factor	dimensionless
K_S	Vented vapor saturation factor	dimensionless
M_V	Stock vapor molecular weight	lbm/lbmole
m_V	Moles of stock vapor vented	lbmole
P_{ATM}	Atmospheric pressure	psia
P_{VA}	Stock vapor pressure determined at T_{LA}	psia
Q	Vented gas volume outflow	sft^3/day
R	Ideal gas law constant, (10.731)	$\left(\frac{ft^3\ psia}{lbmole\ ^oR}\right)$
RVP	Reid Vapor Pressure	psi
S	Saturation parameter, defined by Eq (B-4)	dimensionless
T_{AA}	Average daily ambient temperature	^oF or ^oR
T_{LA}	Average daily liquid surface temperature	^oF or ^oR
T_{VA}	Average daily vapor space temperature	^oF or ^oR
ΔT_A	Daily ambient temperature range	^oF or ^oR
ΔT_V	Daily vapor space temperature range	^oF or ^oR
t_D	Time of a daily period	hr
V_V	Volume of the tank vapor space	ft^3

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SECTION B

NOMENCLATURE (Continued)

SYMBOL	DESCRIPTION	UNITS
ΔV	Volume of gas vented during a single daily thermal breathing cycle	ft^3
y_V	Daily average stock vapor concentration in the vented vapor	mole fraction
y_V^o	Daily average saturated stock vapor concentration	mole fraction
ρ_G	Gas density	$lbmole/ft^3$

B1.0 INTRODUCTION

This section of the Documentation File to API Publication 2518, Second Edition, contains the development of the vented vapor saturation factor, K_S.

The "Vented Vapor Saturation Factor", K_S, is defined as the ratio of the daily average stock vapor concentration in the vented gas, y_V, to the stock vapor concentration, y_V^0, in equilibrium with the stock liquid surface at the daily average liquid surface temperature.

Section B2 presents the derivation of a theoretical equation for estimating the vented vapor saturation factor that is based on an analytical model of the daily thermal breathing process.

Section B3 presents the development of a correlation for estimating the vented vapor saturation factor that is based on test data.

B2.0 VENTED VAPOR SATURATION FACTOR MODEL

B2.1 Model Description

Figure B1 is a schematic of a fixed-roof tank that is partially filled with a volatile liquid stock and equipped with a pressure-vacuum vent. During the daily thermal breathing cycle, the gas mixture in the tank vapor space is initially heated from its minimum condition to its maximum condition (see Section A of this Documentation File for additional detail). Vapor is vented from the tank vapor space when the pressure increases to the pressure setting of the pressure-vacuum vent. As the gas mixture in the tank vapor space is cooled from its maximum condition back to its minimum condition, air is admitted to the tank vapor space when the pressure decreases to the vacuum setting of the pressure-vacuum vent.

Evaporation of stock occurs from the liquid surface as the stock tries to saturate the air that was admitted to the tank vapor space. Test data indicates that there is a region at the top of the tank vapor space under the pressure-vacuum vent where there is a significant concentration gradient.

During the daily thermal breathing cycle, the moles of stock vapor that are expelled from the tank vapor space, m_V, may be estimated by Eq (B-1):

$$m_V = \rho_G \, \Delta V \, y_V \qquad \text{(B-1)}$$

where the term ΔV represents the volume vented during a single thermal breathing cycle (see Section A2, Eq (A-24)).

The vented gas contains less stock vapor per unit volume than the gas near the liquid surface. The daily average stock vapor concentration in the vented vapor is y_V (unsaturated), and the daily average stock vapor concentration near the liquid surface is y_V^o (saturated).

During the daily thermal breathing cycle, stock vapor evaporates and rises upward from the area near the liquid surface to replace the stock vapor lost as gas is vented from the tank vapor space. Stock will continue to evaporate as it tries to establish a saturation condition at the top of the tank vapor space.

The moles of stock that evaporate during a daily thermal breathing cycle may be estimated by Eq (B-2):

$$m_V = K \, A_L \, t_D \, (y_V^o - y_V) \qquad \text{(B-2)}$$

where K is the overall mass transfer coefficient between the liquid surface and the vented vapor.

After a series of repeated daily thermal breathing cycles where the same meteorological conditions occur, the stock vapor concentration in the vented vapor will vary during each thermal breathing cycle in a repeated manner, and the daily average stock vapor concentration in the vented vapor, y_V, will achieve a steady value. This concentration value depends upon the rate at which the stock vapor lost from the tank vapor space is replaced by stock evaporated from the liquid surface.

The steady value of the daily average stock vapor concentration in the vented vapor, y_V, may be determined by equating Eq (B-1) with Eq (B-2) and solving for y_V as follows:

$$\rho_G \, \Delta V \, y_V = K \, A_L \, t_D \, (y_V^o - y_V)$$

$$y_V \left[\frac{\rho_G \, \Delta V}{K \, A_L \, t_D}\right] = (y_V^o - y_V) \tag{B-3}$$

It is useful to define the saturation parameter, S, as follows:

$$S \equiv \left[\frac{\rho_G \, \Delta V}{K \, A_L \, t_D}\right] \tag{B-4}$$

Using this defined saturation parameter, Eq (B-3) may be written as:

$$y_V \, S = (y_V^o - y_V) \tag{B-5}$$

Eq (B-5) may now be solved for y_V to yield:

$$y_V = y_V^o \left[\frac{1}{1 + S}\right] \tag{B-6}$$

B2.2 Vented Vapor Saturation Factor Definition

The vented vapor saturation factor, K_S, is defined by Eq (B-7) as the ratio of the daily average stock vapor concentration in the vented vapor, y_V, to the daily average saturated stock vapor concentration, y_V^o.

$$K_S = \left[\frac{y_V}{y_V{}^o}\right] \tag{B-7}$$

When $K_S = 1$, the vented gas is completely saturated; when $K_S = 0$, the vented gas contains no stock vapor.

B2.3 Saturation Parameter

The saturation parameter, S, as defined by Eq (B-4) may be written in terms of other evaporation loss parameters. First, note Eqs (B-8) through (B-11) as follows:

$$\rho_G = \left[\frac{P_{ATM}}{R\ T_{VA}}\right] \tag{B-8}$$

$$A_L = \left[\frac{\pi\ D^2}{4}\right] \tag{B-9}$$

$$\Delta V = V_V\ K_E \qquad \text{(see Eq (A-25) in Section A)} \tag{B-10}$$

$$V_V = \left[\frac{\pi\ D^2\ H_V}{4}\right] \tag{B-11}$$

Substituting Eqs (B-8) through (B-11) into Eq (B-4), we obtain:

$$S = \left[\frac{P_{ATM}}{R\ T_{VA}}\right]\left[\frac{H_V}{K\ t_D}\right] K_E \tag{B-12}$$

The vapor space expansion factor, K_E, may be expressed in the following simplified form (see Eq (A-36) in Section A5):

$$K_E = \left(\frac{\Delta T_V}{T_{LA}}\right)\left[1 + \left(\frac{0.50\ B}{T_{LA}}\right)\left(\frac{P_{VA}}{P_{ATM} - P_{VA}}\right)\right] \quad \text{(B-13)}$$

Substituting Eq (B-13) into Eq (B-12) and replacing T_{VA} with T_{LA} (since both are absolute temperatures), we obtain:

$$S = \left(\frac{P_{ATM}}{R\ T_{LA}}\right)\left(\frac{H_V}{K\ t_D}\right)\left(\frac{\Delta T_V}{T_{LA}}\right)\left[1 + \left(\frac{0.50\ B}{T_{LA}}\right)\left(\frac{P_{VA}}{P_{ATM} - P_{VA}}\right)\right] \quad \text{(B-14)}$$

It is convenient to define the following dimensionless parameters a and b:

$$a \equiv \left(\frac{P_{ATM}\ H_V\ \Delta T_V}{R\ t_D\ K\ T_{LA}^2}\right) \quad \text{(B-15)}$$

$$b \equiv \left(\frac{0.50\ B}{T_{LA}}\right) \quad \text{(B-16)}$$

We also know that the daily average saturated stock vapor concentration, y_V^o, can be expressed as follows:

$$y_V^o = \left(\frac{P_{VA}}{P_{ATM}}\right) \quad \text{(B-17)}$$

Substituting Eqs (B-15), (B-16) and (B-17) into Eq (B-14), we obtain:

$$S = a\left[1 + b\left(\frac{y_V^o}{1 - y_V^o}\right)\right] \tag{B-18}$$

B2.4 Vented Vapor Saturation Factor Development

Substituting y_V from Eq (B-6) into Eq (B-7) we obtain:

$$K_S = \left(\frac{1}{1 + S}\right) \tag{B-19}$$

Equation (B-19) shows that as the saturation parameter, S, increases, the vented vapor saturation factor, K_S, decrease toward 0. Conversely, as S decreases, the value of K_S increases toward 1.

Using Eq (B-18), the vented vapor saturation factor, K_S, may be written as:

$$\boxed{K_S = \frac{1}{1 + a\left[1 + b\left(\frac{y_V^o}{1 - y_V^o}\right)\right]}} \tag{B-20}$$

Equation (B-20) shows that the vented vapor saturation factor, K_S, depends upon only 3 parameters: a, b and y_V^o.

Inserting the expressions for a, b and y_V^o from Eqs (B-15), (B-16) and (B-17), we obtain the following final expression which contains all of the variables:

$$K_S = \frac{1}{1 + \left[\frac{P_{ATM}\, H_V\, \Delta T_V}{R t_D\, K\, T_{LA}^{\,2}}\right] \left\{1 + \left[\frac{0.50\, B}{T_{LA}}\right] \left[\frac{\left(\frac{P_{VA}}{P_{ATM}}\right)}{1 - \left(\frac{P_{VA}}{P_{ATM}}\right)}\right]\right\}} \qquad \text{(B-21)}$$

It should be noted that K_S will tend toward 1 as H_V tends toward 0. Also, K_S will tend toward 0 as P_{VA} tends toward P_{ATM}.

Insufficient information is currently available to determine the overall mass transfer coefficient, K, and thus Eq (B-21) was used only as a guide to show the dependancy of K_S on P_{VA}, H_V and the other variables.

Although it is possible to improve the above simplified analysis to develop a theoretical relation for the vented vapor saturation factor, K_S, it was decided instead to develop a correlation for K_S based on actual test data, as described in Section B3. However, the above simplified analysis was used as a guide in selecting the analytical form for the correlation equation and in selecting the parameters to include in the correlation.

B3.0 VENTED VAPOR SATURATION FACTOR CORRELATION

This section summarizes the development of a correlation for estimating the vented vapor saturation factor, K_S.

Section B3.1 summarizes the saturation factors that were calculated from the API[38]*, EPA[20] and WOGA[17] test data. The API test data showed that the vented gas was near saturation conditions at all times. The EPA and WOGA Test Data, however, showed that the vented gas was not saturated, with the degree of saturation being less with increasing product vapor pressure, P_{VA}, and increasing vapor space outage, H_V.

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* Numbers in brackets refer to the numbered references listed at the end of this Documentation File.

The fact that the vented gas is not saturated with stock vapor reflects the effect of mass transfer rate limitations from the liquid surface to the area below the pressure-vacuum vent. As the vapor space outage increases, the distance that the stock vapor must travel from the liquid surface to the vent is lengthened. This lengthened distance decreases the mass transfer rate and thus the concentration in the vented gas. For high vapor pressure stocks, since the amount of stock vapor lost in each daily thermal breathing cycle is larger, a higher rate of evaporation from the liquid surface is required to replenish the stock vapor that is lost. Mass transfer rate limitations, however, limit the ability of the stock to replenish the vented vapor at these higher vapor pressures and thus reduce the degree of saturation in the vented gas.

Section B3.2 presents the development of a correlation for the vented vapor saturation factor based on only the API and EPA test data. This correlation showed trends that are similar to those predicted by the theoretical analysis (see Eq (B-19)) in that the saturation factor approaches 1 as the vapor pressure or the outage approach 0, and the saturation factor becomes small as the vapor pressure or outage increase.

Section 3.3 presents the development of a correlation for the vented vapor saturation factor based on the combined set of API, EPA and WOGA test data. This correlation showed the same trends as the correlation that was based on only the API and EPA test data, but there was more scatter of the WOGA test data from the correlation.

B3.1 Summary of API, EPA and WOGA Test Data

Table B1 summarizes the 10 API tests [38] along with the calculated saturation factor, K_S. The saturation factor for the API test data are very close to 1, with an average value for the 10 tests of 0.964.

Table B2 summarizes the 15 EPA tests [20]. It was found that all of the EPA test data was suitable for use in calculating a saturation factor, with the exception of Tests EPA-4A, EPA-4B and EPA-4C. The reason for rejecting these tests is stated at the bottom of Table B2.

Table B3 summarizes the EPA test data along with the calculated saturated factor, K_S, for those tests which were selected in Table B2. Since the average liquid surface temperature was not measured during the EPA tests, the equation indicated in Note 5 at the bottom of Table B3 was used to estimate the average liquid surface temperature.

Table B4 summarizes the 44 WOGA tests [17]. Out of the total of 44 tests, 21 were found suitable to calculate a saturation factor. The reasons for rejecting the other tests is noted at the bottom of Table B4.

Table B5 summarizes the suitable WOGA test data and the calculated saturation factor, K_S. Only the crude oil tests were used to calculate a saturation factor. The vapor pressure at the daily average liquid surface temperature was calculated utilizing the equations noted at the bottom of Table B5. No such relationships were available for the distillate and fuel oil products used in the WOGA test program.

B3.2 Saturation Factor Correlation of API and EPA Test Data

In general, it was found that there was a higher quality in the API test data [38] and EPA test data [20] than in the WOGA test data [17]. The combined set of API and EPA test data were used to develop a saturation factor correlation.

Figure B2 presents the correlation, where the saturation factor, K_S, was found to be related to the product of the vapor pressure, P_{VA}, and the vapor space outage, H_V. The vapor pressure characteristics of the stock used in the EPA tests were readily known because they were single component stocks.

B3.3 Saturation Factor Correlation of API, EPA and WOGA Test Data

The correlation of the API and EPA test data shown in Figure B2 is satisfactory, but is based only on test data from fuel oil (API test data) and single component liquid stocks (EPA test data).

Although it was found that, in general, the API and EPA test data were of higher quality than the WOGA test data, it was decided to develop a single correlation which was fit to the combined set of API, EPA and WOGA test data. This combined data set includes 34 data points that extend up to a $P_{VA}H_V$ value of about 78 psia ft. and include WOGA test data on crude oil.

Table B6 summarizes the 34 data points which were used to develop the saturation factor correlation from the combined set of API, EPA and WOGA test data.

Figure B3 is a plot of $((1/K_S) - 1)$ versus $P_{VA}H_V$ for the API, EPA and WOGA test data. The test data were fit with a least squares linear correlation, as noted on Figure B3. The correlation coefficient, r^2, was 0.76. Eq (B-22) is the resulting correlation.

$$K_S = \frac{1}{1 + 0.0525\ P_{VA}H_V} \qquad \text{(B-22)}$$

Figures B3 and B4 illustrate that the WOGA test data has more scatter in comparison to the API and EPA test data. Part of this scatter is believed to be due to the more uncertain vapor pressure characteristics of the stocks used in the WOGA tests and the fact that only a few vapor samples were taken during each WOGA test.

Figure B4 illustrates the results of the correlation developed in Figure B3, where the saturation factor is plotted versus $P_{VA}H_V$. The correlation indicates that the saturation factor approaches 1 as the vapor pressure or the vapor space outage approach 0. The correlation also shows that the saturation factor becomes small as the vapor pressure or the vapor space outage increase. These trends are in agreement with those that are predicted by Eq (B-21) of the theoretical analysis.

B4.0 CONCLUSION

Equation (B-22) was selected for use in calculating the vented vapor saturation factor, K_S, in API Publication 2518, Second Edition [A7]. This equation was developed from a correlation of the API, EPA and WOGA test data, and exhibits the same trends with varying P_{VA} and H_{VO} that were exhibited by Eq (B-21) of the theoretical analysis.

Table B1 - Saturation Factor, K_S, for API Test Data [38]

Test No.	Q (1) (ft^3/day)	C_V (2) (lbm/ft^3)x10^{-3}	E (1) (lbm/day)	H_V (1) (ft)	T_{AA} (1) (°F)	T_{LA} (1) (°F)	A (1) (-)	B (1) (°R)	P_{VA} at T_{LA} (3) (psia)	M_V (1) (lbm/lbmole)	$P_{VA}H_V$ (psia ft)	K_S (4) (-)
API-1	139	0.109	0.0152	8.85	45.4	55.3	14.348	10,082	0.00536	110.0	0.0474	1.025
API-2	157	0.108	0.0170	8.85	51.9	56.9	14.348	10,082	0.00569	110.0	0.0504	0.958
API-3	188	0.115	0.0216	8.85	52.2	58.3	14.348	10,082	0.00600	110.0	0.0531	0.967
API-4	185	0.118	0.0219	8.85	50.4	58.7	14.348	10,082	0.00609	110.0	0.0539	0.983
API-5	159	0.113	0.0179	8.85	49.2	57.8	14.348	10,082	0.00589	110.0	0.0521	0.965
API-6	78	0.101	0.0079	8.85	47.8	54.9	14.348	10,082	0.00528	110.0	0.0467	0.963
API-7	202	0.165	0.0334	8.85	54.8	65.0	9.260	7,287.2	0.00977	110.0	0.0865	0.866
API-8	210	0.239	0.0502	8.85	65.0	79.6	9.260	7,287.2	0.0142	110.0	0.126	0.884
API-9	207	0.231	0.0478	8.85	57.1	74.8	9.260	7,287.2	0.0126	110.0	0.111	0.958
API-10	185	0.238	0.0441	8.85	60.6	72.9	9.260	7,287.2	0.0120	110.0	0.106	1.033
										Average =	0.0733	0.960

Notes: (1) Measured value from test data.

(2) Calculated value. $C_V = E/Q$

(3) Calculated value. $P_{VA} = \exp[A - (B/T_{LA})]$, where T_{LA} is in °R.

(4) Calculated value. $K_S = [C_V/(P_{VA}M_V/RT_{LA})]$, where T_{LA} is in °R.

Table B2 - Summary of EPA Tests [20] Selected

Test	Product Type	Insulated Tank (Yes/No)	Selected	Reasons for Rejection
EPA-1A	Isopropanol	N	Y	
EPA-1B	Isopropanol	N	Y	
EPA-2A	Ethanol	N	Y	
EPA-2B	Ethanol	N	Y	
EPA-2C	Ethanol	N	Y	
EPA-3A	Glacial Acetic Acid	N	Y	
EPA-3B	Glacial Acetic Acid	N	Y	
EPA-4A	Formaldehyde	Y	N	1
EPA-4B	Formaldehyde	Y	N	1
EPA-4C	Formaldehyde	Y	N	1
EPA-5A	Ethyl Benzene	N	Y	
EPA-5B	Ethyl Benzene	N	Y	
EPA-6A	Cyclohexane	N	Y	
EPA-6B	Cyclohexane	N	Y	
EPA-6C	Cyclohexane	N		

Reasons for Rejection: (1) Tank is insulated.

Table B3 - Saturation Factor, K_S, for EPA Test Data [20]

Test No.	Q (1) (ft^3/day)	C_V (2) (lbm/ft^3)$\times 10^{-3}$	E (1) (lbm/day)	H_V (1) (ft)	T_{AA} (1) (^oF)	T_B (1) (^oF)	Shell Color (1) (-)	α (3) (-)	H_H (1) (Btu/ft^2 day)	T_{LA} (5) (^oF)	A (1) (-)	B (1) (^oR)	P_{VA} at T_{LA} (6) (psia)	M_V (1) (lbm/lbmole)	$P_{VA}H_V$ (psia ft)	K_S (7) (-)
EPA-1A	3,824	3.93	15.0	27.1	65.4	70.0	White	0.17	2470	71.3	16.7687	9113.6	0.674	60.10	18.26	0.553
EPA-1B	4,248	4.06	17.2	27.1	69.1	70.0	White	0.17	2290	72.7	16.7687	9113.6	0.705	60.10	19.11	0.547
EPA-2A	1,313	4.50	5.91	11.4	77.7	70.3	White	0.17	1700	75.8	16.3801	8760.7	1.020	46.02	11.63	0.551
EPA-2B	790	4.32	3.41	11.4	75.4	71.4	White	0.17	2320	76.3	16.3801	8760.7	1.036	46.02	11.81	0.521
EPA-2C	1,435	3.59	5.15	11.4	66.3	70.4	White	0.17	1730	70.9	16.3801	8760.7	0.877	46.02	10.00	0.506
EPA-3A	9,508	2.23	21.2	26.7	62.1	69.9	Gray	0.54	1730	73.9	14.8028	8591.1	0.273	60.05	7.29	0.779
EPA-3B	18,934	2.39	45.3	26.7	65.9	69.8	Gray	0.54	2400	78.3	14.8028	8591.1	0.312	60.05	8.32	0.737
EPA-4A	25,000	1.00	25.0	27.9	70.0	149.6	Gray	0.54	2360	----	-------	------	-----	30.03	-----	-----
EPA-4B	24,000	1.00	24.0	27.9	74.0	147.1	Gray	0.54	2470	----	-------	------	-----	30.03	-----	-----
EPA-4C	22,000	1.00	22.0	27.9	78.8	143.9	Gray	0.54	1840	----	-------	------	-----	30.03	-----	-----
EPA-5A	2,526	4.50	11.4	11.9	80.5	81.7	White	0.17	2140	84.0	14.0362	8423.3	0.233	106.11	2.77	1 062
EPA-5B	3,740	3.84	14.4	11.9	78.8	80.0	White	0.17	2540	82.9	14.0362	8423.3	0.226	106.11	2.69	0.933
EPA-6A	2,965	6.75	20.0	17.8	86.7	79.0	White	0.17	1730	84.7	13.6969	7091.7	1.954	84.16	34.79	0.240
EPA-6B	3,094	5.50	17.0	17.8	80.2	78.7	White	0.17	2510	82.7	13.6969	7091.7	1.863	84.16	33.15	0.204
EPA-6C	2,980	4.82	14.4	17.8	82.0	78.7	White	0.17	2160(4)	83.0	13.6969	7091.7	1.876	84.16	33.39	0.178

Notes:
(1) Measured value from test data.
(2) Calculated value. $E = QC_V$
(3) Value determined from Table E5 in Section E of this Documentation File.
(4) Assumed value. Based on the average of the H_H values for the other EPA tests.
(5) Calculated value. $T_{LA} = 0.437T_{AA} + 0.563T_B + 0.00789\alpha H_H$
(6) Calculated value. $P_{VA} = \exp[A - (B/T_{LA})]$, where T_{LA} is in ^oR.
(7) Calculated value. $K_S = [C_V/(P_{VA}M_V/RT_{LA})]$, where T_{LA} is in ^oR.

Table B4 - Summary of WOGA Tests [17] Selected

Test No.	Product Type	RVP (psi)	Insulated Tank (Yes/No)	Vapor Outflow (sft^3/day)	Selected (Yes/No)	Reasons for Rejection
WOGA-1A	Crude Oil	1.8	N	0	Y	
WOGA-1B	Crude Oil	1.8	N	0	Y	
WOGA-1C	Crude Oil	1.8	N	0	Y	
WOGA-2A	Crude Oil	0.8	Y	31	N	1,4
WOGA-2B	Crude Oil	0.8	Y	42	N	1,4
WOGA-3A	Distillate	---	Y	0	N	1,2
WOGA-3B	Distillate	---	Y	0	N	1,2
WOGA-4A	Crude Oil	1.3	N	0	Y	
WOGA-4B	Crude Oil	1.3	N	0	Y	
WOGA-5	Fuel Oil	---	Y	1,030	N	1,2
WOGA-6	Distillate	---	N	0	N	2
WOGA-7A	Crude Oil	3.4	N	15,300	Y	
WOGA-7B	Crude Oil	3.4	N	29,200	Y	
WOGA-7C	Crude Oil	3.4	N	15,800	Y	
WOGA-8A	Crude Oil	1.2	N	14,930	Y	
WOGA-8B	Crude Oil	1.2	N	19,220	Y	
WOGA-8C	Crude Oil	1.2	N	19,300	Y	
WOGA-9A	Crude Oil	5.3	N	4,740	N	5
WOGA-9B	Crude Oil	5.3	N	5,800	N	5
WOGA-9C	Crude Oil	5.3	N	5,800	N	5
WOGA-10A	Distillate	---	N	0	N	2
WOGA-10B	Distillate	---	N	0	N	2
WOGA-10C	Distillate	---	N	0	N	2
WOGA-11A	Crude Oil	0.1	Y	33	N	1,4
WOGA-11B	Crude Oil	0.1	Y	7	N	1,4
WOGA-12	Crude Oil	15.1	N	430	N	3
WOGA-13A	Crude Oil	0.5	N	18,300	N	4
WOGA-13B	Crude Oil	0.5	N	18,320	N	4
WOGA-14	Distillate	---	N	7,675	N	2
WOGA-15	Crude Oil	3.0	N	1,800	Y	

Table B4 - Summary of WOGA Tests [17] Selected (Continued)

Test No.	Product Type	RVP (psi)	Insulated Tank (Yes/No)	Vapor Outflow (sft^3/day)	Selected (Yes/No)	Reasons for Rejection
WOGA-16A	Crude Oil	5.2	N	4,029	Y	
WOGA-16B	Crude Oil	5.2	N	5,857	Y	
WOGA-16C	Crude Oil	5.2	N	5,454	Y	
WOGA-17A	Crude Oil	5.5	N	17,058	Y	
WOGA-17B	Crude Oil	5.5	N	16,059	Y	
WOGA-18A	Crude Oil	0.4	N	0	N	4
WOGA-18B	Crude Oil	0.4	N	0	N	4
WOGA-18C	Crude Oil	0.4	N	0	N	4
WOGA-19A	Crude Oil	3.0	N	284	Y	
WOGA-19B	Crude Oil	3.0	N	173	Y	
WOGA-20A	Crude Oil	4.1	N	0	Y	
WOGA-20B	Crude Oil	4.1	N	0	Y	
WOGA-21A	Distillate	---	N	27,210	N	2
WOGA-21B	Distillate	---	N	25,680	N	2

Reasons for Rejection:

(1) Tank is insulated.
(2) Product is a distillate or fuel oil. The vapor pressure versus temperature behavior of these stock types was not well established in these tests.
(3) The liquid sample may not be representative of the tank stock during the test.
(4) The RVP was less than 1.0 psi, and the stock vapor pressure is, there-therefore, questionable.
(5) The vented gas volume outflow, Q, appears to be in error.

Table B5 - Saturation Factor, K_S, for WOGA Test Data [17]

Test No.	Q (1) (sft^3/day)	C_V (1) (lbm/sft^3)x10^{-3}	E (2) (lbm/day)	H_V (1) (ft)	T_{AA} (1) (°F)	T_B (1) (°F)	Shell Color (1) (-)	Paint Condition (1) (-)	α (3) (-)	H_H (1) (Btu/ft^2 day)	T_{LA} (5) (°F)	RVP (1) (psi)	A (6) (-)	B (6) (°R)	P_{VA} at T_{LA} (6) (psia)	M_V (1) (lbm/lbmole)	$P_{VA}H_V$ (psia ft)	K_S (7) (-)
WOGA-1A	0	24.0	0	6.2	55	113	Alum., Spec.	Good	0.39	1415(4)	92.0	1.8	12.25	6546	1.469	68.3	9.11	1.416
WOGA-1B	0	28.0	0	6.2	56	98	Alum., Spec.	Good	0.39	1415(4)	84.0	1.8	12.25	6546	1.234	67.0	7.65	1.976
WOGA-1C	0	22.3	0	6.2	53	90	Alum., Spec.	Good	0.39	1415(4)	78.2	1.8	12.25	6546	1.084	64.5	6.72	1.842
WOGA-2A	31	7.30	0.226	9.3	55	150	Gray, Light	Good	0.54	1415(4)	114.5	0.8	13.04	7532	0.925	41.9	8.61	1.160
WOGA-2B	42	7.30	0.307	9.3	51	150	Gray, Light	Good	0.54	1415(4)	112.8	0.8	13.04	7532	0.890	41.9	8.28	1.203
WOGA-3A	0	0.814	0	4.0	52	150	Alum., Diff.	Good	0.60	940	111.6	---	---	----	-----	52.2	----	-----
WOGA-3B	0	0.814	0	4.0	58	150	Alum., Diff.	Good	0.60	1310	116.0	---	---	----	-----	52.2	----	-----
WOGA-4A	0	4.66	0	12.4	64	55	Alum., Diff.	Poor	0.68	1415(4)	66.5	1.3	12.57	6942	0.536	67.7	6.65	0.725
WOGA-4B	0	4.66	0	12.4	59	55	Alum., Diff.	Poor	0.68	1415(4)	64.3	1.3	12.57	6942	0.507	67.7	6.29	0.763
WOGA-5	1,030	0.790	8.14	3.3	52	180	Alum., Diff.	Poor	0.68	1415(4)	131.7	---	---	----	-----	124.4	----	-----
WOGA-6	0	0.822	0	8.5	56	90	Peach	Good	0.34	1570	79.4	---	---	----	-----	95.9	----	-----
WOGA-7A	15,300	5.08	77.7	39.6	64	56	Gray, Med.	Good	0.68	1415(4)	67.1	3.4	11.64	5773	1.976	69.0	78.26	0.211
WOGA-7B	29,200	5.08	148.	39.6	66	56	Gray, Med.	Good	0.68	933	65.4	3.4	11.64	5773	1.907	69.0	75.53	0.218
WOGA-7C	15,800	5.08	80.3	39.6	62	56	Gray, Med.	Good	0.68	1415(4)	66.2	3.4	11.64	5773	1.939	69.0	76.80	0.214
WOGA-8A	14,930	5.38	80.3	37.3	62	65	Gray, Med.	Good	0.68	1780	73.2	1.2	12.64	7039	0.566	66.7	21.11	0.815
WOGA-8B	19,220	5.38	103.	37.3	64	65	Gray, Med.	Good	0.68	1415(4)	72.2	1.2	12.64	7039	0.552	66.7	20.60	0.834
WOGA-8C	19,300	5.38	104.	37.3	65	65	Gray, Med.	Good	0.68	1415(4)	72.6	1.2	12.64	7039	0.558	66.7	20.80	0.826
WOGA-9A	4,740	20.9	99.1	23.2	60	73	Gray, Med.	Good	0.68	2050	78.3	5.3	11.21	5233	4.406	55.0	102.23	0.498
WOGA-9B	5,800	20.9	121.	23.2	63	73	Gray, Med.	Good	0.68	2050	79.6	5.3	11.21	5233	4.511	55.0	104.65	0.488
WOGA-9C	5,800	20.9	121.	23.2	64	73	Gray, Med.	Good	0.68	1850	79.0	5.3	11.21	5233	4.462	55.0	103.53	0.492
WOGA-10A	0	0.311	0	3.6	58	60	Peach	Good	0.34	1415(4)	62.9	---	---	----	-----	120.3	----	-----
WOGA-10B	0	0.311	0	3.6	60	60	Peach	Good	0.34	1450	63.9	---	---	----	-----	120.3	----	-----
WOGA-10C	0	0.311	0	3.6	56	60	Peach	Good	0.34	1570	62.5	---	---	----	-----	120.3	----	-----
WOGA-11A	33	1.56	0.0515	2.0	54	158	Alum., Diff.	Poor	0.68	1080	118.3	0.2	14.38	9217	0.209	29.2	0.42	1.644
WOGA-11B	7	1.56	0.0109	2.0	56	158	Alum., Diff.	Poor	0.68	1415(4)	121.0	0.2	14.38	9217	0.225	29.2	0.45	1.533
WOGA-12	430	6.30	2.71	7.6	51	72	White	Good	0.17	1415(4)	64.7	0.4	13.71	8375	0.104	50.4	0.79	6.747
WOGA-13A	18,300	7.05	129.	35.8	62	92	White	Good	0.17	1400	80.8	0.5	13.49	8104	0.222	63.9	7.96	2.879
WOGA-13B	18,320	7.80	143.	35.8	61	83	White	Good	0.17	1610	75.5	0.5	13.49	8104	0.192	64.4	6.86	3.630
WOGA-14	7,675	0.185	1.42	40.1	59	65	White	Good	0.17	1415(4)	64.3	---	---	----	-----	103.8	----	-----
WOGA-15	1,800	24.2	43.6	2.9	73	65	White	Good	0.17	1415(4)	70.4	3.0	11.76	5926	1.787	50.6	5.18	1.522

Table B5 - Saturation Factor, K_S, for WOGA Test Data [17] (Continued)

Test No.	Q (1) (sft^3/day)	C_V (1) (lbm/sft^3)x10^{-3}	E (2) (lbm/day)	H_V (1) (ft)	T_{AA} (1) (°F)	T_B (1) (°F)	Shell Color (1) (-)	Paint Condition (1) (-)	α (3) (-)	H_H (1) (Btu/ft^2 day)	T_{LA} (5) (°F)	RVP (1) (psi)	A (6) (-)	B (6) (°R)	P_{VA} at T_{LA} (6) (psia)	M_V (1) (lbm/lbmole)	$P_{VA}H_V$ (psia ft)	K_S (7) (-)
WOGA-16A	4,029	24.5	98.7	2.3	69	56	White	Good	0.17	1020	63.0	5.2	11.23	5257	3.230	63.9	7.43	0.666
WOGA-16B	5,857	24.5	143.	2.3	70	56	White	Good	0.17	984	63.4	5.2	11.23	5257	3.255	63.9	7.49	0.661
WOGA-16C	5,454	24.5	134.	2.3	64	56	White	Good	0.17	1415(4)	61.4	5.2	11.23	5257	3.132	63.9	7.20	0.685
WOGA-17A	17,058	33.9	578.	6.9	66	65	White	Good	0.17	2050	68.2	5.5	11.17	5189	3.820	52.4	26.36	0.959
WOGA-17B	16,059	33.9	544.	6.9	69	65	White	Good	0.17	1850	69.2	5.5	11.17	5189	3.892	52.4	26.85	0.943
WOGA-18A	0	1.65	0	1.8	65	67	White	Good	0.17	1415(4)	68.0	0.4	13.71	8375	0.115	21.4	0.21	3.790
WOGA-18B	0	1.65	0	1.8	59	67	White	Good	0.17	1415(4)	65.4	0.4	13.71	8375	0.106	21.4	0.19	4.080
WOGA-18C	0	1.65	0	1.8	62	67	White	Good	0.17	1415(4)	66.7	0.4	13.71	8375	0.111	21.4	0.20	3.932
WOGA-19A	284	23.1	6.56	2.5	69	63	White	Good	0.17	1415(4)	67.5	3.0	11.76	5926	1.681	53.4	4.20	1.456
WOGA-19B	173	23.1	4.00	2.5	73	63	White	Good	0.17	1415(4)	69.3	3.0	11.76	5926	1.746	53.4	4.37	1.406
WOGA-20A	0	23.2	0	4.0	61	74	Green	Good	0.59	811	72.1	4.1	11.46	5546	2.804	60.9	11.22	0.775
WOGA-20B	0	23.2	0	4.0	56	74	Green	Good	0.59	1080	71.2	4.1	11.46	5546	2.755	60.9	11.02	0.788
WOGA-21A	27,210	0.367	9.99	21.7	56	66	Black	Good	0:94	881	68.2	---	---	----	-----	37.2	-----	-----
WOGA-21B	25,680	0.367	9.42	21.7	58	66	Black	Good	0.94	1420	72.2	---	---	----	-----	37.2	-----	-----

Notes:
(1) Measured value from test data.
(2) Calculated value. $E = QC_V$
(3) Value taken from Tables E3 and E5 in Section E of this Documentation File.
(4) Value determined from the average H_H measured in all of the WOGA tests.
(5) Calculated value. $T_{LA} = 0.437T_{AA} + 0.563T_B + 0.00789\alpha H_H$.
(6) Calculated values. $A = 12.82 - 0.9672 \ln(RVP)$
$B = 7261 - 1216 \ln(RVP)$
$P_{VA} = \exp[A - (B/T_{LA})]$, where T_{LA} is in °R.
(7) Calculated value. $K_S = [C_V/(P_{VA}M_V/RT_{LA})]$, where T_{LA} is in °R.

Table B6 - Summary of Test Data Used to Develop the Vented Vapor Saturation Factor Correlation

Test No.	K_S (-)	$[(1/K_S)-1]$ (-)	$P_{VA}H_V$ (psia ft)
API- 1	1.025	------	0.0474
API- 2	0.958	0.0434	0.0504
API- 3	0.967	0.0338	0.0531
API- 4	0.983	0.0177	0.0539
API- 5	0.965	0.0363	0.0521
API- 6	0.963	0.0380	0.0467
API- 7	0.866	0.154	0.0865
API- 8	0.884	0.131	0.126
API- 9	0.958	0.0442	0.111
API-10	1.033	------	0.106
EPA-1A	0.553	0.809	18.26
EPA-1B	0.547	0.827	19.11
EPA-2A	0.551	0.816	11.63
EPA-2B	0.521	0.918	11.81
EPA-2C	0.506	0.975	10.00
EPA-3A	0.779	0.284	7.29
EPA-3B	0.737	0.356	8.32
EPA-5A	1.062	-----	2.77
EPA-5B	0.933	0.0716	2.69
EPA-6A	0.240	3.17	34.79
EPA-6B	0.204	3.90	33.15
EPA-6C	0.178	4.62	33.39
WOGA-1A	1.416	-----	9.11
WOGA-1B	1.976	-----	7.65
WOGA-1C	1.842	-----	6.72
WOGA-4A	0.725	0.379	6.65
WOGA-4B	0.763	0.311	6.29
WOGA-7A	0.211	3.74	78.26
WOGA-7B	0.218	3.59	75.53
WOGA-7C	0.214	3.67	76.80
WOGA-8A	0.815	0.227	21.11
WOGA-8B	0.834	0.199	20.60
WOGA-8C	0.826	0.211	20.80
WOGA-15	1.522	-----	5.18
WOGA-16A	0.666	0.502	7.43
WOGA-16B	0.661	0.513	7.49
WOGA-16C	0.685	0.460	7.20
WOGA-17A	0.959	0.0428	26.36
WOGA-17B	0.943	0.0604	26.85
WOGA-19A	1.456	-----	4.20
WOGA-19B	1.406	-----	4.37
WOGA-20A	0.775	0.290	11.22
WOGA-20B	0.780	0.282	11.02

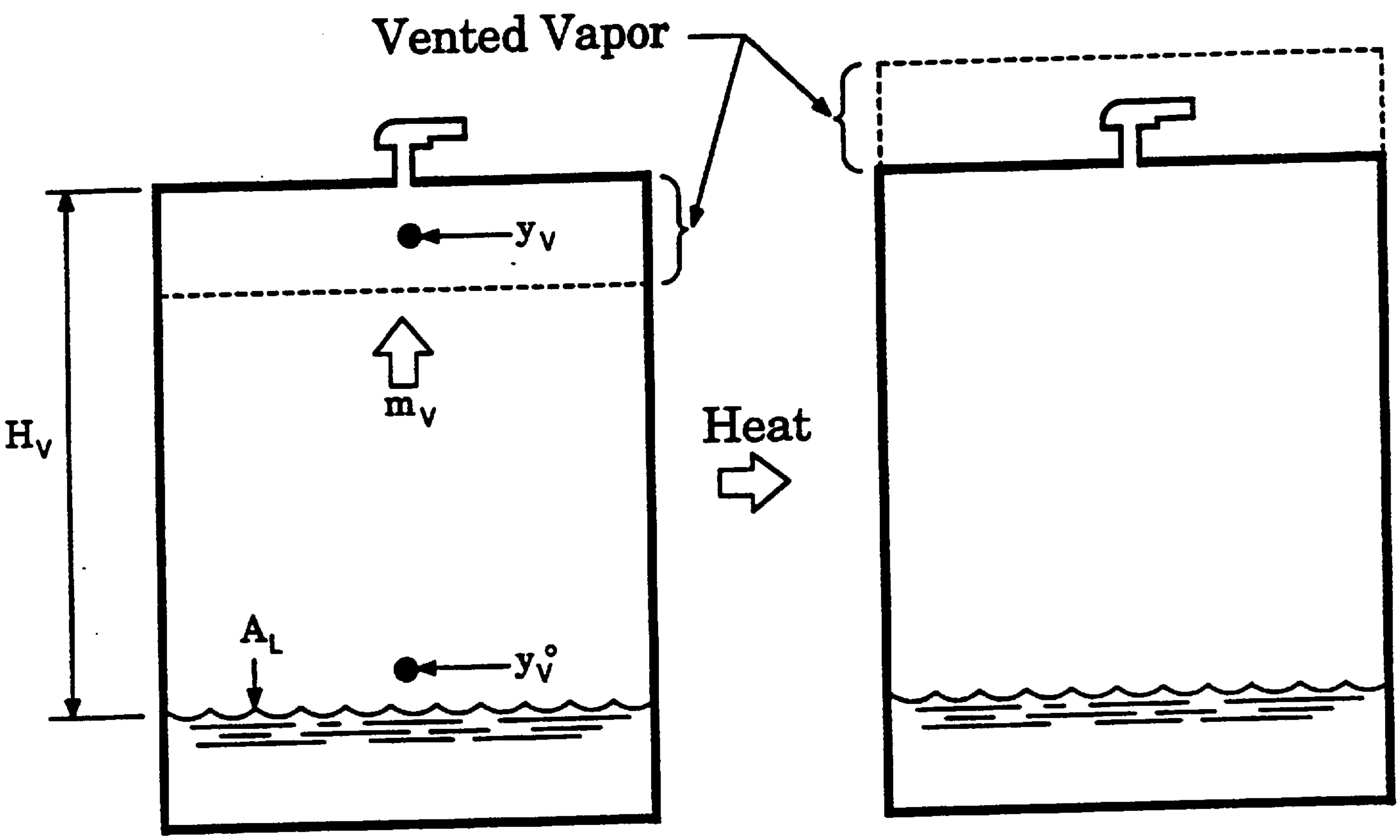

Figure B1 - Schematic of the Tank Vapor Space for the Vented Vapor Saturation Factor Analysis

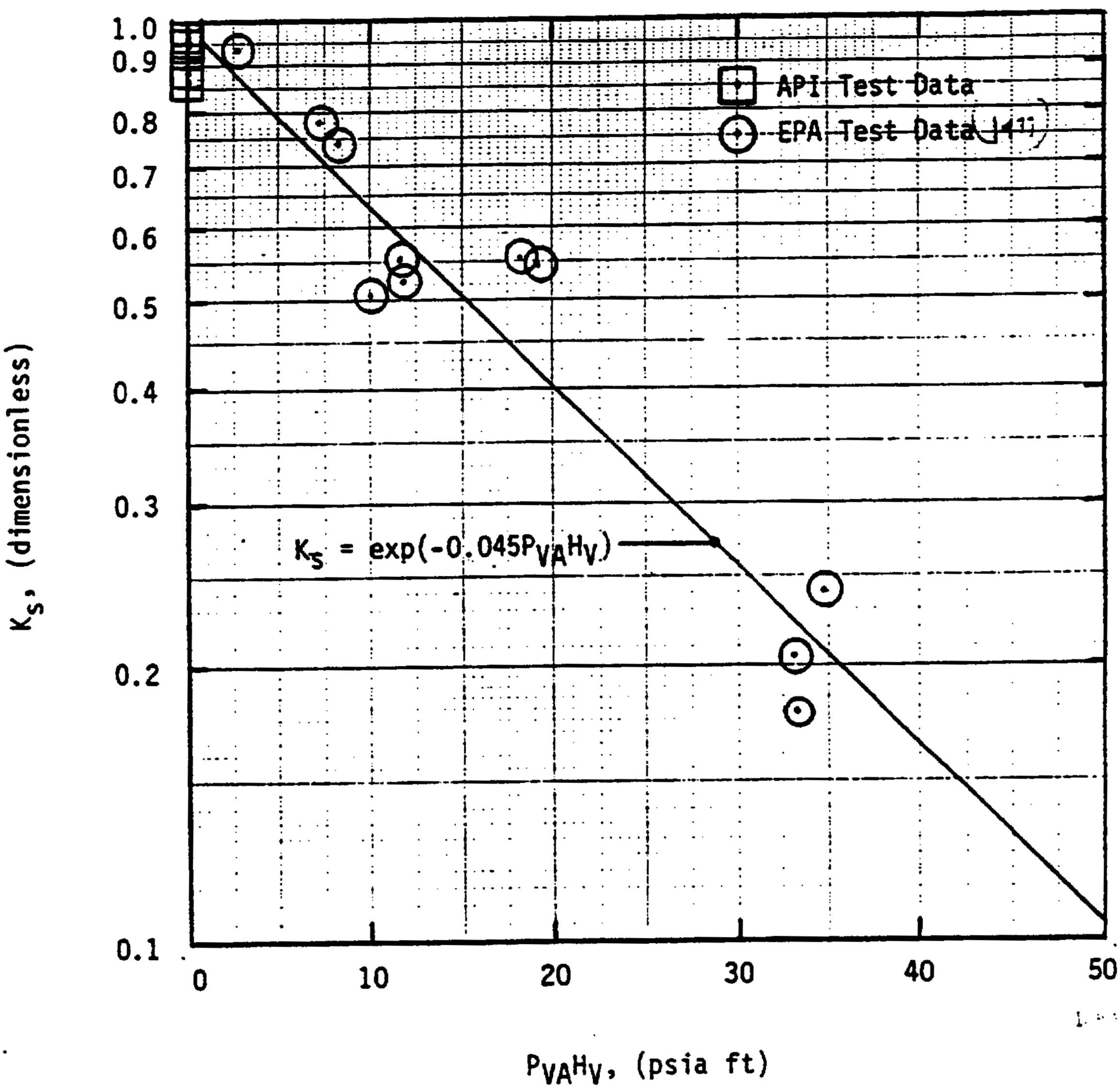

Figure B2 - Saturation Factor, K_S, Versus $P_{VA}H_V$ for the API and EPA Test Data

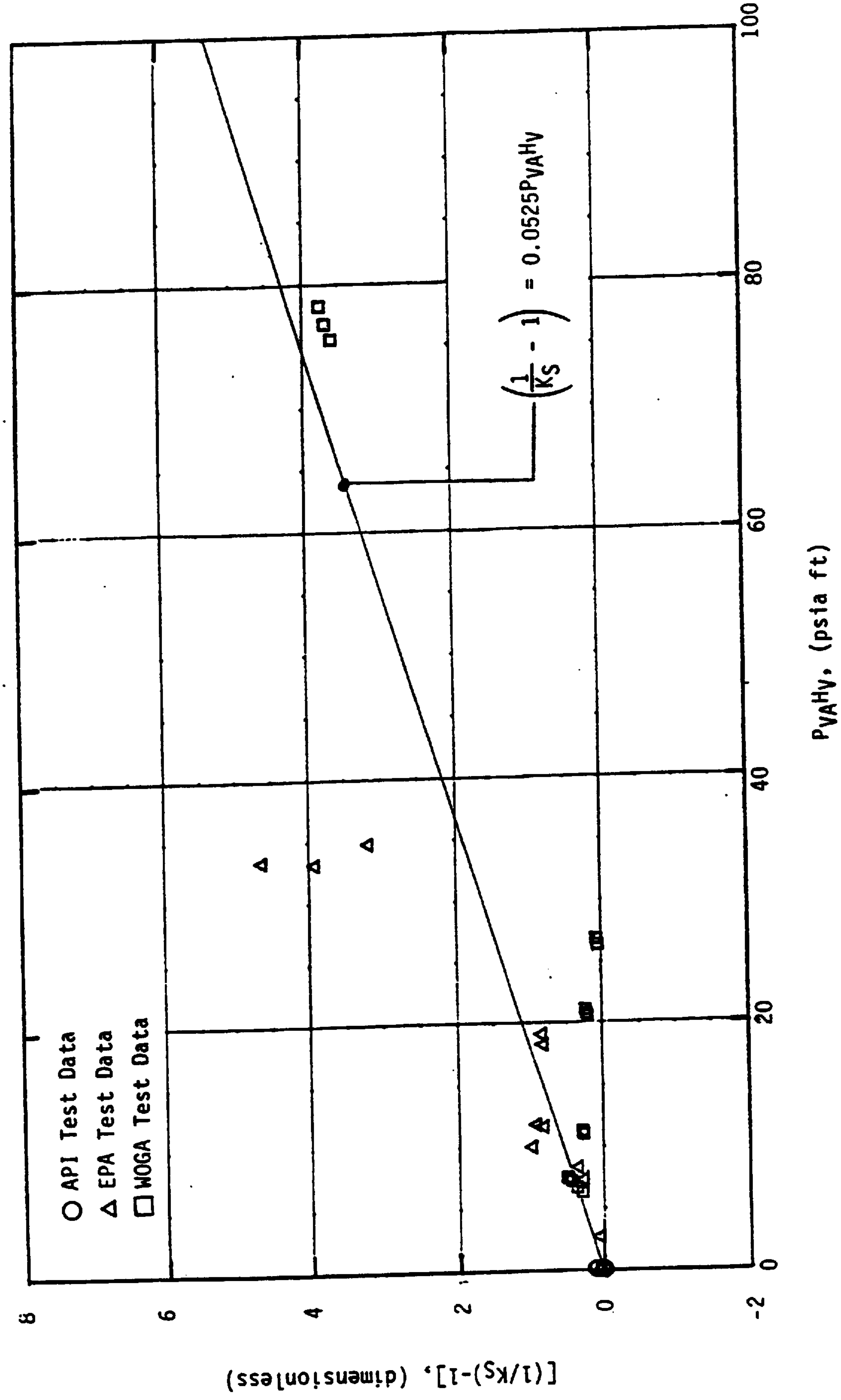

Figure B3 - Saturation Factor, K_S, Correlation

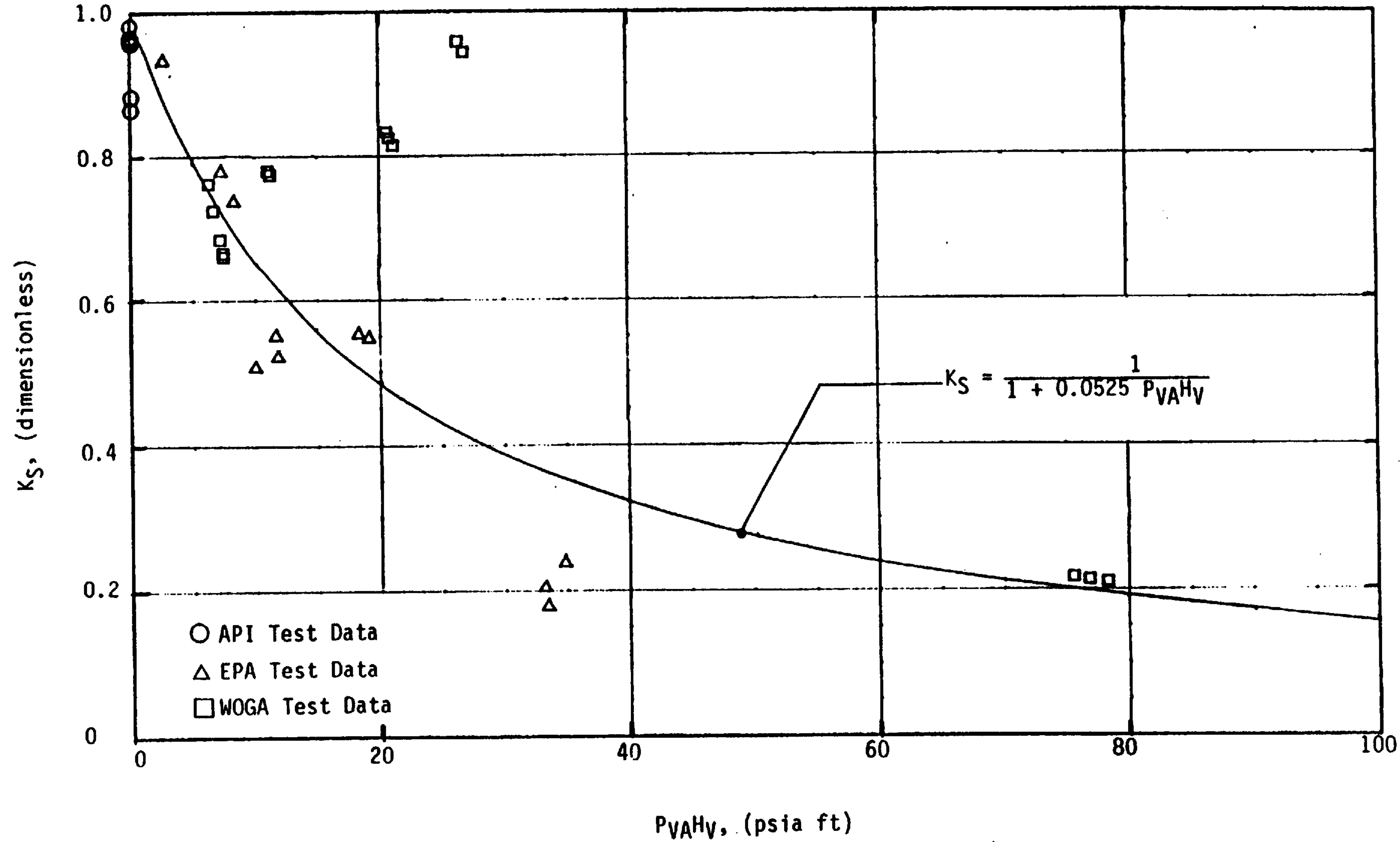

Figure B4 - Saturation Factor, K_S, Versus $P_{VA}H_V$ for the API, EPA and WOGA Test Data

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SECTION C

DEVELOPMENT OF
VAPOR SPACE TEMPERATURE FACTOR, K_T

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NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
A	Area	ft^2
B	Defined by Eq (C-35)	B/hr ft^2
C	Ambient temperature range factor, defined by Eq (C-44)	dimensionless
c	Heat capacity	B/lbm ^oF
D	Diameter	ft
E	Vapor space aspect ratio, defined by Eq (C-77)	dimensionless
e	Defined by Eqs (C-19), (C-20) and (C-21)	dimensionless
F	Solar insolation factor, defined by Eq (C-78)	dimensionless
f	Defined by Eqs (C-22), (C-23) and (C-24)	dimensionless
G	Heat transfer coefficient ratio, defined by Eq (C-79)	dimensionless
g	Defined by Eqs (C-25), (C-26) and (C-27)	^oF
H	Height	ft
H_H	Daily total solar insolation on a horizontal surface	B/day ft^2
h	Heat transfer coefficient	B/hr ft^2 ^oF
I	Solar insolation intensity	B/hr ft^2
J	Solar absorptance ratio, defined by Eq (C-80)	dimensionless
K_{SN}	Defined by Eq (C-68)	dimensionless
K_T	Vapor space temperature factor, defined by Eq (C-60)	dimensionless
m	Mass	lbm
q	Heat transfer rate	B/hr
r_{GD}	Solar reflectivity of the ground	dimensionless
r_H	Ratio of I_H to H_H, defined by Eq (C-71)	day/hr
T	Temperature	^oF
ΔT	Temperature change	^oF
t	Time	hr
U	Overall heat transfer coefficient	B/hr ft^2 ^oF
θ	Zenith angle, or the angle between the sun and the normal to a horizontal surface	deg.
α	Solar absorptance	dimensionless
τ	Atmospheric solar transmittance	dimensionless

SUBSCRIPTS

A	Ambient (or air)
AV	Average
B	Beam component of solar insolation
D	Diffuse component of solar insolation
G	Gas
GD	Ground
H	Horizontal surface solar insolation
I	Inside
L	Liquid
MN	Minimum
MX	Maximum
N	North shell (or the half of the tank shell facing away from the sun)
NI	North shell inside
NO	North shell outside
O	Outside
R	Roof
RI	Roof inside
RO	Roof outside
S	South shell (or the half of the tank shell facing toward the sun)
SI	Soutn shell inside
SN	Solar noon
SO	South shell outside
T	Temperature

C1.0 INTRODUCTION

This section of the Documentation File to API Publication 2518, Second Edition, presents the development of the equation for the vapor space temperature factor, K_T, which is defined as the ratio of the gas space temperature range, ΔT_G, to the ambient temperature range, ΔT_A.

Section C2 describes the heat transfer model. The major assumptions used in the model development are:

- Assumption 1
  The gas space is fully mixed (i.e. it is at a uniform temperature and composition).

- Assumption 2
  The liquid space is fully mixed (i.e. it is at a uniform temperature and composition), and remains at a constant temperature during the daily cycle.

- Assumption 3
  The tank wall in the gas space can be treated as three (3) separate elements: (1) the roof; (2) the half of the tank wall facing away from the sun; and (3) the half of the tank wall facing the sun. Each tank wall element can be characterized by a single temperature, which varies during the daily cycle.

- Assumption 4
  The affects of rain and snow precipitation are not included in the model.

These assumptions are the same as those upon which the API Computer Model is based [30, 38]*.

* Numbers in brackets refer to the numbered references listed at the end of this Documentation File.

Section C3 presents the heat balance differential equations for each of the tank wall elements and the gas space (see Eqs (C-1), (C-3), (C-5) and (C-7)). These ordinary differential equations are essentially the same as those used in the API Computer Model [30, 38], where they are solved by stepwise numerical integration.

A sensitivity analysis [30] of the API Computer Model showed that the gas and tank wall heat capacity terms in the differential equations have a negligible affect on the computed results. Thus, the following additional assumption was made:

- Assumption 5
  The heat capacity terms in the energy balance equations can be neglected in comparison to the other heat transfer terms.

With this assumption, the differential equations reduce to a set of four (4) simultaneous algebraic equations (see Eqs (C-16), (C-17), (C-18) and (C-29)).

Section C4 presents the solution to these simultaneous equations by solving for the gas temperature, T_G (see Eq (C-36)), and gas temperature range, ΔT_G (see Eqs (C-58) and (C-59)).

Section C5 presents the vapor space temperature factor equation for the general case of a two color fixed-roof tank, where the roof and shell are painted different colors (see Eqs (C-74) through (C-80)).

Section C6 presents the vapor space temperature factor equation for the simplified case of a two color fixed-roof tank where typical solar insolation parameters are used (see Eqs (C-89) through (C-94)).

Sections C7, C8 and C9 present the vapor space temperature factor equation for progressively simplified cases where more typical information is used instead of detail information for a particular tank (see Eqs (C-97), (C-106), (C-110) and (C-115)). As less detail information is used for the calculation of K_T, the estimation equations become simpler, but the estimated value of K_T becomes less accurate for a specific tank.

C2.0 HEAT TRANSFER MODEL DESCRIPTION

Figure C1 is a schematic of the energy flows and temperatures for a fixed-roof tank. The gas space tank wall is divided into three (3) tank wall elements:

- the roof,
- the half of the gas space tank shell that faces away from the sun (referred to herein as the "north shell"), and
- the half of the gas space tank shell that faces toward the sun (referred to herein as the "south shell").

Each of these tank wall elements is characterized by a single, different temperature, T_R, T_N and T_S, respectively. The temperature of each wall element varies with time over the course of the daily cycle in response to a heat balance on the wall element.

The elements exchange heat on both their inside and outside surfaces. The inside of each element exchanges heat with the gas, which is characterized by a single temperature, T_G, by natural convention heat transfer. Heat transfer on the inside surface by long wave length thermal radiation, however, is neglected because the magnitude of this heat transfer rate is small in comparison to the natural convection heat transfer rate.

The outside of each element exchanges heat with the ambient air by convection due to the wind. In addition, the outside of each element receives solar insolation due to beam solar insolation (except the north shell), diffuse solar insolation, and ground reflected solar insolation. Each wall element also exchanges heat by long wave length thermal radiation with the tank surroundings. This last mode of heat transfer is incorporated in the outside heat transfer coefficient for each element, h_{RO}, h_{NO} and h_{SO}, respectively.

It should be noted that the thermal resistance of any thermal insulation material applied to the outside surface of the roof and shell elements can be incorporated in the outside heat transfer coefficients h_{RO}, h_{NO} and h_{SO}.

The gas space exchanges heat by natural convection with the wall elements and the liquid surface, which is assumed to be at a constant liquid temperature, T_L, during the daily cycle. The gas space is assumed to be fully mixed, so that it can be characterized by a single temperature, T_G.

C3.0 HEAT BALANCES

Sections C3.1 through C3.4 describe the heat balances that can be written for each of the four elements.

C3.1 Roof Heat Balance

$$q_{RO} + q_{RI} = m_R c_R \left[\frac{dT_R}{dt}\right] \qquad \text{(C-1)}$$

The term on the right hand side of Eq (C-1), which represents the heat capacity effect of the roof, will be neglected because its magnitude at most times during the course of the daily heating cycle is small in comparison to the other terms. Eq (C-1) then reduces to:

$$q_{RO} + q_{RI} = 0 \qquad \text{(C-2)}$$

C3.2 North Shell Heat Balance

$$q_{NO} + q_{NI} = m_N c_N \left[\frac{dT_N}{dt}\right] \qquad \text{(C-3)}$$

The term on the right hand side of Eq (C-3) will again be neglected because its magnitude is small in comparison to the other terms. Eq (C-3) then reduces to:

$$q_{NO} + q_{NI} = 0 \qquad \text{(C-4)}$$

C3.3 South Shell Heat Balance

$$q_{SO} + q_{SI} = m_S c_S \left[\frac{dT_S}{dt}\right] \quad \text{(C-5)}$$

The term on the right hand side of Eq (C-5) will again be neglected because its magnitude is small in comparison to the other terms. Eq (C-5) then reduces to:

$$q_{SO} \bullet q_{SI} = 0 \quad \text{(C-6)}$$

C3.4 Gas Space Heat Balance

$$q_{RI} + q_{NI} + q_{SI} + q_L = -m_G c_G \left[\frac{dT_G}{dt}\right] \quad \text{(C-7)}$$

The term on the right hand side of Eq (C-7) will again be neglected because its magnitude is small in comparison to the other terms. Eq (C-7) then reduces to:

$$q_{RI} + q_{NI} + q_{SI} + q_L = 0 \quad \text{(C-8)}$$

C3.5 Heat Transfer Equations

Eqs (C-9) through (C-15) are the heat transfer equations for each of the terms q_{RO}, q_{RI}, q_{NO}, q_{NI}, q_{SO}, q_{SI} and q_L that are used in Eqs (C-1) through (C-8).

$$q_{RO} = h_{RO}A_R\,(T_A - T_R) + \alpha_R\,(A_R I_B \cos\theta + A_R I_D) \quad \text{(C-9)}$$

$$q_{RI} = h_{RI}A_R\,(T_G - T_R) \quad \text{(C-10)}$$

$$q_{NO} = h_{NO}A_N\,(T_A - T_N) + \alpha_N\left[\frac{1}{2}A_N I_D + \frac{1}{2}A_N r_{GD}\,(I_B \cos\theta + I_D)\right] \quad \text{(C-11)}$$

$$q_{NI} = h_{NI}A_N\,(T_G - T_N) \qquad \text{(C-12)}$$

$$q_{SO} = h_{SO}A_S\,(T_A - T_S) + \alpha_S \left[DH_G I_B \operatorname{Sin}\theta + \frac{1}{2}A_S I_D + \frac{1}{2}A_S r_{GD}\,(I_B \operatorname{Cos}\theta + I_D)\right] \qquad \text{(C-13)}$$

$$q_{SI} = h_{SI}A_S\,(T_G - T_S) \qquad \text{(C-14)}$$

$$q_L = h_L A_L\,(T_G - T_L) \qquad \text{(C-15)}$$

C3.6 Tank Element Temperature Equations

Eqs (C-9) through (C-15) can be substituted into the tank element energy balance relations, Eqs (C-2), (C-4), and (C-6), to result in the following tank element temperature equations, Eqs (C-16) through (C-18).

$$T_R = e_R T_G + f_R T_A + g_R \qquad \text{(C-16)}$$

$$T_N = e_N T_G + f_N T_A + g_N \qquad \text{(C-17)}$$

$$T_S = e_S T_G + f_S T_A + g_S \qquad \text{(C-18)}$$

where e_R, e_N, e_S, f_R, f_N, f_S, g_R, g_N and g_S are defined by Eqs (C-19) through (C-27).

$$e_R = \left(\frac{h_{RI}}{h_{RI} + h_{RO}}\right) \qquad \text{(C-19)}$$

$$e_N = \left[\frac{h_{NI}}{h_{NI} + h_{NO}}\right] \qquad (C\text{-}20)$$

$$e_S = \left[\frac{h_{SI}}{h_{SI} + h_{SO}}\right] \qquad (C\text{-}21)$$

$$f_R = \left[\frac{h_{RO}}{h_{RI} + h_{RO}}\right] \qquad (C\text{-}22)$$

$$f_N = \left[\frac{h_{NO}}{h_{NI} + h_{NO}}\right] \qquad (C\text{-}23)$$

$$f_S = \left[\frac{h_{SO}}{h_{SI} + h_{SO}}\right] \qquad (C\text{-}24)$$

$$g_R = \left[\frac{\alpha_R \left(I_B \cos\theta + I_D\right)}{h_{RI} + h_{RO}}\right] \qquad (C\text{-}25)$$

$$g_N = \left[\frac{\alpha_N \left[\frac{1}{2} I_D + \frac{1}{2} r_{GD} \left(I_B \cos\theta + I_D\right)\right]}{h_{NI} + h_{NO}}\right] \qquad (C\text{-}26)$$

$$g_S = \left[\frac{\alpha_S \left[\frac{2}{\pi} I_B \operatorname{Sin} \theta + \frac{1}{2} I_D + \frac{1}{2} r_{GD} (I_B \operatorname{Cos} \theta + I_D)\right]}{h_{SI} + h_{SO}}\right] \qquad \text{(C-27)}$$

C4.0 VAPOR SPACE TEMPERATURE FACTOR

C4.1 Gas Space Temperature Equation

The gas space temperature equation can be developed from the gas space energy balance equation, Eq (C-8). Substituting Eqs (C-10), (C-12), (C-14) and (C-15) into Eq (C-8), we obtain:

$$\begin{aligned} &h_{RI}A_R (T_G - T_R) + h_{NI}A_N (T_G - T_N) + \\ &h_{SI}A_S (T_G - T_S) + h_L A_L (T_G - T_L) = 0 \end{aligned} \qquad \text{(C-28)}$$

Eq (C-28) may be rewritten as follows:

$$\begin{aligned} &T_G (h_{RI}A_R + h_{NI}A_N + h_{SI}A_S + h_L A_L) - \\ &T_R (h_{RI}A_R) - T_N (h_{NI}A_N) - \\ &T_S (h_{SI}A_S) - T_L (h_L A_L) = 0 \end{aligned} \qquad \text{(C-29)}$$

Eqs (C-16), (C-17) and (C-18) may now be substituted into Eq (C-29) for the terms T_R, T_N and T_S, respectively. The resulting equation may be rearranged by factoring out the temperatures T_G, T_A and T_L to obtain:

$$\begin{aligned} &T_G [h_{RI}A_R (1 - e_R) + h_{NI}A_N (1 - e_N) + h_{SI}A_S (1 - e_S) + h_L A_L] = \\ &T_A (h_{RI}A_R f_R + h_{NI}A_N f_N + h_{SI}A_S f_S) + T_L (h_L A_L) + \\ &(h_{RI}A_R g_R + h_{NI}A_N g_N + h_{SI}A_S g_S) \end{aligned} \qquad \text{(C-30)}$$

Substituting the expressions for e_R, e_N, e_S, f_R, f_N, f_S, g_R, g_N and g_S found in Eqs (C-19) through (C-27), the above Eq (C-30) becomes:

$$T_G (U_R A_R + U_N A_N + U_S A_S + h_L A_L) = T_A (U_R A_R + U_N A_N + U_S A_S) + T_L (h_L A_L) + BA_L \qquad \text{(C-31)}$$

where U_R, U_N, U_S and B are defined by Eqs (C-32) through (C-35).

$$U_R = \left[\frac{h_{RI} h_{RO}}{h_{RI} + h_{RO}}\right] \qquad \text{(C-32)}$$

$$U_N = \left[\frac{h_{NI} h_{NO}}{h_{NI} + h_{NO}}\right] \qquad \text{(C-33)}$$

$$U_S = \left[\frac{h_{SI}\ h_{SO}}{h_{SI} + h_{SO}}\right] \qquad \text{(C-34)}$$

$$B = \left[\left(\frac{U_R}{h_{RO}}\right)\left(\frac{A_R}{A_L}\right)\alpha_R (I_B \text{ Cos } \theta + I_D) + \left(\frac{U_N}{h_{NO}}\right)\left(\frac{A_N}{A_L}\right)\alpha_N \left[\frac{1}{2} I_D + \frac{1}{2} r_{GD} (I_B \text{ Cos } \theta + I_D)\right] + \left(\frac{U_S}{h_{SO}}\right)\left(\frac{A_S}{A_L}\right)\alpha_S \left[\frac{2}{\pi} I_B \text{ Sin } \theta + \frac{1}{2} I_D + \frac{1}{2} r_{GD} (I_B \text{ Cos } \theta + I_D)\right]\right] \qquad \text{(C-35)}$$

Eq (C-31) may now be solved for T_G to obtain:

$$T_G = \frac{T_A(U_R A_R + U_N A_N + U_S A_S) + T_L(h_L A_L) + BA_L}{(U_R A_R + U_N A_N + U_S A_S + h_L A_L)} \qquad \text{(C-36)}$$

C4.2 Maximum Gas Space Temperature

The maximum gas space temperature, $T_{G,MX}$, will generally occur at Solar Noon. Eq (C-36) then becomes:

$$T_{G,MX} = \frac{T_{A,SN}(U_R A_R + U_N A_N + U_S A_S) + T_L(h_L A_L) + B_{SN} A_L}{(U_R A_R + U_N A_N + U_S A_S + h_L A_L)} \quad \text{(C-37)}$$

where B_{SN} represents Eq (C-35) with the terms I_B, I_D and θ evaluated at Solar Noon.

C4.3 Minimum Gas Space Temperature

The minimum gas space temperature, $T_{G,MN}$, will occur in the night at the time of minimum ambient temperature, $T_{A,MN}$, when there is no solar insolation (i.e. when B = 0). Eq (C-36) then becomes:

$$T_{G,MN} = \frac{T_{A,MN}(U_R A_R + U_N A_N + U_S A_S) + T_L(h_L A_L)}{(U_R A_R + U_N A_N + U_S A_S + h_L A_L)} \quad \text{(C-38)}$$

C4.4 Average Gas Space Temperature

The average gas space temperature, $T_{G,AV}$, is defined by Eq (C-39):

$$T_{G,AV} = \frac{T_{G,MX} + T_{G,MN}}{2} \quad \text{(C-39)}$$

Substituting Eqs (C-37) and (C-38) into Eq (C-39), we obtain:

$$T_{G,AV} = \frac{T_{A,AV}\,(U_R A_R + U_N A_N + U_S A_S) + T_L(h_L A_L) + \frac{1}{2} B_{SN} A_L}{(U_R A_R + U_N A_N + U_S A_S + h_L A_L)} \quad \text{(C-40)}$$

C4.5 Gas Space Temperature Change

The gas space temperature change, ΔT_G, may be determined by subtracting Eq (C-38) from Eq (C-37) to yield:

$$\Delta T_G = (T_{G,MX} - T_{G,MN}) \qquad \text{(C-41)}$$

$$\Delta T_G = \frac{\Delta T_{A,SN}(U_R A_R + U_N A_N + U_S A_S) + B_{SN} A_L}{(U_R A_R + U_N A_N + U_S A_S + h_L A_L)} \qquad \text{(C-42)}$$

where $\Delta T_{A,SN}$ is are defined as follows:

$$\Delta T_{A,SN} \equiv (T_{A,SN} - T_{A,MN}) \qquad \text{(C-43)}$$

C4.6 Ambient Temperature Range Factor

It is convenient to define the ambient temperature range factor, C, as follows:

$$C \equiv \frac{\Delta T_{A,SN}}{\Delta T_A} \qquad \text{(C-44)}$$

or

$$\Delta T_{A,SN} = C\ \Delta T_A \qquad \text{(C-45)}$$

where ΔT_A is defined as follows:

$$\Delta T_A \equiv (T_{A,MX} - T_{A,MN}) \qquad \text{(C-46)}$$

Figure C2 depicts a sinusoidally varying daily ambient temperature. The ambient temperature varies from its minimum value, $T_{A,MN}$, at time t_{MN} to its maximum value, $T_{A,MX}$, at time t_{MX}. This sinusoidal variation is described by Eq (C-47).

$$T_A = T_{A,AV} + \frac{\Delta T_A}{2} \text{ Sin} \left[\left(\frac{360}{24} \right) (t - t_{MX} + 6) \right] \quad \text{(C-47)}$$

It is common for the maximum ambient temperature to occur about 2 hr after Solar Noon, or at 14:00 hrs. For this reason, we will select:

$$t_{MX} = 14 \text{ hr (or 14:00 hrs)} \quad \text{(C-48)}$$

With this value for t_{MX}, Eq (C-47) becomes:

$$T_A = T_{A,AV} + \frac{\Delta T_A}{2} \text{ Sin} \left[\left(\frac{360}{24} \right) (t - 8) \right] \quad \text{(C-49)}$$

Solar Noon occurs at t_{SN}:

$$t_{SN} = 12 \text{ hr (or 12:00 hrs)} \quad \text{(C-50)}$$

The ambient temperature at Solar Noon, $T_{A,SN}$, from Eq (C-49) is:

$$T_{A,SN} = T_{A,AV} + \frac{\Delta T_A}{2} \text{ Sin} \left[\left(\frac{360}{24} \right) (12 - 8) \right]$$

$$T_{A,SN} = T_{A,AV} + 0.433013 \, \Delta T_A \quad \text{(C-51)}$$

We can now calculate C from Eq (C-44) using Eqs (C-43) and (C-51) as follows:

$$C = \frac{\Delta T_{A,SN}}{\Delta T_A}$$

$$C = \frac{T_{A,SN} - T_{A,MN}}{\Delta T_A}$$

$$C = \frac{T_{A,AV} + 0.433013\Delta T_A - T_{A,MN}}{\Delta T_A}$$

$$C = \frac{T_{A,MN} + 0.5\Delta T_A + 0.433013\Delta T_A - T_{A,MN}}{\Delta T_A}$$

$$C = 0.933013 \quad \text{(C-52)}$$

C4.7 Area Equations

For a fixed-roof tank with a flat roof, the areas A_R, A_N, A_S and A_L may be determined from Eqs (C-53) through (C-56).

$$A_R = \frac{\pi D^2}{4} \quad \text{(C-53)}$$

$$A_N = \frac{\pi D H_G}{2} \quad \text{(C-54)}$$

$$A_S = \frac{\pi D H_G}{2} \quad \text{(C-55)}$$

$$A_L = \frac{\pi D^2}{4} \quad \text{(C-56)}$$

C4.8 Gas Space Temperature Change Equation

Using the area relationships of Eqs (C-53) through (C-56) and Eq (C-45), we may rewrite Eqs (C-40), (C-42) and (C-35), respectively as follows:

$$T_{G,AV} = \frac{T_{A,AV}\left[U_R + U_N\left(\frac{2H_G}{D}\right) + U_S\left(\frac{2H_G}{D}\right)\right] + T_L h_L + \frac{1}{2}B_{SN}}{\left[U_R + U_N\left(\frac{2H_G}{D}\right) + U_S\left(\frac{2H_G}{D}\right) + h_L\right]} \qquad \text{(C-57)}$$

$$\Delta T_G = \frac{\Delta T_A C\left[U_R + U_N\left(\frac{2H_G}{D}\right) + U_S\left(\frac{2H_G}{D}\right)\right] + B_{SN}}{\left[U_R + U_N\left(\frac{2H_G}{D}\right) + U_S\left(\frac{2H_G}{D}\right) + h_L\right]} \qquad \text{(C-58)}$$

$$B_{SN} = \Bigg[\left(\frac{U_R}{h_{RO}}\right) \alpha_R \left(I_B \cos\theta + I_D\right) +$$

$$\left(\frac{U_N}{h_{NO}}\right)\left(\frac{2H_G}{D}\right) \alpha_N \left[\frac{1}{2} I_D + \frac{1}{2} r_{GD} \left(I_B \cos\theta + I_D\right)\right] +$$

$$\left(\frac{U_S}{h_{SO}}\right)\left(\frac{2H_G}{D}\right) \alpha_S \left[\frac{2}{\pi} I_B \sin\theta + \frac{1}{2} I_D + \frac{1}{2} r_{GD} \left(I_B \cos\theta + I_D\right)\right]\Bigg]_{SN} \qquad \text{(C-59)}$$

The SN at the end of Eq (C-59) indicates that the terms I_B, I_D and θ are evaluated at Solar Noon.

C4.9 Vapor Space Temperature Factor

The vapor space temperature factor, K_T, is defined as the ratio of ΔT_G to ΔT_A, as follows:

$$K_T = \left(\frac{\Delta T_G}{\Delta T_A}\right) \tag{C-60}$$

Using Eq (C-58), K_T becomes:

$$K_T = \frac{C\left[U_R + U_N\left(\frac{2H_G}{D}\right) + U_S\left(\frac{2H_G}{D}\right)\right] + \frac{B_{SN}}{\Delta T_A}}{\left[U_R + U_N\left(\frac{2H_G}{D}\right) + U_S\left(\frac{2H_G}{D}\right) + h_L\right]} \tag{C-61}$$

where B_{SN} is determined from Eq (C-59).

C5.0 TWO COLOR TANK

If the tank roof is painted a different color than the tank shell, then the solar absorptance of the roof is α_R and the solar absorptance of the shell is α_S, where:

$$\alpha_N = \alpha_S \tag{C-62}$$

To simplify Eqs (C-57), (C-59) and (C-61), we will assume that:

$$h_O \equiv h_{RO} = h_{NO} = h_{SO} \tag{C-63}$$

$$h_I \equiv h_{RI} = h_{NI} = h_{SI} = h_L \tag{C-64}$$

$$U \equiv U_R = U_N = U_S \tag{C-65}$$

Using these simplifications, Eqs (C-57) and (C-61) reduce to:

$$K_T = \frac{C\left[1 + 4\left(\frac{H_G}{D}\right)\right] + K_{SN}}{\left[2 + 4\left(\frac{H_G}{D}\right) + \frac{h_I}{h_O}\right]} \tag{C-66}$$

$$T_{G,AV} = \frac{T_{A,AV}\left[1 + 4\left(\frac{H_G}{D}\right)\right] + T_L\left(1 + \frac{h_I}{h_O}\right) + \frac{1}{2}K_{SN}\,\Delta T_A}{\left[2 + 4\left(\frac{H_G}{D}\right) + \frac{h_I}{h_O}\right]} \tag{C-67}$$

where:

$$K_{SN} \equiv \frac{B_{SN}}{U\,\Delta T_A} \tag{C-68}$$

$$K_{SN} = \left(\frac{\alpha_S}{h_0 \Delta T_A}\right) \left\{ \left[\left(\frac{\alpha_R}{\alpha_S}\right) + 2r_{GD}\left(\frac{H_G}{D}\right) \right] (I_B \cos\theta + I_D) + 2\left(\frac{H_G}{D}\right) \left(\frac{2}{\pi} I_B \sin\theta + I_D\right) \right\}_{SN} \quad \text{(C-69)}$$

It is convenient to rewrite Eq (C-69) in terms of I_H and I_D instead of I_B and I_D. Note the following relation, Eq (C-70), between I_H, I_B and I_D, and the relation, Eq (C-72), between I_H and H_H.

$$I_H = I_B \cos\theta + I_D \quad \text{(C-70)}$$

$$r_H = \frac{I_H}{H_H} \quad \text{(C-71)}$$

$$I_H = r_H H_H \quad \text{(C-72)}$$

Using Eqs (C-70) and (C-72), Eq (C-69) may be rewritten as follows:

$$K_{SN} = \left(\frac{\alpha_S r_H H_H}{h_0 \Delta T_A}\right) \left\{ \left[\left(\frac{\alpha_R}{\alpha_S}\right) + 2r_{GD}\left(\frac{H_G}{D}\right) \right] + 2\left(\frac{H_G}{D}\right) \left[\left(\frac{2}{\pi}\right) \left(1 - \frac{I_D}{I_H}\right) \tan\theta + \frac{I_D}{I_H} \right] \right\}_{SN} \quad \text{(C-73)}$$

It is convenient to define the dimensionless parameters E, F, G and J as described by Eqs (C-77), (C-78), (C-79) and (C-80), respectively. Using these defined parameters, Eqs (C-66), (C-67) and (C-73) may be rewritten as follows for the case of a two color fixed-roof tank.

Two Color Fixed-Roof Tank

$$K_T = \frac{C(1 + 4E) + K_{SN}}{(2 + 4E + G)} \qquad \text{(C-74)}$$

$$T_{G,AV} = \frac{T_{A,AV}(1 + 4E) + T_L(1 + G) + \frac{1}{2}K_{SN}\,\Delta T_A}{(2 + 4E + G)} \qquad \text{(C-75)}$$

$$K_{SN} = F\left\{(J + 2r_{GD}E) + 2E\left[\left(\frac{2}{\pi}\right)\left(1 - \frac{I_D}{I_H}\right)\text{Tan}\,\theta + \frac{I_D}{I_H}\right]\right\}_{SN} \qquad \text{(C-76)}$$

where:

$$E = \left(\frac{H_G}{D}\right) \qquad \text{(C-77)}$$

$$F = \left(\frac{\alpha_S r_H H_H}{h_O \Delta T_A}\right) \qquad \text{(C-78)}$$

$$G = \left(\frac{h_I}{h_O}\right) \qquad \text{(C-79)}$$

$$J = \left(\frac{\alpha_R}{\alpha_S}\right) \qquad \text{(C-80)}$$

C6.0 TYPICAL SOLAR INSOLATION PARAMETERS

The expression for K_{SN}, Eq (C-76), may be simplified for the case of the typical solar insolation parameters used to generate the API Computer Data Base [39]. These typical solar insolation parameters are developed in Section D of this Documentation File and are based on the following assumed conditions:

- Ground reflectivity, r_{GD}, of 0.1,
- Tank site latitude is 35 deg. north,
- Tank site elevation is 2000 ft. above sea level, and
- The year day number is 105 (April 15).

For the entire API Computer Data Base, parameters τ_D, τ_B, r_H and θ are the following constant parameters (see Table D2):

$$\tau_D = 0.0767938 \quad \text{(C-81)}$$

$$\tau_B = 0.660790 \quad \text{(C-82)}$$

$$r_H = 0.133277 \quad \text{(C-83)}$$

$$\theta = 25.5848 \text{ deg.} \quad \text{(C-84)}$$

The ratio I_D/I_H can be expressed in terms of τ_D and τ_B as follows:

$$\frac{I_D}{I_H} = \left(\frac{\tau_D}{\tau_B + \tau_D}\right) \quad \text{(C-85)}$$

Using the values of τ_D and τ_B listed by Eqs (C-81) and (C-82), we can calculate the ratio I_D/I_H from Eq (C-85) as follows:

$$\frac{I_D}{I_H} = \left(\frac{0.0767938}{0.660790 + 0.0767938}\right)$$

$$= 0.104115 \quad \text{(C-86)}$$

Substituting the above values for I_D/I_H, r_{GD}, r_H and θ into Eqs (C-76) and (C-78), we obtain:

$$K_{SN} = F\,(J + 0.954378\,E) \qquad \text{(C-87)}$$

$$F = \left[\frac{0.133277\,\alpha_S\,H_H}{h_O\,\Delta T_A}\right] \qquad \text{(C-88)}$$

Eqs (C-52) and (C-87) may be substituted into Eqs (C-74) and (C-75) to yield the following result of K_T and $T_{G,AV}$ for the case of a two color fixed-roof tank with typical solar insolation parameters:

Two Color Fixed-Roof Tank With
<u>Typical Solar Insolation Parameters:</u>

$$K_T = \frac{0.933(1 + 4E) + F\,(J + 0.954E)}{(2 + 4E + G)} \qquad \text{(C-89)}$$

$$T_{G,AV} = \frac{T_{A,AV}\,(1 + 4E) + T_L\,(1 + G) + \frac{1}{2}\Delta T_A F\,(J + 0.954E)}{(2 + 4E + G)} \qquad \text{(C-90)}$$

where:

$$E = \left[\frac{H_G}{D}\right] \qquad \text{(C-91)}$$

$$F = \left[\frac{0.133\,\alpha_S\,H_H}{h_O\,\Delta T_A}\right] \qquad \text{(C-92)}$$

$$G = \left[\frac{h_I}{h_O}\right] \qquad \text{(C-93)}$$

$$J = \left[\frac{\alpha_R}{\alpha_S}\right] \qquad \text{(C-94)}$$

C7.0 ONE COLOR TANK

If the roof and shell of the fixed-roof tank are painted the same color, the solar absorptance of the roof and shell paint can be represented by the same value, α:

$$\alpha \equiv \alpha_S = \alpha_R \tag{C-95}$$

Substituting these values into Eq (C-94), we see that:

$$J = 1 \tag{C-96}$$

Eqs (C-95) and (C-96) may be substituted into Eqs (C-89) and (C-90) to give the following result of K_T and $T_{G,AV}$ for the case of a one color fixed-roof tank with typcial solar insolation parameters:

One Color Fixed-Roof Tank With
<u>Typical Solar Insolation Parameters:</u>

$$K_T = \frac{0.933(1 + 4E) + F(1 + 0.954E)}{(2 + 4E + G)} \tag{C-97}$$

$$T_{G,AV} = \frac{T_{A,AV}\ (1 + 4E) + T_L\ (1 + G) + \frac{1}{2}\Delta T_A F\ (1 + 0.954E)}{(2 + 4E + G)} \tag{C-98}$$

where:

$$E = \left(\frac{H_G}{D}\right) \tag{C-99}$$

$$F = \left(\frac{0.133\ \alpha\ H_H}{h_O\ \Delta T_A}\right) \tag{C-100}$$

$$G = \left(\frac{h_I}{h_O}\right) \tag{C-101}$$

Thus, the vapor space temperature factor, K_T, depends only on the three dimensionless parameters, E, F and G.

Figures C3 through C6 illustrate the dependency of K_T on E, F and G.

C8.0 TYPICAL HEAT TRANSFER COEFFICIENTS AND TYPICAL VAPOR SPACE ASPECT RATIO

Figures C7 and C8 show the effect of heat transfer coefficient ratio, G, on the average percent difference of estimated emissions compared to the API Computer Data Base [39] and the API Test Data [33]. These figures show that the following average value may be selected for G:

$$G = 0.45 \qquad \text{(C-102)}$$

This value of G corresponds to the following average values for the inside and outside heat transfer coefficients, h_I and h_O, respectively:

$$h_I = 0.65 \text{ B/hr ft}^2 \, {}^oF \qquad \text{(C-103)}$$

$$h_O = 1.45 \text{ B/hr ft}^2 \, {}^oF \qquad \text{(C-104)}$$

Figure C5, which is for a value of G = 0.50, shows that K_T depends little on the value of the vapor space aspect ratio, E, as the insolation factor, F, varies from 1 to 10. An average value of E may be selected as follows:

$$E = 1.0 \qquad \text{(C-105)}$$

Substituting the typical values of G, h_I, h_O, and E listed in Eqs (C-102) through (C-105) into Eqs (C-89) through (C-94) for a two color fixed-roof tank, we obtain the following results for K_T, ΔT_V and $T_{G,AV}$:

Two Color Fixed-Roof Tank With
Typical Solar Insolation Parameters,
Typical Heat Transfer Coefficients, and
Typical Vapor Space Aspect Ratio:

$$K_T = 0.723 + 0.0279\left(\frac{\alpha H_H}{\Delta T_A}\right) \quad \text{(C-106)}$$

$$\Delta T_V = 0.723\Delta T_A + 0.0279\alpha H_H \quad \text{(C-107)}$$

$$T_{G,AV} = 0.775T_{A,AV} + 0.225T_L + 0.0140\alpha H_H \quad \text{(C-108)}$$

where:

$$\alpha = \frac{\alpha_S + \alpha_R}{2} \quad \text{(C-109)}$$

Substituting the typical values of G, h_I, h_O and E listed in Eqs (C-102) through (C-105) into Eqs (C-97) through (C-101) for a one color fixed-roof tank, we obtain the following results for K_T, ΔT_V and $T_{G,AV}$:

One Color Fixed-Roof Tank With
Typical Solar Insolation Parameters,
Typical Heat Transfer Coefficients, and
Typical Vapor Space Aspect Ratio:

$$K_T = 0.723 + 0.0279\left(\frac{\alpha H_H}{\Delta T_A}\right) \quad \text{(C-110)}$$

$$\Delta T_V = 0.723\ \Delta T_A + 0.0279\ \alpha H_H \quad \text{(C-111)}$$

$$T_{G,AV} = 0.775T_{A,AV} + 0.225T_L + 0.0140\alpha H_H \quad \text{(C-112)}$$

C9.0 TYPICAL METEOROLOGICAL PARAMETERS AND TYPICAL PAINT SOLAR ABSORPTANCE

Figure C9 is a plot of the ambient temperature range, ΔT_A, as a function of the daily total solar insolation on a horizontal surface, H_H, for the selected U.S. locations listed in Table C1 [the meteorological data are from Table 6 in Ref. A7]. Figure C10 is a plot of the ratio $(H_H/\Delta T_A)$ as a function of ΔT_A for the same locations presented in Figure C9. For these locations, the average annual value of $(H_H/\Delta T_A)$ is:

$$\frac{H_H}{\Delta T_A} = 66.0 \text{ B/ft}^2 \text{ day } ^oF \qquad \text{(C-113)}$$

If specific information is not available on the tank paint color and paint condition, a white shell and white roof, with the paint in good condition, may be assumed. For this assumed condition, the following value of paint solar absorptance may be used:

$$\alpha = 0.17 \qquad \text{(C-114)}$$

Substituting the typical values for $(H_H/\Delta T_A)$ and α from Eqs (C-113) and (C-114) into Eqs (C-110) through (C-112), we obtain the following typical result for K_T, ΔT_V and $T_{G,AV}$.

One Color Fixed-Roof Tank With
Typical Solar Insolation Parameters,
Typical Heat Transfer Coefficients,
Typical Vapor Space Aspect Ratio,
Typical Meteorological Conditions, and
Typical Paint Solar Absorptance:

$$K_T = 1.04 \qquad \text{(C-115)}$$

$$\Delta T_V = 1.04\ \Delta T_A \qquad \text{(C-116)}$$

$$T_{G,AV} = 0.775T_{A,AV} + 0.225T_L + 0.157\Delta T_A \qquad \text{(C-117)}$$

C10.0 CONCLUSION

In summary, Equations (C-61), (C-74), (C-89), (C-97), (C-106), (C-110) or (C-115) may be used to estimate K_T, depending upon the level of detail in the information available for a specific tank. As less information is available, the equation used for the calculation of K_T becomes simpler, but the calculated value of K_T will be less accurate for the specific tank.

Equation (C-107) was selected for use in calculating the daily vapor temperature range, ΔT_V, in API Publication 2518, Second Edition [A7]. This equation is based on a comprehensive analytical heat transfer model of the tank vapor space during a daily heating cycle. Equation (C-107) was developed from a more complete expression, Eq (C-58), by incorporating several simplifications that make the calculations more user friendly, with little loss in accuracy.

Table C1 - Annual Average Meteorological Data for Selected U.S. Locations [22,35]

Location	$T_{A,MX}$ (°F)	$T_{A,MN}$ (°F)	H_H (B/day ft²)	$T_{A,AV}$ (°F)	ΔT_A (°F)	$\left(\frac{H_H}{\Delta T_A}\right)$ (B/day ft² °F)
Birmingham, AL	73.20	51.10	1345	62.15	22.10	60.860
Montgomery, AL	75.90	53.90	1388	64.90	22.00	63.091
Homer, AK	43.20	29.50	838	36.35	13.70	61.168
Phoenix, AZ	85.10	57.30	1869	71.20	27.80	67.230
Tucson, AZ	81.70	54.20	1872	67.95	27.50	68.073
Fort Smith, AZ	72.50	49.00	1404	60.75	23.50	59.745
Little Rock, AR	72.90	50.80	1404	61.85	22.10	63.529
Bakersfield, CA	77.70	53.30	1749	65.50	24.40	71.680
Long Beach, CA	74.20	53.50	1598	63.85	20.70	77.198
Los Angeles, CA	70.10	55.00	1594	62.55	15.10	105.563
Sacramento, CA	73.40	47.80	1643	60.60	25.60	64.180
San Francisco, CA	64.90	48.30	1553	56.60	16.60	93.554
Santa Maria, CA	68.30	45.30	1608	56.80	23.00	69.913
Denver, CO	64.30	36.20	1568	50.25	28.10	55.801
Grand Junction, CO	65.70	39.60	1659	52.65	26.10	63.563
Wilmington, DE	63.50	44.50	1208	54.00	19.00	63.579
Atlanta, GA	71.30	51.10	1345	61.20	20.20	66.584
Savannah, GA	76.70	55.10	1365	65.90	21.60	63.194
Honolulu, HI	84.20	69.70	1639	76.95	14.50	113.034
Chicago, IL	58.70	39.70	1215	49.20	19.00	63.947
Springfield, IL	62.60	42.50	1302	52.55	20.10	64.776
Indianapolis, IN	62.00	42.20	1302	52.10	19.80	65.758
Wichita, KS	67.60	45.10	1502	56.35	22.50	66.756
Louisville, KY	66.10	46.20	1216	56.15	19.90	61.106
Baton Rouge, LA	78.00	57.00	1379	67.50	21.00	65.667
Lake Charleston, LA	77.60	58.30	1365	67.95	19.30	70.725
New Orleans, LA	77.70	58.70	1437	68.20	19.00	75.632
Detroit, MI	58.20	38.90	1120	48.55	19.30	58.031
Grand Rapids, MI	57.20	37.70	1135	47.45	19.50	58.205
Minneapolis, MN	54.20	35.20	1170	44.70	19.00	61.579

Table C1 - Annual Average Meteorological Data for Selected U.S. Locations [22,35] (Continued)

Location	$T_{A,MX}$ (°F)	$T_{A,MN}$ (°F)	H_H (B/day ft²)	$T_{A,AV}$ (°F)	ΔT_A (°F)	$\left(\frac{H_H}{\Delta T_A}\right)$ (B/day ft² °F)
Jackson, MS	76.30	52.90	1409	64.60	23.40	60.214
Billingsw, MT	57.90	35.40	1325	46.65	22.50	58.889
Las Vegas, NV	79.60	52.80	1864	66.20	26.80	69.552
Newark, NJ	62.50	45.90	1165	54.20	16.60	70.181
Roswell, NM	75.30	47.50	1810	61.40	27.80	65.108
Buffalo, NY	55.80	39.30	1034	47.55	16.50	62.667
New York, NY	61.00	47.50	1171	54.25	13.50	86.741
Cleveland, OH	58.50	40.70	1091	49.60	17.80	61.292
Columbus, OH	61.50	41.80	1123	51.65	19.70	57.005
Toledo, OH	58.80	38.30	1133	48.55	20.50	55.268
Oklahoma City, OK	71.20	48.60	1461	59.90	22.60	64.646
Tulsa, OK	71.30	49.20	1373	60.25	22.10	62.127
Astoria, OR	58.10	43.10	1000	50.60	15.00	66.667
Portland, OR	62.00	44.00	1067	53.00	18.00	59.278
Philadelphia, PA	63.40	45.10	1169	54.25	18.30	63.880
Pittsburg, PA	59.50	40.70	1069	50.30	19.20	55.677
Providence, RI	59.30	41.20	1112	50.25	18.10	61.436
Columbia, SC	75.30	51.20	1380	63.25	24.10	57.261
Sioux Falls, SD	56.70	33.90	1290	45.30	22.80	56.579
Memphis, TN	71.60	51.90	1366	61.75	19.70	69.340
Corpus Ch., TX	81.60	62.50	1521	72.05	19.10	79.634
Houston, TX	79.10	57.40	1351	68.25	21.70	62.258
Midland-Od., TX	77.00	49.90	1802	63.45	27.10	66.494
Salt Lake, UT	64.00	39.30	1603	51.65	24.70	64.899
Richmond, VA	68.80	46.50	1248	57.65	22.30	55.964
Seattle, WA	58.90	43.90	1053	51.40	15.00	70.200
Charleston, WV	65.50	44.00	1123	54.75	21.50	52.233
Hungtinton, WV	65.30	45.00	1176	55.15	20.30	57.931
Cheyenne, WY	58.30	33.10	1491	45.70	25.20	59.167

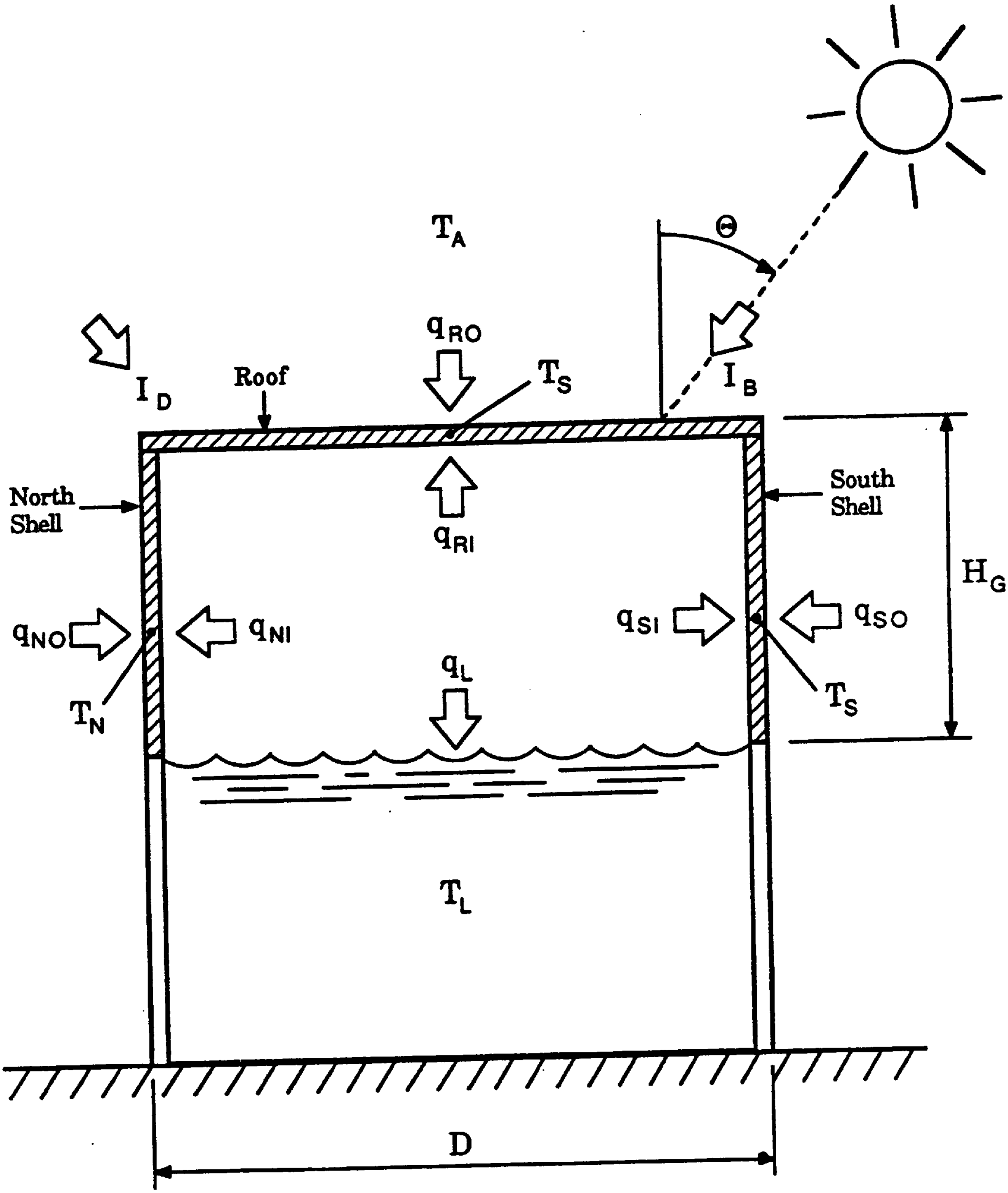

Figure C1 - Schematic of Energy Flows and Temperatures

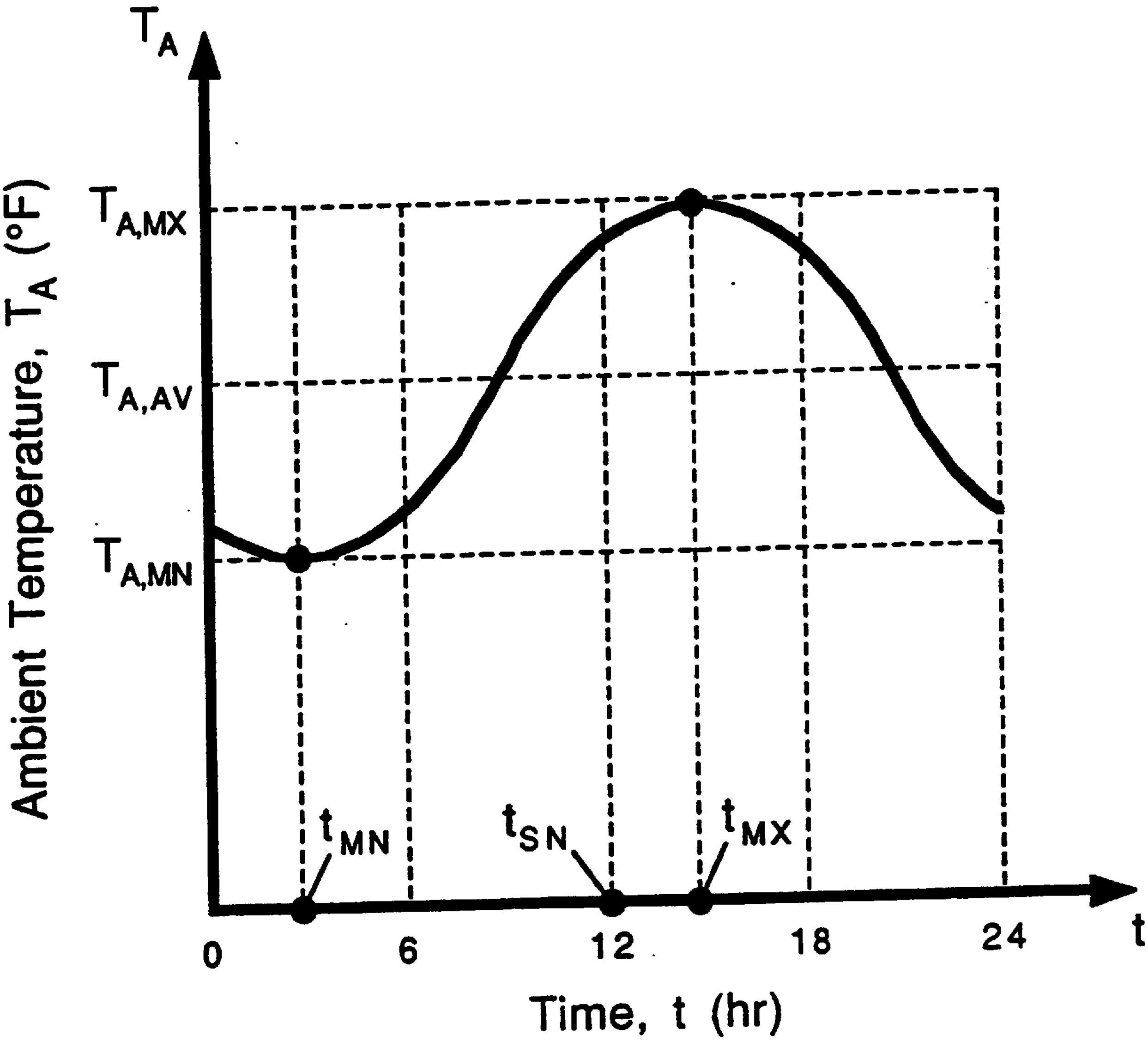

Figure C2 - Sinusoidal Daily Ambient Temperature Variation

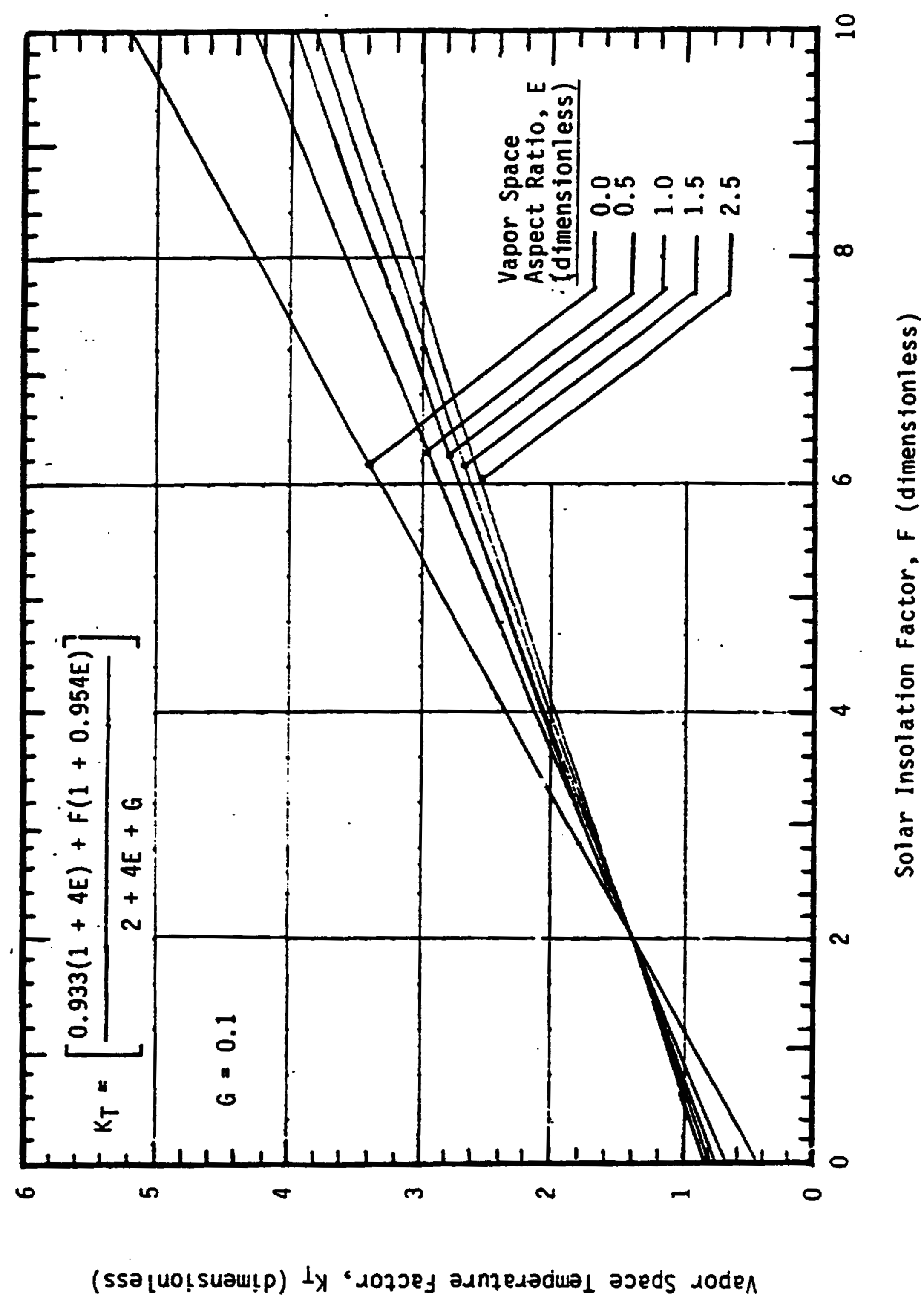

Figure C3 - Vapor Space Temperature Factor, K_T, for a Heat Transfer Coefficient Ratio, G, of 0.1

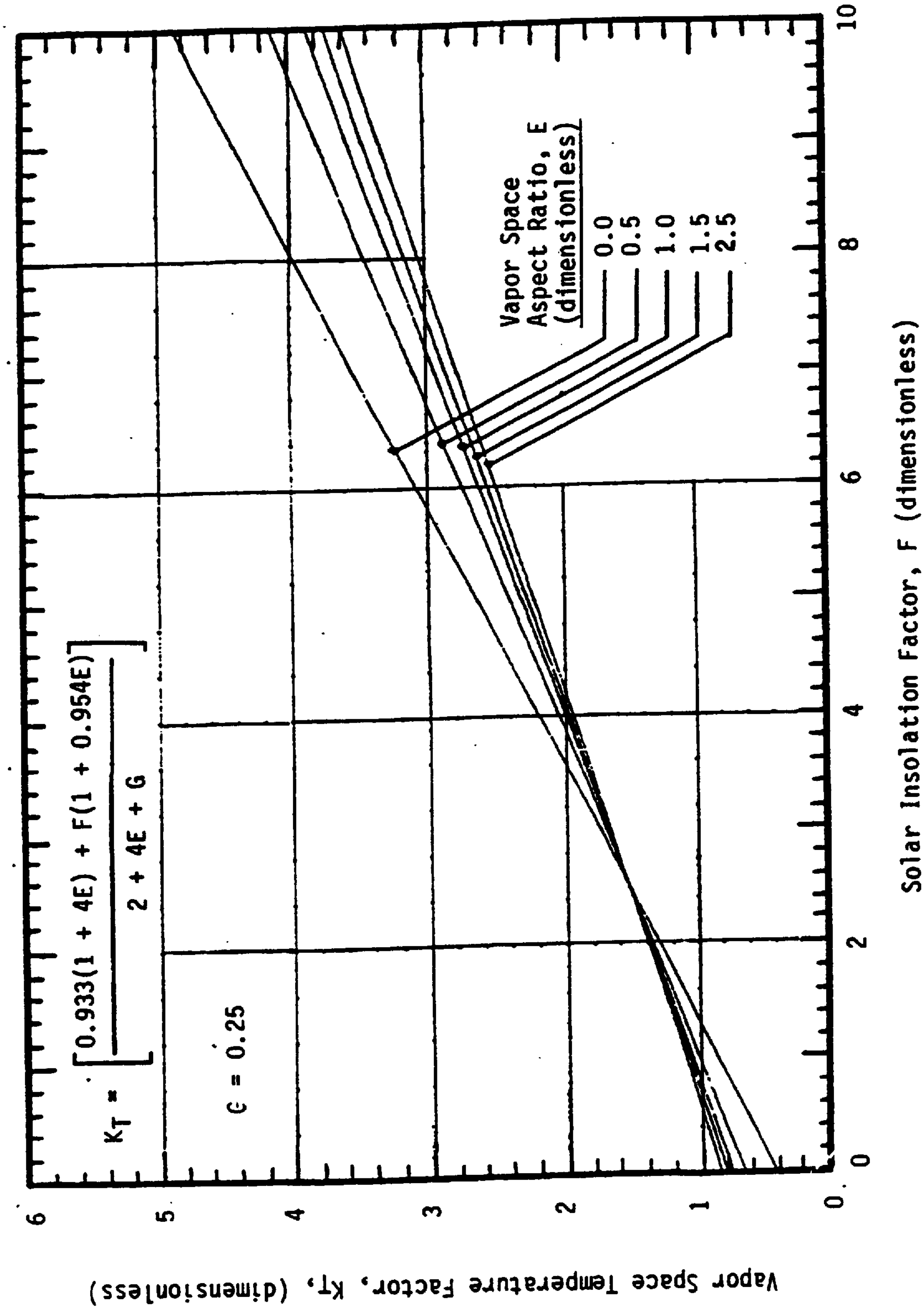

Figure C4 - Vapor Space Temperature Factor, KT,
for a Heat Transfer Coefficient Ratio, G, of 0.25

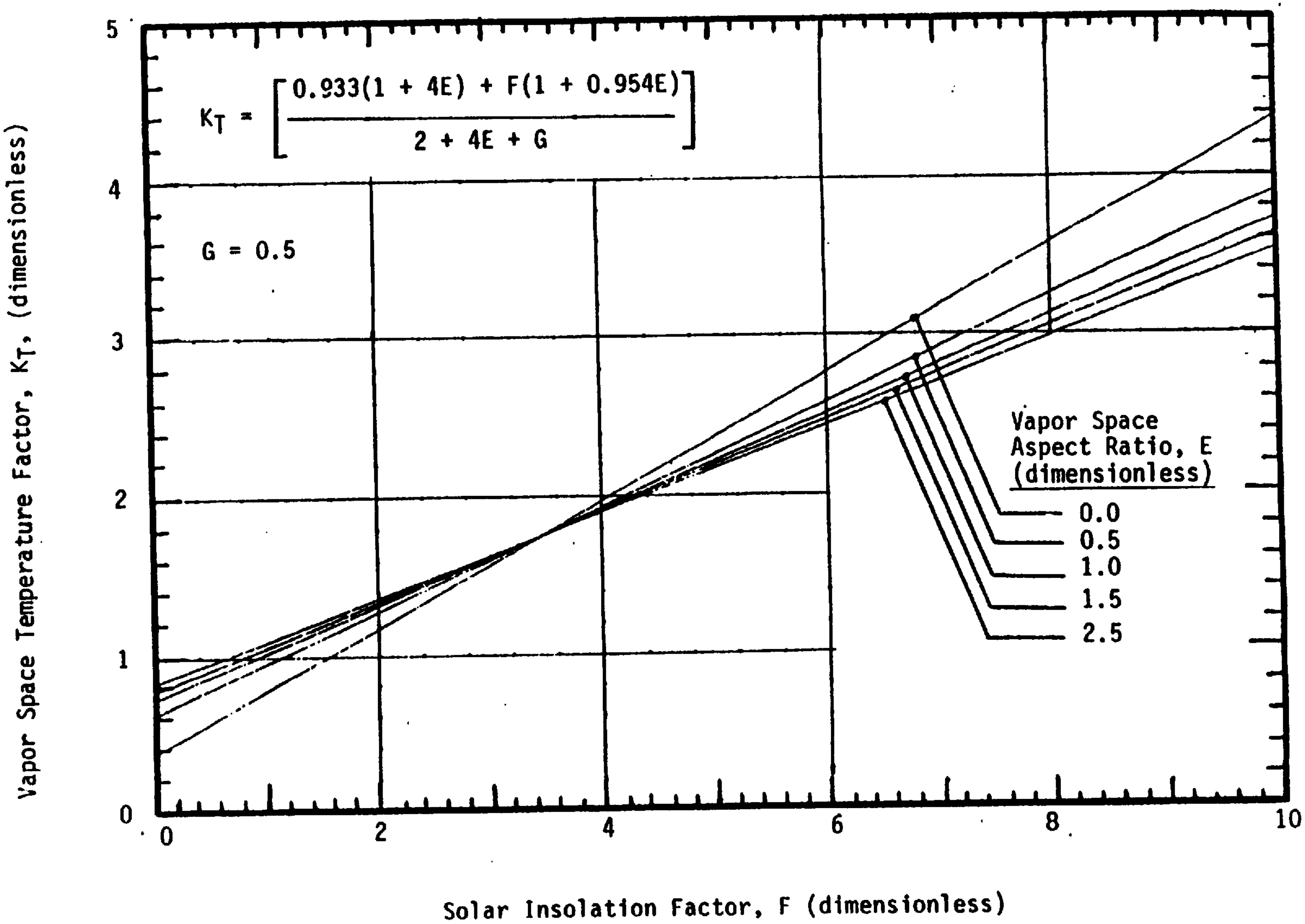

Figure C5 - Vapor Space Temperature Factor, K_T,
for a Heat Transfer Coefficient Ratio, G, of 0.5

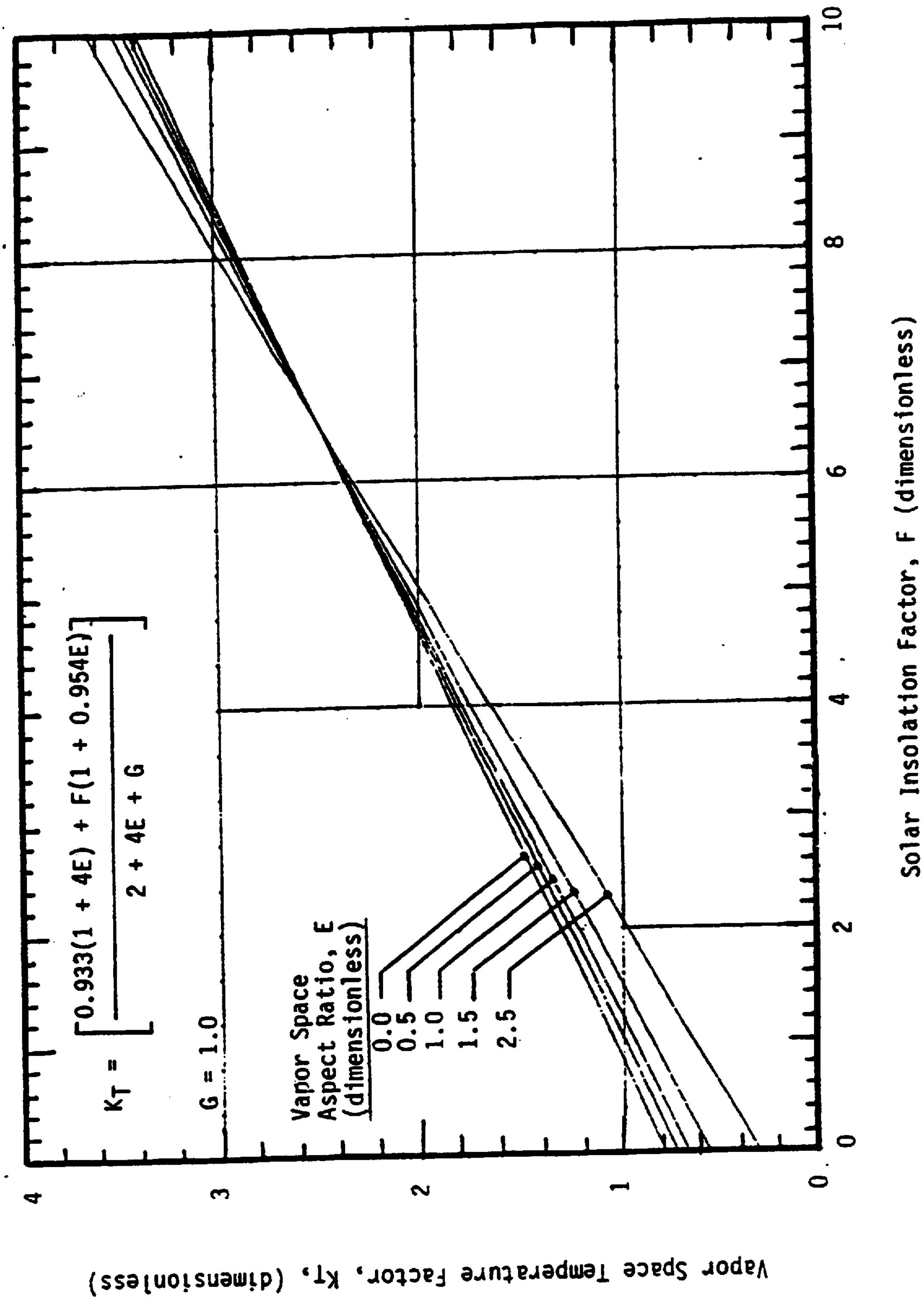

Figure C6 - Vapor Space Temperature Factor, K_T, for a Heat Transfer Coefficient Ratio, G, of 1.0

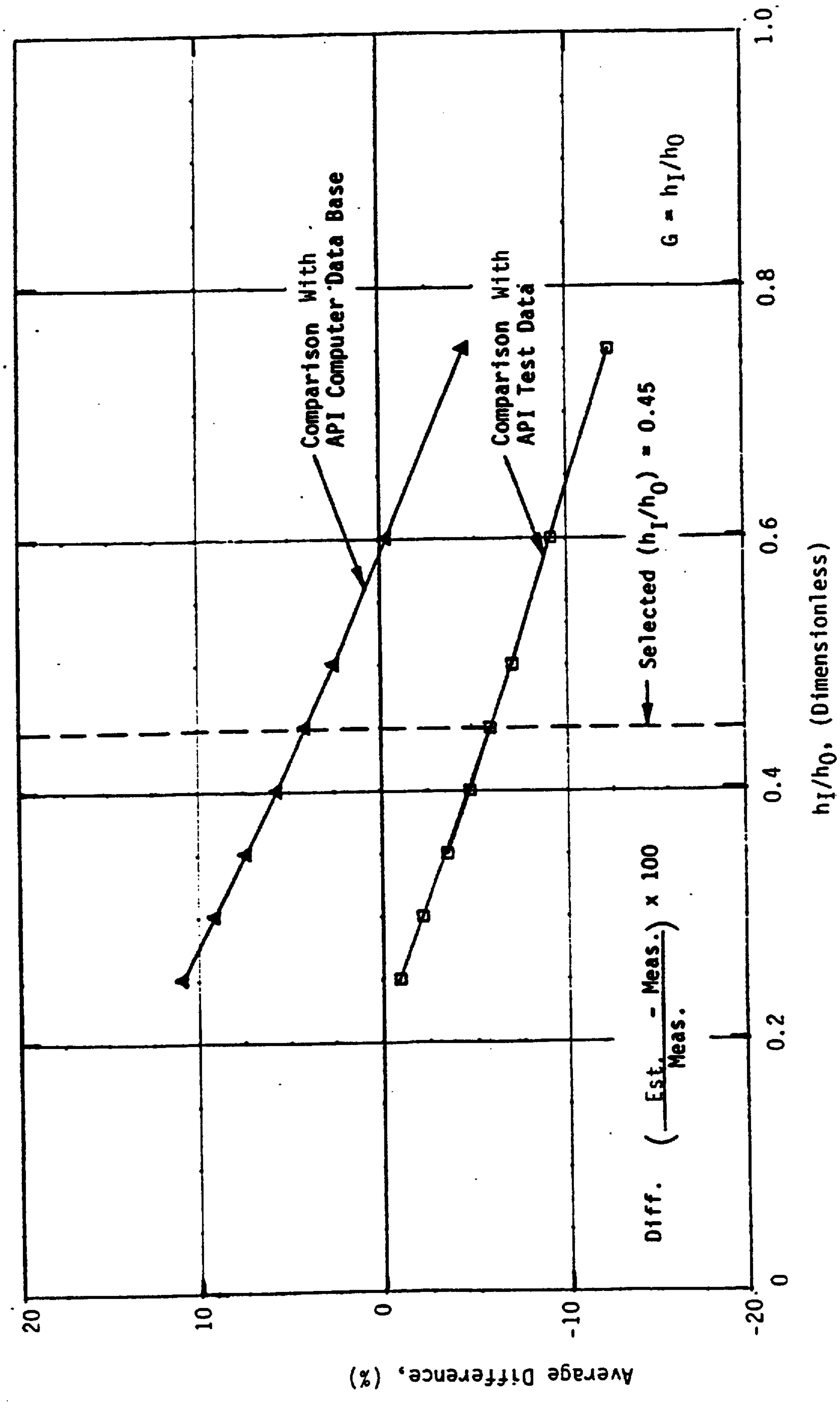

Figure C7 - Effect of Heat Transfer Coefficient Ratio, h_I/h_O, on the Average Difference of Estimated Emissions

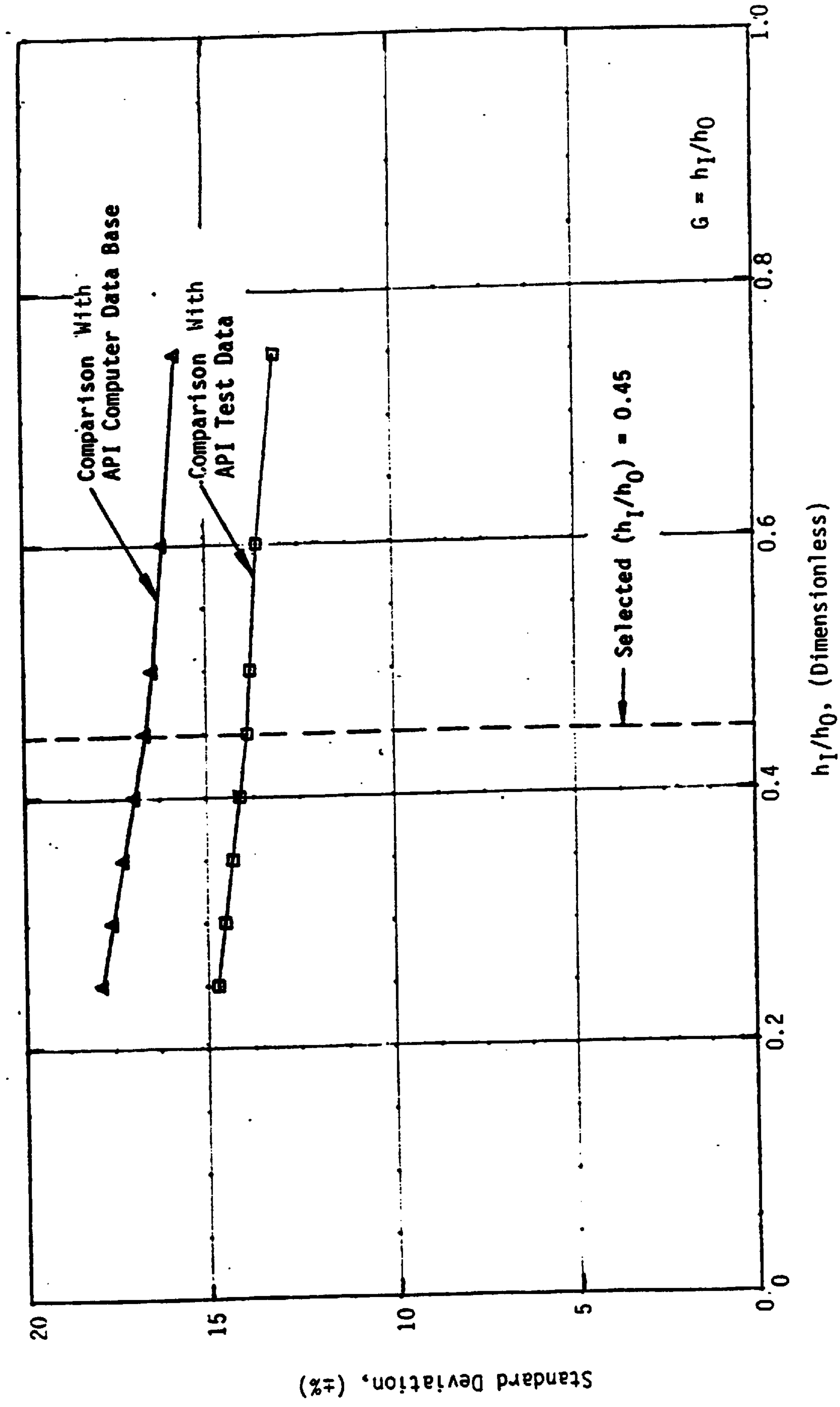

Figure C8 - Effect of Heat Transfer Coefficient Ratio, h_I/h_O, on the Standard Deviation in Average Difference of Estimated Emissions

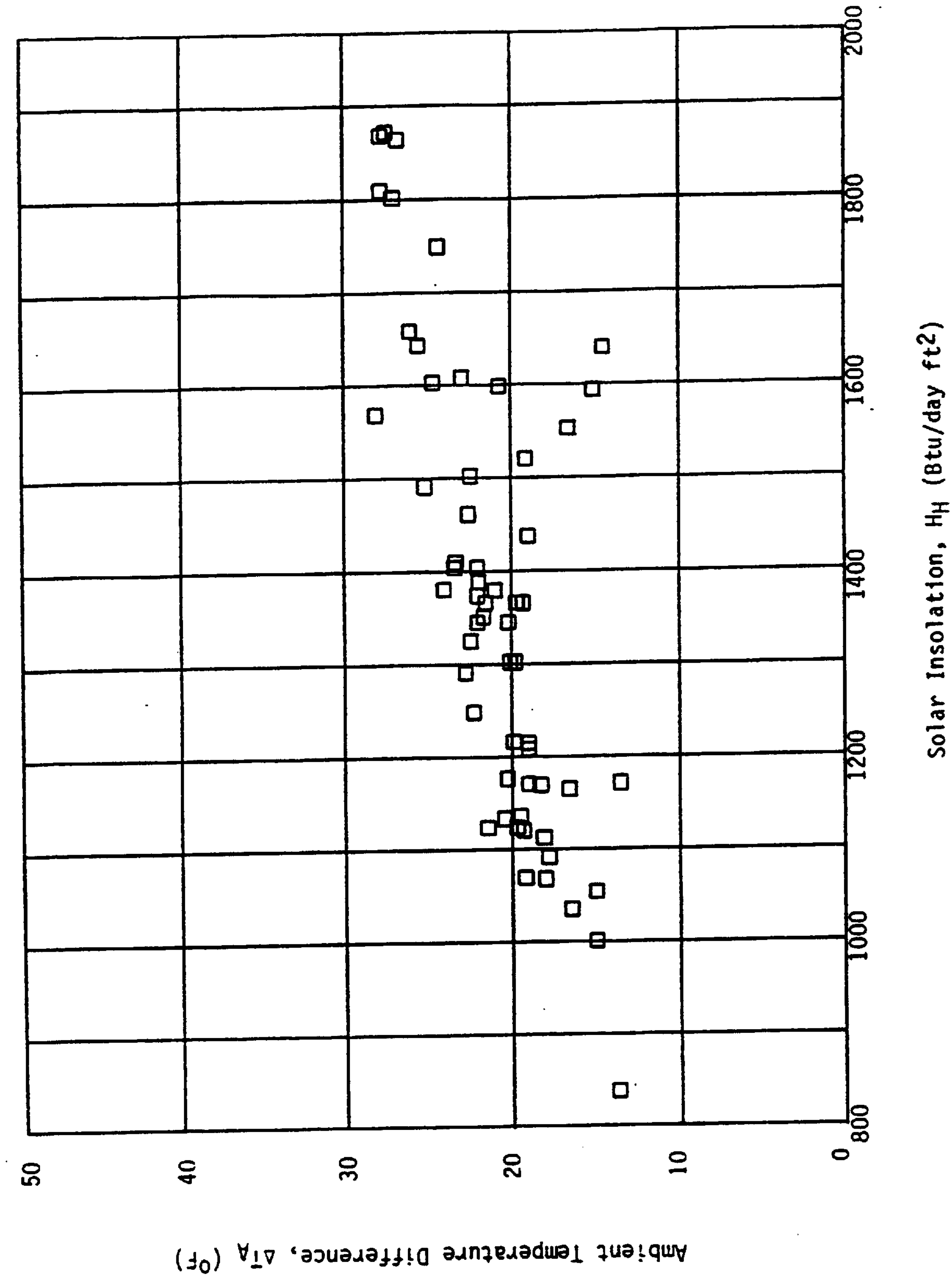

Figure C9 - ΔT_A Versus H_H for Selected U.S. Locations

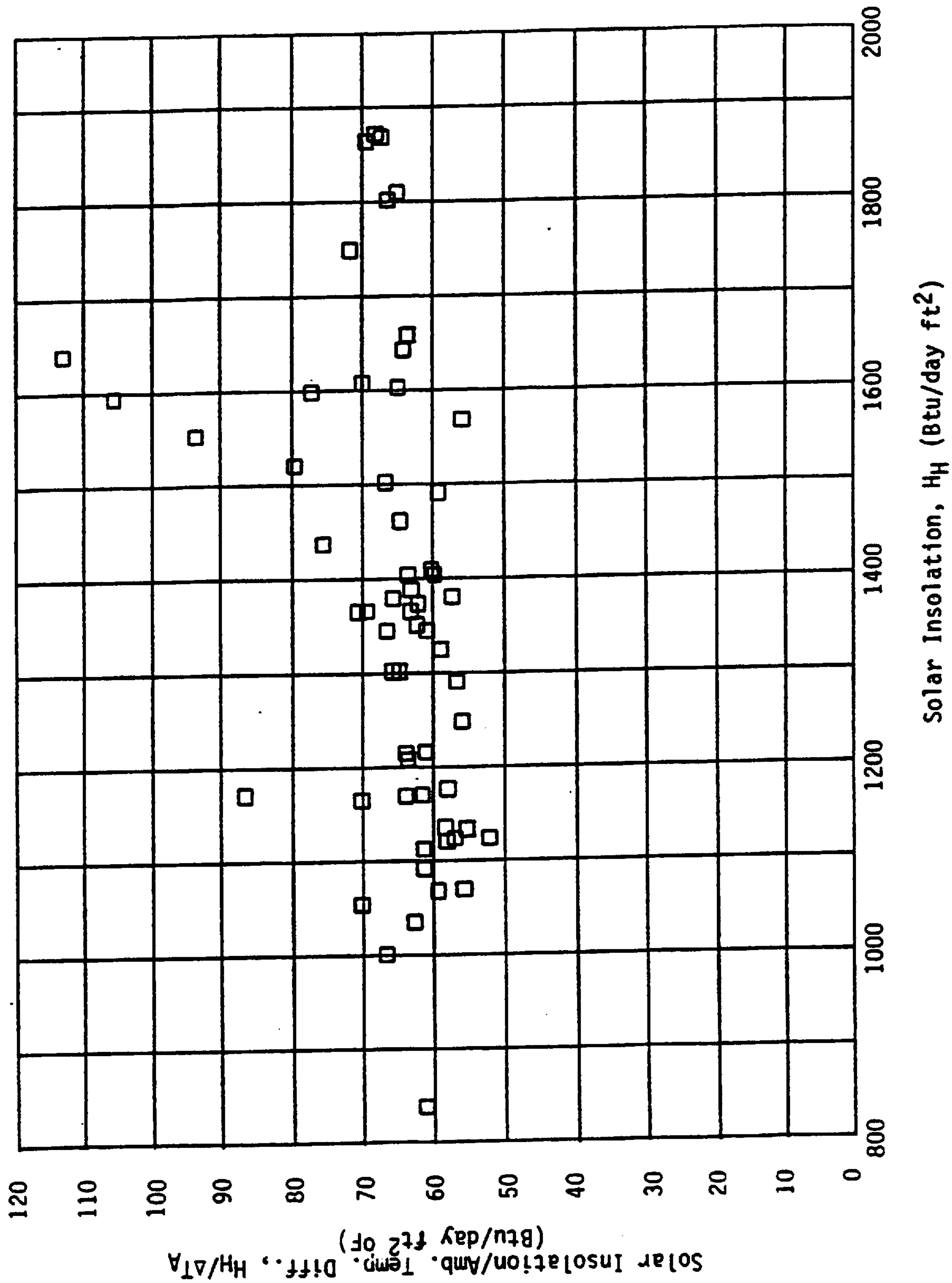

Figure C10 - $H_H/\Delta T_A$ Versus H_H for Selected U.S. Locations

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SECTION D

DEVELOPMENT OF
SOLAR INSOLATION PARAMETERS

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SECTION D

CONTENTS

TABLES

API PUBLICATION 2518
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NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
A	Altitude	ft
a	Defined by Eq (D-12)	---
a_0	Defined by Eq (D-7)	---
a_0^*	Defined by Eq (D-4)	---
a_1	Defined by Eq (D-8)	---
a_1^*	Defined by Eq (D-5)	---
b	Defined by Eq (D-13)	---
H_H	Daily total solar insolation on a horizontal surface	B/day ft^2
$I_{B,SN}$	Beam solar insolation at solar noon	B/nr ft^2
$I_{D,SN}$	Diffuse solar insolation at solar noon	B/hr ft^2
$I_{H,SN}$	Hourly total solar insolation on a horizontal surface at solar noon	B/hr ft^2
k	Defined by Eq (D-9)	---
k^*	Defined by Eq (D-6)	---
n	Year day number	---
r_0	Correction factor for climate type from Table D1	---
r_1	Correction factor for climate type from Table D1	---
r_K	Correction factor for climate type from Table D1	---
$r_{H,SN}$	Ratio of $I_{H,SN}$ to H_H	---
δ	Declination angle	deg.
θ_{SN}	Zenith angle at solar noon	deg.
$\tau_{B,SN}$	Atmospheric transmittance for beam solar insolation at solar noon	---
$\tau_{D,SN}$	Atmospheric transmittance for diffuse solar insolation at solar noon	---
ϕ	Latitude	deg.
ω	Sunset hour angle	deg.

Subscripts:

B	Beam	
D	Diffuse	
H	Horizontal	
SN	Solar Noon	

D1.0 INTRODUCTION

This section of the Documentation File to API Publication 2518, Second Edition, contains equations that may be used to determine the solar insolation parameters required to calculate the vapor space temperature factor, K_T. These equations have been selected from Duffie and Beckman [24]* and are arranged in the order required to calculate $I_{H,SN}$, $I_{D,SN}$, and $I_{B,SN}$ given n, ϕ, H_H and A.

Section D2 presents the equations to calculate each of the required solar insolation parameters.

Section D3 presents sample calculations illustrating the use of the equations for a sample problem. Table D2 summarizes the results of the sample problem. These results are also used in Section C6 of this Documentation File to develop an equation for the vapor space temperature factor, K_T.

D2.0 SOLAR INSOLATION EQUATIONS

D2.1 Declination, δ

The declination, δ, is the angular position of the sun at solar noon with respect to the plane of the equator, where a north declination is considered positive. The declination varies between -23.45^o and $+23.45^o$ and is only a function of the day of the year, n, where $1 \leq n \leq 365$.

$$\delta = 23.45 \operatorname{Sin}\left[\frac{360\ (284 + n)}{365}\right] \qquad \text{(D-1)}$$

[see Ref. 24, pg. 11, Eq (1.6.1)]

* Numbers in brackets refer to the numbered references listed at the end of this Documentation File.

D2.2 Zenith Angle at Solar Noon, θ_{SN}

The zenith angle at solar noon, θ_{SN}, is the angle at solar noon between the beam radiation and the normal to a horizontal surface. At solar noon, the zenith angle is a function of only the declination, δ, and latitude, ϕ.

$$\text{Cos}\ \theta_{SN} = \text{Cos}\ \delta\ \text{Cos}\ \phi + \text{Sin}\ \delta\ \text{Sin}\ \phi \qquad \text{(D-2)}$$

[see Ref. 24, pg. 13, Eq (1.6.4)]

D2.3 Sunset Hour Angle, ω

The sunset hour angle, ω, is the angular displacement of the sun, west of the local meridian, at sunset due to the rotation of the earth on its axis at 15^{0} per hour.

$$\text{Cos}\ \omega = -\text{Tan}\ \phi\ \text{Tan}\ \delta \qquad \text{(D-3)}$$

[see Ref. 24, pg. 13, Eq (1.6.7)]

D2.4 Atmospheric Transmittance for Beam Solar Insolation at Solar Noon, $\tau_{B,SN}$

The atmospheric transmittance for beam solar insolation at solar noon, $\tau_{B,SN}$, may be determined from Eq (D-10). The constants a_0^*, a_1^*, and k^* must first be determined from Eqs (D-4) through (D-6) for the specified altitude, A. The constants r_0, r_1 and r_K may be selected from Table D1.

$$a_0^* = 0.4237 - 0.00821\ [6.0 - (A/3281)]^2 \qquad \text{(D-4)}$$

[see Ref. 24, pg. 62, Eq (2.8.2)]

$$a_1^* = 0.5055 + 0.00595\ [6.5 - (A/3281)]^2 \qquad \text{(D-5)}$$

[see Ref. 24, pg. 62, Eq (2.8.3)]

$$k^* = 0.2711 + 0.01858\,[2.5 - (A/3281)]^2 \qquad \text{(D-6)}$$

[see Ref. 24, pg. 62, Eq (2.8.4)]

Table D1 - Correction Factors for Climate Type*

Climate Type	r_0	r_1	r_K
Tropical	0.95	0.98	1.02
Mid-Latitude Summer	0.97	0.99	1.02
Subarctic Summer	0.99	0.99	1.01
Mid-Latitude Winter	1.03	1.01	1.00

* See Ref. 24, pg. 62, Table 2.8.1.

$$a_0 = a_0^* r_0 \qquad \text{[see Ref. 24, pg. 63]} \qquad \text{(D-7)}$$

$$a_1 = a_1^* r_1 \qquad \text{[see Ref. 24, pg. 63]} \qquad \text{(D-8)}$$

$$k = k^* r_K \qquad \text{[see Ref. 24, pg. 63]} \qquad \text{(D-9)}$$

$$\tau_{B,SN} = a_0 + a_1 \exp(-k/\cos\theta_{SN}) \qquad \text{(D-10)}$$

[see Ref. 24, pg. 62, Eq (2.8.1)]

D2.5 Atmospheric Transmittance for Diffuse Solar Insolation at Solar Noon, $\tau_{D,SN}$

The atmospheric transmittance for diffuse solar insolation, at solar noon, $\tau_{D,SN}$, may be determined by Eq (D-11).

$$\tau_{D,SN} = 0.2710 - 0.2939\tau_{D,SN} \qquad \text{(D-11)}$$

[see Ref. 24, pg. 64, Eq (2.8.7)]

D2.6 Ratio of Hourly to Daily Total Solar Insolation on a Horizontal Surface at Solar Noon, $r_{H,SN}$

The ratio $r_{H,SN}$ is the ratio of the hourly total solar insolation on a horizontal surface at solar noon, $I_{H,SN}$, to the daily total solar insolation on a horizontal surface, H_H. This ratio may be calculated from Eq (D-14), where the coefficients a and b are first determined from Eqs (D-12) and (D-13), respectively.

$$a = 0.4090 + 0.5016 \text{ Sin } (\omega - 60) \qquad \text{(D-12)}$$

[see Ref. 24, pg. 79, Eq (2.13.2a)]

$$b = 0.6609 - 0.4767 \text{ Sin } (\omega - 60) \qquad \text{(D-13)}$$

[see Ref. 24, pg. 79, Eq (2.13.2b)]

$$r_{H,SN} = \left(\frac{\pi}{24}\right) \left[\frac{(a + b)(1 - \text{Cos } \omega)}{\text{Sin } \omega - (2\pi\omega/360) \text{ Cos } \omega}\right] \qquad \text{(D-14)}$$

[see Ref. 24, pg. 79, Eq (2.13.1)]

D2.7 Hourly Total Solar Insolation on a Horizontal Surface at Solar Noon, $I_{H,SN}$

The hourly total solar insolation on a horizontal surface at solar noon, $I_{H,SN}$, may be determined from the ratio $r_{H,SN}$ and the daily total solar insolation on a horizontal surface, H_H, using Eq (D-15).

$$I_{H,SN} = r_{H,SN} H_H \qquad \text{(D-15)}$$

D2.8 Diffuse Solar Insolation at Solar Noon, $I_{D,SN}$

The diffuse solar insolation at solar noon, $I_{D,SN}$, may be determined from $I_{H,SN}$, $\tau_{B,SN}$ and $\tau_{D,SN}$ using Eq (D-16).

$$I_{D,SN} = I_{H,SN} \left[\frac{\tau_{D,SN}}{\tau_{B,SN} + \tau_{D,SN}} \right] \quad \text{(D-16)}$$

D2.9 Beam Solar Insolation at Solar Noon, $I_{B,SN}$

The beam solar insolation at solar noon, $I_{B,SN}$, may be determined from $I_{H,SN}$, $I_{D,SN}$ and θ_{SN} using Eq (D-17).

$$I_{B,SN} = \left[\frac{I_{H,SN} - I_{D,SN}}{\cos \theta_{SN}} \right] \quad \text{(D-17)}$$

D3.0 SAMPLE CALCULATIONS

This section presents sample calculations illustrating how Eqs (D-1) through (D-17) may be used to determine the solar insolation parameters for a sample problem.

The Given Conditions chosen for this sample problem are the same as those that were used to develop the API Computer Data Base [39].

Given Conditions:

n = 105 year day number
ϕ = 35 deg. north latitude
A = 2000 ft. altitude
H_H = 1500 B/day ft^2

The Calculated Results of this sample problem are summarized in Table D2. These results are also used in Section C6 to develop an equation for the vapor space temperature factor, K_T, for the case of a "two color fixed-roof tank with typical solar insolation parameters" (see Eqs (C-84) through (C-88)).

D3.1 Calculate δ from Eq (D-1)

$$\delta = (23.45) \text{ Sin } \left[\frac{360\ (284 + 105)}{365}\right]$$

$$= 9.41490^{o}$$

D3.2 Calculate θ_{SN} from Eq (D-2)

$$\text{Cos } \theta_{SN} = \text{Cos } (9.41490) \text{ Cos } (35) + \text{Sin } (9.41490) \text{ Sin } (35)$$
$$= 0.90195$$
$$\theta_{SN} = 25.5848^{o}$$

D3.3 Calculate ω from Eq (D-3)

$$\text{Cos } \omega = -\text{ Tan } (35) \text{ Tan } (9.41490)$$
$$= -0.116106$$
$$\omega = 96.6674^{o}$$

D3.4 Calculate a_0^*, a_1^* and k^* from Eqs (D-4) through (D-6)

$$a_0^* = 0.4237 - 0.00821\ [6.0 - (2000/3281)]^2$$
$$= 0.185144$$
$$a_1^* = 0.5055 + 0.00595\ [6.5 - (2000/3281)]^2$$
$$= 0.711948$$
$$k^* = 0.2711 + 0.01858\ [2.5 - (2000/3281)]^2$$
$$= 0.337499$$

D3.5 Determine r_0, r_1 and r_K from Table D1

$r_0 = 0.97$

$r_1 = 0.99$

$r_K = 1.02$

D3.6 Calculate a_0, a_1 and k from Eqs (D-7) through (D-9)

$$a_0 = (0.185144)(0.97)$$
$$= 0.179590$$
$$a_1 = (0.711948)(0.99)$$
$$= 0.704829$$
$$k = (0.337499)(1.02)$$
$$= 0.344249$$

D3.7 Calculate $\tau_{B,SN}$ from Eq (D-10)

$$\tau_{B,SN} = 0.179590 + 0.704829 \exp (-0.344249/\text{Cos } (25.5848))$$
$$= 0.660790$$

D3.8 Calculate $\tau_{D,SN}$ from Eq (D-11)

$$\tau_{D,SN} = (0.2710) - (0.2939)(0.660790)$$
$$= 0.0767938$$

D3.9 Calculate a and b from Eqs (D-12) and (D-13)

$$a = 0.4090 + 0.5016 \text{ Sin } (96.6674 - 60)$$
$$= 0.708540$$
$$b = 0.6609 - 0.4767 \text{ Sin } (96.6674 - 60)$$
$$= 0.376230$$

D3.10 Calculate $r_{H,SN}$ from Eq (D-14)

$$r_{H,SN} = \left(\frac{\pi}{24}\right) \left\{ \frac{[(0.708540) + (0.376230)][1 - \text{Cos } (96.6674)]}{\text{Sin } (96.6674) - (2\pi)(96.6674/360) \text{ Cos } (96.6674)} \right\}$$

$$= 0.133277$$

D3.11 Calculate $I_{H,SN}$ from Eq (D-15)

$$I_{H,SN} = (0.133277)(1500)$$
$$= 199.915 \text{ B/hr ft}^2$$

D3.12 Calculate $I_{D,SN}$ from Eq (D-16)

$$I_{D,SN} = (199.915)\left[\frac{0.0767938}{0.660790 + 0.0767938}\right]$$

$$= 20.8142 \text{ B/hr ft}^2$$

D3.13 Calculate $I_{B,SN}$ from Eq (D-17)

$$I_{B,SN} = \frac{(199.915 - 20.8142)}{\text{Cos }(25.5848)}$$

$$= 198.571 \text{ B/hr ft}^2$$

D4.0 CONCLUSION

The typical solar insolation parameters developed in this Section D of the Documentation File were used in Section C6 to develop the equation for calculating the daily vapor temperature range, ΔT_V.

Table D2 - Summary of Sample Problem Results

Symbol	Description	Value	Units
	Given Information		
n	Year Day Number	105	---
ϕ	Latitude	35	deg. north
H_H	Daily Total Solar Insolation on a Horizontal Surface	1500	B/day ft^2
A	Altitude	2000	ft
	Calculated Results		
δ	Declination Angle	9.41490	deg. north
θ_{SN}	Zenith Angle at Solar Noon	25.5848	deg.
ω	Sunset Angle	96.6674	deg.
a_0^*	---	0.185144	---
a_1^*	---	0.711948	---
k^*	---	0.337499	---
r_0	---	0.97	---
r_1	---	0.99	---
r_k	---	1.02	---
[illegible]	---	0.179590	---
a_1	---	0.704829	---
k	---	0.344249	---
$\tau_{B,SN}$	Atmospheric Transmittance for Beam Solar Insolation at Solar Noon	0.660790	---
$\tau_{D,SN}$	Atmospheric Transmittance for Diffuse Solar Insolation at Solar Noon	0.0767938	---
a	---	0.708540	---
b	---	0.376230	---
$r_{H,SN}$	Ratio of $I_{H,SN}$ to H_H	0.133277	---
$I_{H,SN}$	Hourly Total Solar Insolation on a Horizontal Surface at Solar Noon	199.915	B/hr ft^2
$I_{D,SN}$	Diffuse Solar Insolation at Solar Noon	20.8142	B/hr ft^2
$I_{B,SN}$	Beam Solar Insolation at Solar Noon	198.571	B/hr ft^2

API PUBLICATION 2518
DOCUMENTATION FILE

SECTION E

DEVELOPMENT OF
PAINT SOLAR ABSORPTANCE, α

API PUBLICATION 2518
DOCUMENTATION FILE
SECTION E

CONTENTS

API PUBLICATION 2518
DOCUMENTATION FILE
SECTION E

NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
F_p	Paint factor	dimensionless
α	Solar absorptance of paint	dimensionless
α_G	Solar absorptance of paint in good condition	dimensionless
α_P	Solar absorptance of paint in poor condition	dimensionless
ρ	Solar reflectance of paint	dimensionless
τ	Solar transmittance of paint	dimensionless

E1.0 INTRODUCTION

This section of the Documentation File to API Publication 2518, Second Edition, contains a development of the solar absorptance, α, for selected paint colors, paint types and paint conditions. The values developed are based on information that was presented in Appendix IV of API Publication 2518, First Edition [A6]*.

Section E2 presents fundamental definitions and a relationship between solar absorptance and solar reflectance.

Section E3 describes the work that resulted in the paint factors, F_p, that appear in API Publication 2518, First Edition.

Section E4 describes the relationship between solar absorptance and paint factor.

Section E5 develops a relationship between the solar absorptance of paints in poor condition and good condition.

Section E6 summarizes the set of solar absorptance values that were selected for use in API Publication 2518, Second Edition.

E2.0 SOLAR ABSORPTANCE FUNDAMENTALS

Solar radiation that impinges on a surface is either: (1) absorbed by the surface; (2) reflected from the surface; or (3) transmitted through the surface. The fraction of the incident solar radiation (referred to as "insolation") that is absorbed is referred to as the absorptivity, α, of the surface; the fraction that is reflected is referred to as the reflectivity, ρ, of the surface; and the fraction that is transmitted is referred to as the transmittance, τ, of the surface, where:

* Numbers in brackets refer to the numbered references listed at the end of this Documentation File.

$$\alpha + \rho + \tau = 1 \tag{E-1}$$

For the metal surfaces of fixed-roof tanks, the transmittance is zero, or:

$$\tau = 0 \tag{E-2}$$

Eq (E-1) then reduces to:

$$\alpha + \rho = 1 \tag{E-3}$$

The following discussion focuses primarily on the values of absorptance, α, of a surface for use in calculating the thermal breathing losses of fixed-roof tanks. If the reflectance, ρ, of a surface is known, Eq (E-3) may be used to determine the corresponding absorptance, α, of the surface.

The exterior surface of fixed-roof tanks is normally coated with a paint to reduce corrosion. A wide range of paint colors have been used, sometimes with a different color on the tank roof than on the tank shell.

The absorptance of tank paint depends upon the paint color, paint type and paint condition. Newly painted tank surfaces, or painted surfaces in a good condition will have a lower absorptance than weathered painted surfaces or painted surfaces in poor condition.

E3.0 DEVELOPMENT OF PAINT FACTORS FOR API PUBLICATION 2518, FIRST EDITION

At the time that the First Edition of API Publication 2518 [A6] was published, the importance of the effect of paint absorptance on the thermal breathing loss was recognized. A paint with a low absorptivity, such as white paint, was known to affect the thermal breathing loss in two significant ways:

1. It reduces the transfer of heat to and from the tank vapor space and therefore reduces the volume of thermal breathing loss.

2. It reduces the transfer of heat to the bulk liquid and therefore reduces the thermal breathing loss by lowering the stock vapor pressure.

During the development of the First Edition to API Publication 2518, a Paint Factor Task Group was formed and was given the assignment of developing a practical correlation of the effect of paint on the thermal breathing loss from fixed-roof tanks. Through discussions and correspondence, the task group worked with paint chemists and the staff of one large paint manufacturer. In addition, pertinent literature was studied and analyzed. Evaporation loss tests, other than those used in developing the breathing loss correlation [see Eq (3) in Ref. A6], were studied and tabulated [see Table IV-2 in Ref. A6]. Tests were performed to determine the difference in liquid body temperature in large tanks painted aluminum versus those painted white. Tests were performed with both artificial light and sunlight on various painted surfaces to determine their reflectance.

In this discussion, reflectance refers to measurements made with a spectrophotometer which utilizes an integrating sphere. On this scale, 100 represents the reflectance of pure magnesium oxide (MgO) sprayed on tile until no increase in the instrument reading can be observed. This instrument measures only the visible spectrum. Although heat for evaporation is partially supplied to a tank by the nonvisible (infared) portion of the sun's rays, it was assumed that the effect of this portion is proportional to the visible (measured) portion of the sun's rays. It was not concluded, however, that this relationship will hold for all paint formulations and climatic conditions.

In developing the correlation for thermal breathing loss [Eq (3) in Ref. A6], test data from 64 painted tanks were selected for detailed analysis. The paint classification for the 64 tanks tested is as follows:

Table E1 - Paint Classification for Tanks Tested

Roof Color	Shell Color	Number of Tanks
White	White	18
Aluminum	White	2
White	Aluminum	4
Aluminum	Aluminum	4
White	Gray	12
Gray	Gray	24
Total		64

At the time that the First Edition of API Publication 2518 was published, little loss data on fixed-roof tanks with paint colors other than white, aluminum or gray was available.

Early in the study of paint reflectance, a definite relationship appeared to exist between relative loss and tank paint reflectance. It also became obvious that the broad paint classifications of white, aluminum, gray, etc. were not sufficiently definitive. Paints have a wide range of reflectance, varying from a freshly painted laboratory sample to a surface in a dirty and extremely weathered condition.

Paints of the same nominal color and in the same condition have a wide range of reflectance, depending upon formulation. One paint manufacturer reported that the reflectance of new white paint on a tank might range between 0.80 and 0.86, with a maximum of 0.88, and that the reflectance of new black paint on a tank might range between 0.04 and 0.08. New aluminum paint also has a wide range of reflectance, depending upon the grade of aluminum powder and the type of formulation. One type of aluminum paint, formulated with a specular type of pigment (polished scales), may have a reflectance that might range between 0.60 to 0.70, with an average of 0.68. Another type of aluminum paint, utilizing a diffuse type of pigment, may have a reflectance as low as 0.35. Aluminum paints of intermediate reflectance can be formulated from mixtures of these two paint types. Thus, aluminum color paints cover a wide range on the total reflectance scale.

Approximate reflectance values for various paint colors and paint conditions are presented in Table E2. These values are based on: (1) the thermal breathing loss correlation test data [see Tables II-1, II-2 and II-3 in Ref. A6]; (2) supplementary test data; (3) information supplied by paint manufacturers; and, (4) the results of field tests conducted by the task group.

For reference purposes, Table E3 lists the reflectance values of various paint colors and paint conditions reported by Nelson [3].

Table E4 summarizes the set of paint factors, Fp, that were developed by the Paint Factor Task Group for use with the thermal breathing loss correlation [Eq

(3) in Ref. A6]. These paint factors were compiled by the task group from a judicious review of all available data. These paint factors do not represent a precise evaluation of the effect of tank paints on evaporation loss from tanks. They do, however, present useful and reasonable paint factors that are based on the alignment of the relative test data and on the agreement of the test data for aluminum painted tanks and gray-painted tanks.

E4.0 RELATIONSHIP BETWEEN SOLAR ABSORPTANCE AND PAINT FACTORS

Figure E1 [from Fig. IV-3 of Ref. A6] illustrates the effect of solar reflectance, ρ, on the paint factor, Fp. This figure shows a linear relationship between ρ and Fp for values of Fp $\leq$ 1.5. Eq (E-3) expresses this linear relationship:

$$Fp = 1.74 - 0.90\,\rho \qquad \text{(E-3)}$$

Substituting Eq (E-2) into (E-3) and solving for the solar absorptance, α, we obtain:

$$\boxed{\alpha = 1.11\,Fp - 0.94} \qquad \text{(E-4)}$$

Eq (E-4) was used to convert the values of paint factor, Fp, to solar absorptance, α, in Table E4.

E5.0 EFFECT OF PAINT CONDITION ON SOLAR ABSORPTANCE

The solar absorptance values listed in Table E4 include values for paint in good condition, α_G, and values for paint in poor condition, αp.

Figure E2 is a plot of αp versus α_G for each of the paints listed in Table E4. The values plotted may be fit with a linear relationship that must go through the point where $\alpha_G = 1$ and $\alpha p = 1$. Eq (E-5) expresses this linear relationship:

$$\boxed{\alpha p = 0.2 + 0.8\,\alpha_G} \qquad \text{(E-5)}$$

E6.0 CONCLUSION

Table E5 summarizes the set of solar absorptance values that were selected for use in API Publication 2518, Second Edition. The values selected were based upon a careful evaluation of the values presented in Tables E2 and E4.

Use was made of the values in Table E4 for only the cases where the tank roof and shell are painted the same color. Also, Eq (E-5) was used to determine the poor condition values from the good condition values for gray and red color paints.

The values of Nelson [3] listed in Table E3 were not incorporated into Table E5, but are listed in this section of the Documentation File only for reference.

Table E2 - Solar Reflectance and Solar Absorptance of Tank Paints [A6]

Paint Color	Paint Shade or Type	Paint Condition	Solar Reflectance ρ (1) (dimensionless)	Solar Absorptance α (2) (dimensionless)
Magnesium Oxide (3)	----	----	1.00(1)	0.00
White	----	Good	0.83	0.17
Aluminum	Specular	Good	0.65	0.35
Aluminum	Specular	Average	0.60	0.40
Aluminum	Diffuse	Good	0.45	0.55
Aluminum	Diffuse	Average	0.40	0.60
Aluminum	Diffuse	Extremely Weathered	0.30	0.70
Red	Primer	Good	0.11	0.89
Black	----	----	0.06	0.94

Notes: (1) Values of ρ are from Table IV-1 of Ref. A6.
(2) Values of α are calculated from the relationship:
$\alpha = 1-\rho$
(3) Magnesium oxide is the reflectance standard whose value is assumed to be 1.00.

Table E3 - Solar Reflectance and Solar Absorptance of Tanks Paints [3]

Paint Color	Paint Shade or Type	Paint Condition	Solar Absorptance α (dimensionless)	Solar Reflectance ρ (dimensionless)
Aluminum	---	New	0.330	0.670
Aluminum	---	---	0.408	0.592
Aluminum	---	Weathered	0.645	0.355
Black	---	---	1.000	0.000
Blue	Light	---	0.150	0.850
Blue	Pale	---	0.272	0.728
Blue	Dark	---	0.505	0.495
Blue	---	---	0.545	0.455
Cream	Light	---	0.115	0.885
Gray	Glossy	---	0.190	0.810
Gray	Light	---	0.430	0.570
Gray	---	---	0.530	0.470
Green	Light	---	0.215	0.785
Green	---	---	0.592	0.408
Green	Dark	---	0.596	0.404
Green	Dark	---	0.787	0.213
Metal	Bare	---	0.900	0.100
Pink	Light	---	0.135	0.865
Red	Iron Oxide	---	0.305	0.695
Red	---	---	0.724	0.276
Red	Dark	---	0.787	0.213
Red	Bright	---	0.828	0.172
Tan	---	---	0.355	0.645
White	---	---	0.100	0.900
Yellow	---	---	0.435	0.565

Table E4 - Paint Factor and Solar Absorptance of Selected Tank Paint Colors and Conditions [A6]

Tank Color		Paint Factor, Fp (1) (dimensionless)		Solar Absorptance, α (2) (dimensionless)	
Roof	Shell	Good Condition	Poor Condition	Good Condition	Poor Condition
White	White	1.00	1.15	0.170	0.337
Aluminum (Specular)	White	1.04	1.18	0.214	0.370
White	Aluminum (Specular)	1.16	1.24	0.348	0.436
Aluminum (Specular)	Aluminum (Specular)	1.20	1.29	0.392	0.492
White	Aluminum (Diffuse)	1.30	1.38	0.503	0.592
Aluminum (Diffuse)	Aluminum (Diffuse)	1.39	1.46	0.603	0.681
White	Gray	1.30	1.38	0.503	0.592
Light Gray	Light Gray	1.33	----	0.536	-----
Medium Gray	Medium Gray	1.46	----	0.681	-----

Notes: (1) Values of Fp are from Table 2 of Ref. A6.
(2) Values of α are calculated from the relationship: $\alpha = 1.11\ Fp - 0.94$

Table E5 - Solar Absorptance for Selected Tank Paint Colors and Conditions

Paint Color	Paint Shade or Type	Solar Absorptance, α (dimensionless) 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	----	0.17	0.34

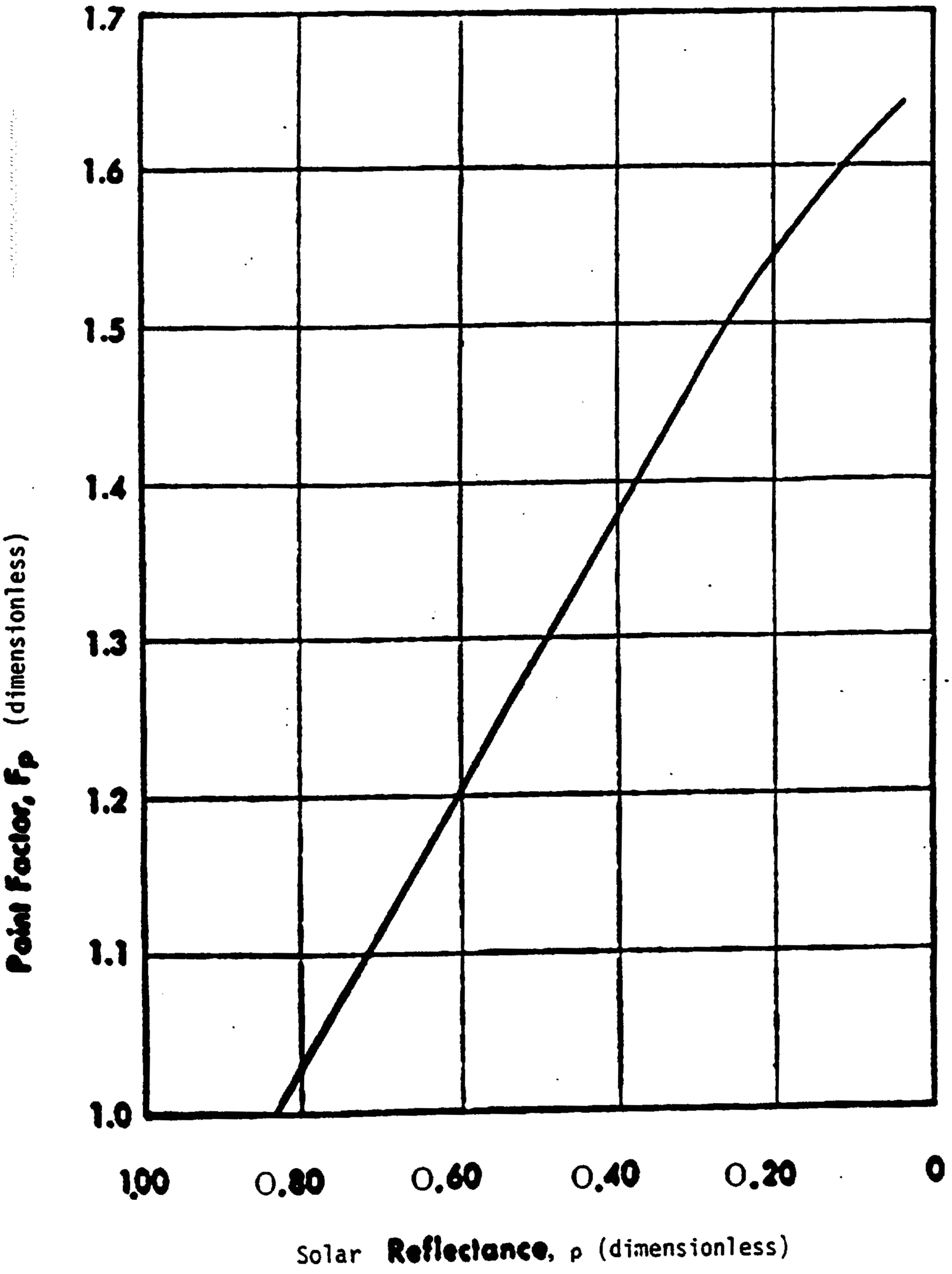

Figure E1 - Effect of Solar Reflectance on Paint Factor
[From Fig. IV-3 of Ref. A6]

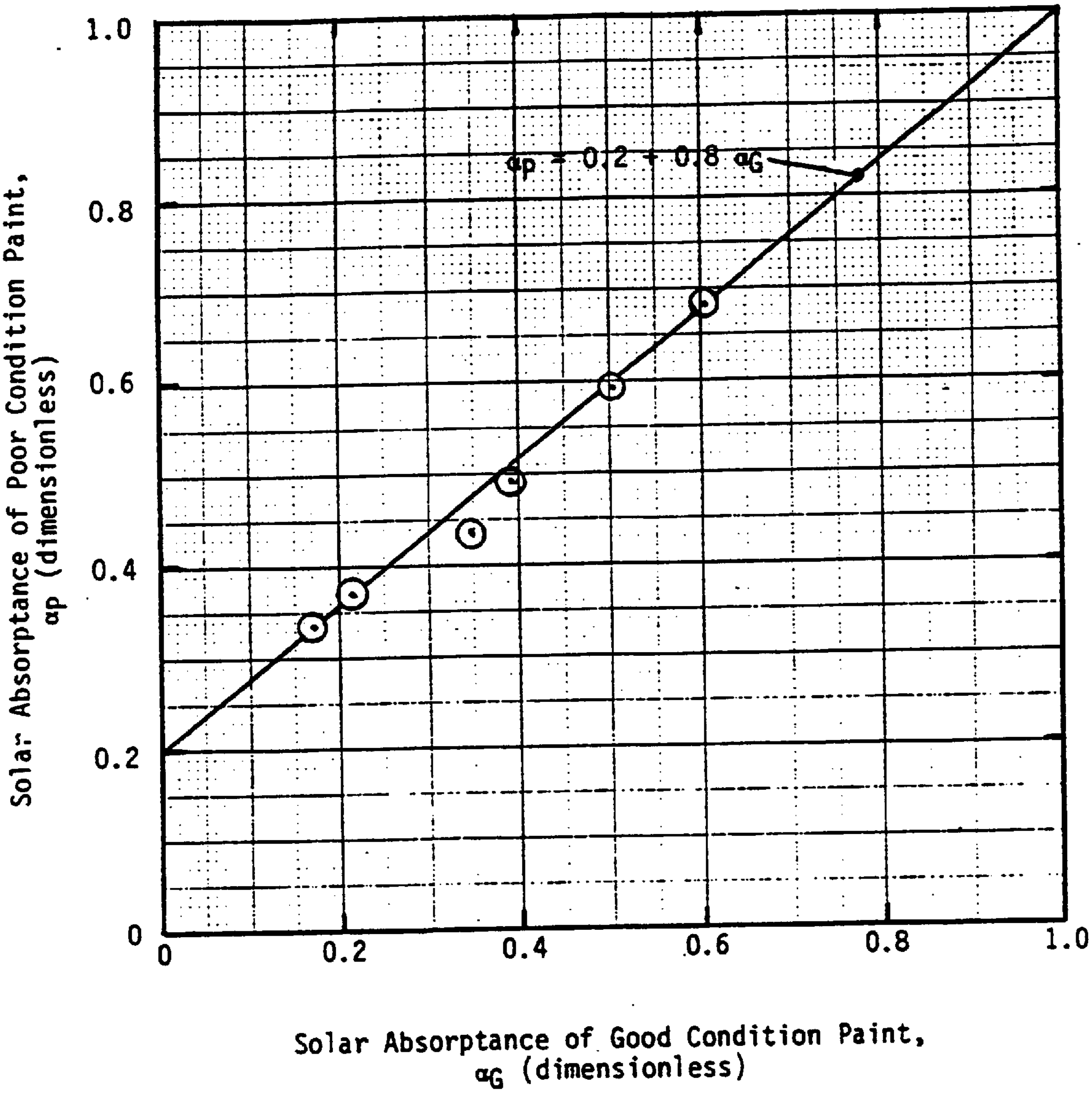

Figure E2 - Effect of Paint Condition on Solar Absorptance

API PUBLICATION 2518
DOCUMENTATION FILE

SECTION F

DEVELOPMENT OF
LIQUID SURFACE TEMPERATURE EQUATIONS

API PUBLICATION 2518
DOCUMENTATION FILE
SECTION F

CONTENTS

API PUBLICATION 2518
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SECTION F

NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
A	Area	ft^2
a	Defined by Eq (F-21)	dimensionless
b	Defined by Eq (F-22)	dimensionless
c	Heat capacity	B/lbm ^oF
G	Defined by Eq (F-9)	dimensionless
H_H	Daily total solar insolation on a horizontal surface	B/day ft^2
h	Heat transfer coefficient	B/hr ft^2 ^oF
K_L	Defined by Eq (F-6)	dimensionless
k	Thermal conductivity	B/hr ft ^oF
T	Temperature	^oF
ΔT	Temperature change	^oF
α	Solar absorptance	dimensionless
ρ	Density	lbm/ft^3

SUBSCRIPTS

A	Ambient
AA	Ambient, Daily Average
B	Liquid Bulk
BA	Liquid Bulk, Daily Average
BN	Liquid Bulk, Daily Minimum
BX	Liquid Bulk, Daily Maximum
G	Gas
GA	Gas, Daily Average
GN	Gas, Daily Minimum
GX	Gas, Daily Maximum
L	Liquid Surface
LA	Liquid Surface, Daily Average
LN	Liquid Surface, Daily Minimum
LX	Liquid Surface, Daily Maximum

F1.0 INTRODUCTION

This section of the Documentation File to API Publication 2518, Second Edition, presents the development of the equations required to determine the daily maximum liquid surface temperature, T_{LX}, the daily average liquid surface temperature, T_{LA}, and the daily minimum liquid surface temperature, T_{LN}.

Section F2 develops an equation for estimating the liquid bulk temperature, T_B, when this temperature is not available from tank operating records. This equation is based on data from in API Publication 2518, First Edition [A6]*.

Section F3 presents an equation for determining the daily average gas space temperature, T_{GA}.

Section F4 develops an equation for determining the daily liquid surface temperature range, ΔT_L. This theoretical equation is confirmed by a correlation developed from the API Computer Data Base [39].

Section F5 develops an equation for determining the daily average liquid surface temperature, T_{LA}. This theoretical equations is confirmed by the API Test Data [33,38].

Section F6 presents a summary of the equations required to calculate the daily maximum liquid surface temperature, T_{LX}, the daily average liquid surface temperature, T_{LA}, and the daily minimum liquid surface temperature, T_{LN}. The equations are presented in the order required for calculation.

F2.0 LIQUID BULK TEMPERATURE

The liquid bulk temperature, T_B, is the average temperature of the liquid stock in the storage tank. This information is usually available from tank gaging records or other tank operating records.

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* Numbers in brackets refer to the numbered references listed at the end of this Documentation File.

If the liquid bulk temperature is not available, it may be estimated from the daily average ambient temperature, T_{AA}, and the tank shell paint solar absorptance, α, using Eq (F-1).

$$T_B = T_{AA} + 6\alpha - 1 \qquad \text{(F-1)}$$

Figure F1 is a plot of liquid bulk temperature, T_B, above that in a white tank versus shell paint solar absorptance, α. This figure is from Figure IV-2 of API Publication 2518, First Edition [A6]. Eq (F-1) was developed from the straight line on Figure F1 and from the assumption that the liquid bulk temperature in a white tank is the same as the average ambient temperature, T_{AA}.

F3.0 AVERAGE GAS SPACE TEMPERATURE

The following equation may be used to determine the daily average gas space temperature, T_{GA}. Refer to Eq (C-108) in Section C8 of this Documentation File for the development of this equation.

$$T_{GA} = 0.775T_{AA} + 0.225T_{LA} + 0.0140\ \alpha\ H_H \qquad \text{(F-2)}$$

F4.0 LIQUID SURFACE TEMPERATURE RANGE

This section contains the development of two equations for the daily liquid surface temperature range, ΔT_L: (1) a correlation from the API Computer Data Base [39]; and (2) a theoretical equation from a heat transfer analysis.

F4.1 Liquid Surface Temperature Range Correlation

A correlation between the liquid surface temperature range, ΔT_L, and the gas space temperature range, ΔT_G, was developed from the 560 sets of calculated results that are contained in the API Computer Data Base [39].

The daily liquid surface temperature range, ΔT_L, and the daily gas space temperature range, ΔT_G, are defined by Eqs (F-3) and (F-4).

$$\Delta T_L = T_{LX} - T_{LN} \quad \text{(F-3)}$$

$$\Delta T_G = T_{GX} - T_{GN} \quad \text{(F-4)}$$

Figures F2, F3 and F4 are plots of liquid surface temperature range, ΔT_L, versus gas space temperature range, ΔT_G, from the API Computer Data Base [39]. Each of these figures contains about 1/3 of the 560 calculated values in the API Computer Data Base.

The resulting correlation is shown in Eq (F-5):

$$\boxed{\Delta T_L = 0.534050 \Delta T_G - 2.810841} \quad \text{(F-5)}$$

Although the data in Figures F2 through F4 exhibit a slight curvature, the linear correlation results in an excellent fit of the values, with a correlation coefficient of 0.998344.

F4.2 Liquid Surface Temperature Range Equation

This section contains the development of a theoretical equation for the liquid surface temperature range, ΔT_L, from a heat transfer analysis.

The API Test Data [33,38] indicates that the top layer of liquid stock behaves thermally as if it were a layer of solid material during the daily thermal heating cycle. Heat is transferred in a vertical direction through this top layer by steady periodic heat transfer.

The case of heat transfer between a fluid medium with a steady periodic temperature change in contact with the plane surface of a semi-infinite solid material is treated by Jakob [Jakob, M., "Heat Transfer", Volume 1, John Wiley & Sons, Inc., 1949, pp. 296-299]. This analysis may be applied to the top layer of liquid stock in a storage tank and results in Eq (F-6), (F-7) and (F-8):

$$K_L \equiv \frac{\Delta T_L}{\Delta T_G} \quad \text{(F-6)}$$

or

$$\Delta T_L = K_L \, \Delta T_G \quad \text{(F-7)}$$

where:

$$K_L = \left[\frac{1}{1 + 2G^{1/2} + 2G}\right]^{1/2} \quad \text{(F-8)}$$

$$G = \left[\frac{\pi \, \rho_L \, c_L \, k_L}{24 \, h_G^{\,2}}\right] \quad \text{(F-9)}$$

The following values for ρ_L, c_L and k_L from the API Base Case [39] were used to calculated G and K_L:

$$\rho_L = 53 \text{ lbm/ft}^3 \quad \text{(F-10)}$$

$$c_L = 0.45 \text{ Btu/lbm } ^oF \quad \text{(F-11)}$$

$$k_L = 0.08 \text{ Btu/hr ft } ^oF \quad \text{(F-12)}$$

$$h_G = 0.65 \text{ Btu/hr ft}^2 \, ^oF \quad \text{(F-13)}$$

The resulting values calculated for G and K_L from Eqs (F-9) and (F-8), respectively, are:

$$G = 0.5911 \quad \text{(F-14)}$$

$$K_L = 0.5185 \quad \text{(F-15)}$$

This value for K_L is supported by the correlation result of Eq (F-5).

The value for K_L listed in Eq (F-15) may be rounded to 0.500 for ease of calculation. Finally, substituting this value for K_L into Eq (F-7), we obtain:

$$\boxed{\Delta T_L = 0.500\ \Delta T_G} \qquad \text{(F-16)}$$

F5.0 AVERAGE LIQUID SURFACE TEMPERATURE

F5.1 Heat Transfer Model

This section develops a simplified equation for estimating the daily average liquid surface temperature, T_{LA}, from the liquid bulk temperature, T_B, and the daily average gas space temperature, T_{GA}.

Figure F5 is a schematic of the energy flows and temperatures near the liquid surface. The heat transfer equations are Eqs (F-17) and (F-18).

$$q_G = h_G\ A_L\ (T_G - T_L) \qquad \text{(F-17)}$$

$$q_L = h_L\ A_L\ (T_L - T_B) \qquad \text{(F-18)}$$

The heat balance equation at the liquid surface is:

$$q_G = q_L \qquad \text{(F-19)}$$

Substituting Eqs (F-17) and (F-18) into Eq (F-19) and solving for T_L we obtain:

$$T_L = a\ T_G + b\ T_B \qquad \text{(F-20)}$$

where:

$$a = \left(\frac{h_G}{h_G + h_L}\right) \qquad \text{(F-21)}$$

$$b = \left[\frac{h_L}{h_G + h_L}\right] \quad \text{(F-22)}$$

The ratio a/b may be determined from Eqs (F-21) and (F-22) as follows:

$$\frac{a}{b} = \frac{h_G}{h_L} \quad \text{(F-23)}$$

Substituting Eq (F-23) into Eq (F-22) we obtain the following relationship between b and a.

$$b = 1 - a \quad \text{(F-24)}$$

During the daily thermal breathing process, the liquid bulk temperature, T_B, can be assumed to be constant. At the maximum, average and minimum gas space temperature conditions, Eq (F-20) becomes:

$$T_{LX} = aT_{GX} + bT_B \quad \text{(F-25)}$$

$$T_{LA} = aT_{GA} + bT_B \quad \text{(F-26)}$$

$$T_{LN} = aT_{GN} + bT_B \quad \text{(F-27)}$$

The daily liquid surface temperature range, ΔT_L, and the daily gas space temperature range, ΔT_G, were defined by Eqs (F-3) and (F-4). Substituting Eqs (F-25) and (F-27) into Eq (F-3), we obtain:

$$\Delta T_L = (aT_{GX} + bT_B) - (aT_{GN} + bT_B)$$

$$\Delta T_L = a(T_{GX} - T_{GN})$$

$$\Delta T_L = a\Delta T_G \quad \text{(F-28)}$$

From Eq (F-16) in Section F4.2, we know that a = 0.500. Substituting this value for a into Eq (F-28), we obtain b = 0.500. Substituting these values for a and b into Eqs (F-25), (F-26) and (F-27), we obtain:

$$T_{LX} = 0.500T_{GX} + 0.500T_B \quad \text{(F-29)}$$

$$T_{LA} = 0.500T_{GA} + 0.500T_B \quad \text{(F-30)}$$

$$T_{LN} = 0.500T_{GN} + 0.500T_B \quad \text{(F-31)}$$

F5.2 Comparison With Test Data

To compare the results of this analysis with the API Test Data [33,38], it is first convenient to form the ratio $(T_{LA} - T_B)/(T_{GA} - T_B)$ using Eq (F-30) from the above analysis as follows:

$$\left(\frac{T_{LA} - T_B}{T_{GA} - T_B}\right) = \left[\frac{(0.500T_{GA} + 0.500T_B) - T_B}{T_{GA} - T_B}\right] = 0.500 \quad \text{(F-32)}$$

Table F1 presents the above ratio calculated from API Tests 1 through 6. API Tests 7 through 10 could not be used for this comparison since the liquid surface thermocouple appeared to be reading the gas temperature rather than the liquid surface temperature. The average value calculated for the ratio $(T_{LA} - T_B)/(T_{GA} - T_B)$ from the API Test Data is 0.467. This value calculated from test data is close to the value of 0.500 in Eq (F-32), thus verifying the heat transfer analysis in Section F5.1.

F5.3 Average Liquid Surface Temperature Equation

Substituting Eq (F-2) for T_{GA} into Eq (F-30) and solving for T_{LA}, we obtain finally the following expression for the daily average liquid surface temperature, T_{LA}.

$$\boxed{T_{LA} = 0.437T_{AA} + 0.563T_B + 0.00789\alpha H_H} \quad \text{(F-33)}$$

F6.0 CONCLUSION

The equations that are required to calculate T_{LA}, T_{LX} and T_{LN} are summarized below. These equations are presented in the order that is required for calculation.

1. Determine T_B

T_B = value from tank operating data

or

$$T_B = T_{AA} + 6\alpha - 1 \qquad \text{(F-34)}$$

2. Determine T_{LA}

$$T_{LA} = 0.437T_{AA} + 0.563T_B + 0.00789\alpha H_H \qquad \text{(F-35)}$$

3. Determine ΔT_V

$$\Delta T_V = 0.723\Delta T_A + 0.0279\alpha H_H \qquad \text{(F-36)}$$

4. Determine ΔT_L

$$\Delta T_L = 0.500\Delta T_V \qquad \text{(F-37)}$$

5. Determine T_{LX}

$$T_{LX} = T_{LA} + 0.500\Delta T_L \qquad \text{(F-38)}$$

6. Determine T_{LN}

$$T_{LN} = T_{LA} - 0.500\Delta T_L \qquad \text{(F-39)}$$

It is possible to combine some of the above equations to reduce the number of equations, but they are listed separately here for clarity.

Table F1 - Temperature Difference Ratio (TLA - TBA)/(TGA - TBA) Calculated From the API Test Data [33,38]

Test No.	T_{BA} (°F)	T_{LA} (°F)	T_{GA} (°F)	$(T_{LA}-T_{BA})$ (°F)	$(T_{GA}-T_{BA})$ (°F)	$\left(\frac{T_{LA}-T_{BA}}{T_{GA}-T_{BA}}\right)$ (dimensionless)
API-1	52.8	58.2	65.3	5.4	12.5	0.432
API-2	52.7	60.0	67.3	7.3	14.6	0.500
API-3	53.2	61.0	70.5	7.8	17.3	0.451
API-4	53.9	61.8	70.2	7.9	16.3	0.485
API-5	53.7	60.5	67.3	6.8	13.6	0.500
API-6	53.8	56.5	60.0	2.7	6.2	0.435
Average						0.467

Note: (1) The mean values T_{BA}, T_{LA}, T_{VA} listed in this table were calculated from the maximum and minimum values measured in the API tests [33,38].

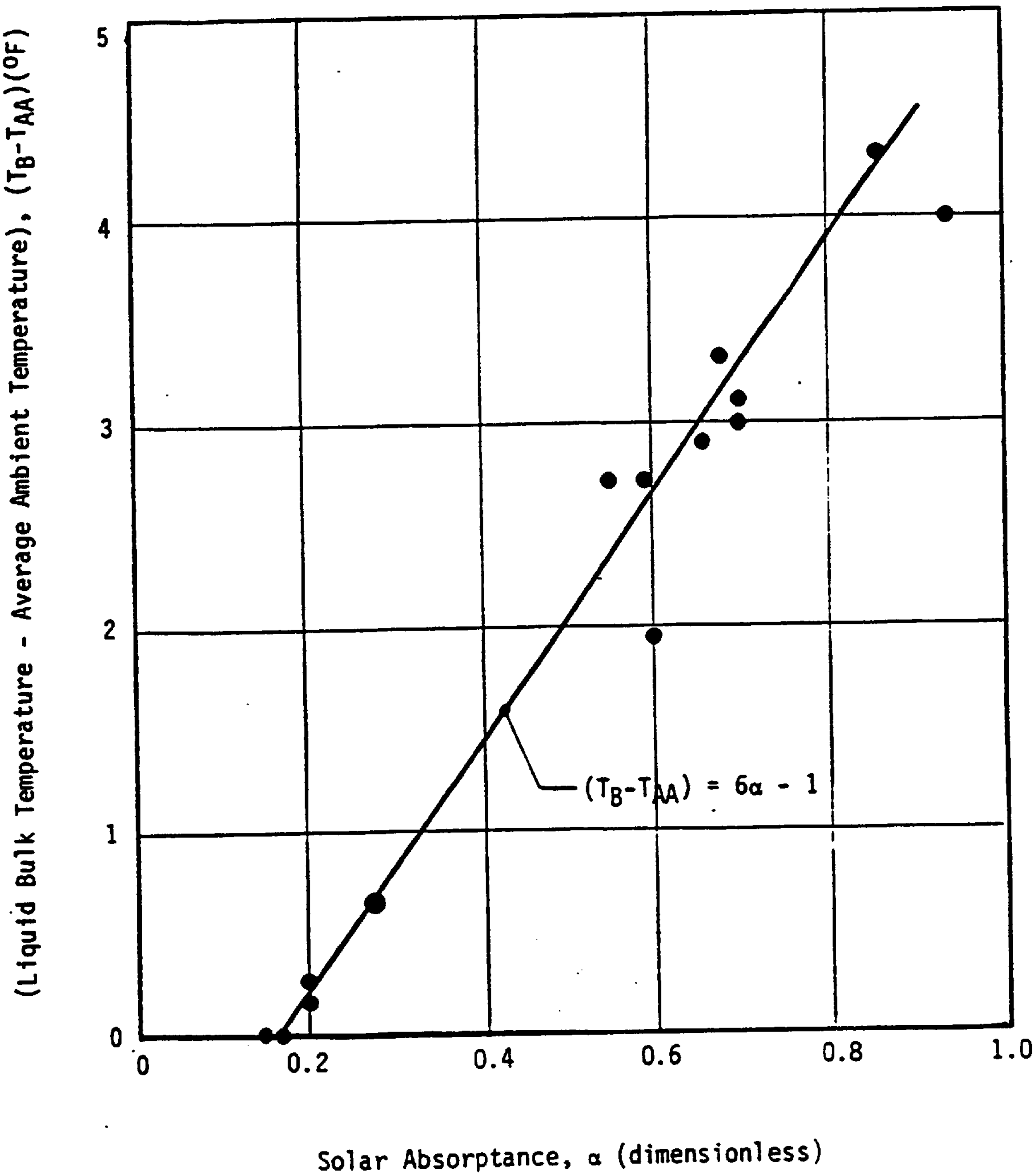

Figure F1 - Effect of Paint Solar Absorptance on the Liquid Bulk Temperature [A6]

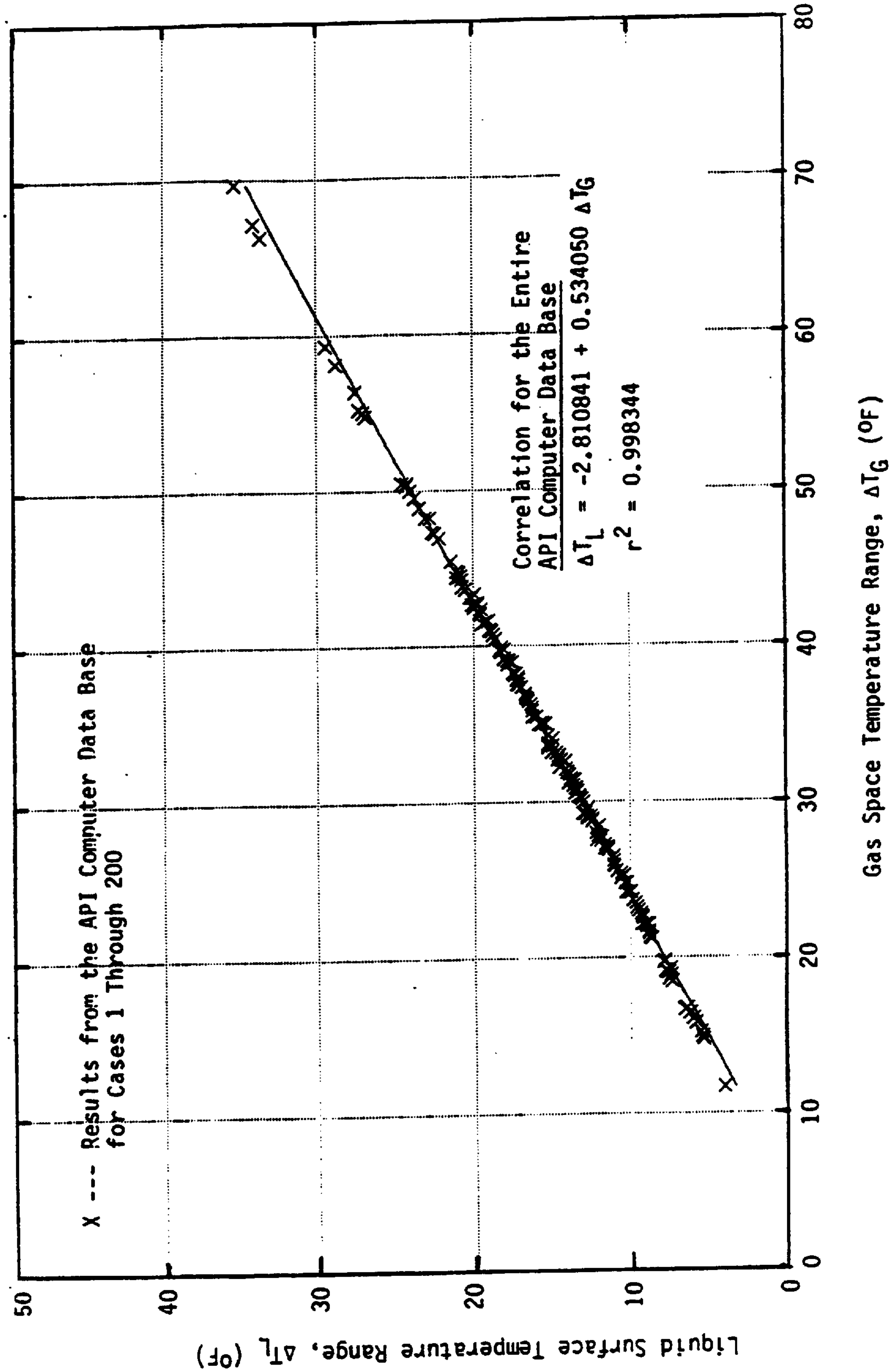

Figure F2 - Liquid Surface Temperature Range Versus Vapor Space Temperature Range for API Computer Data Base Cases 1 Through 200

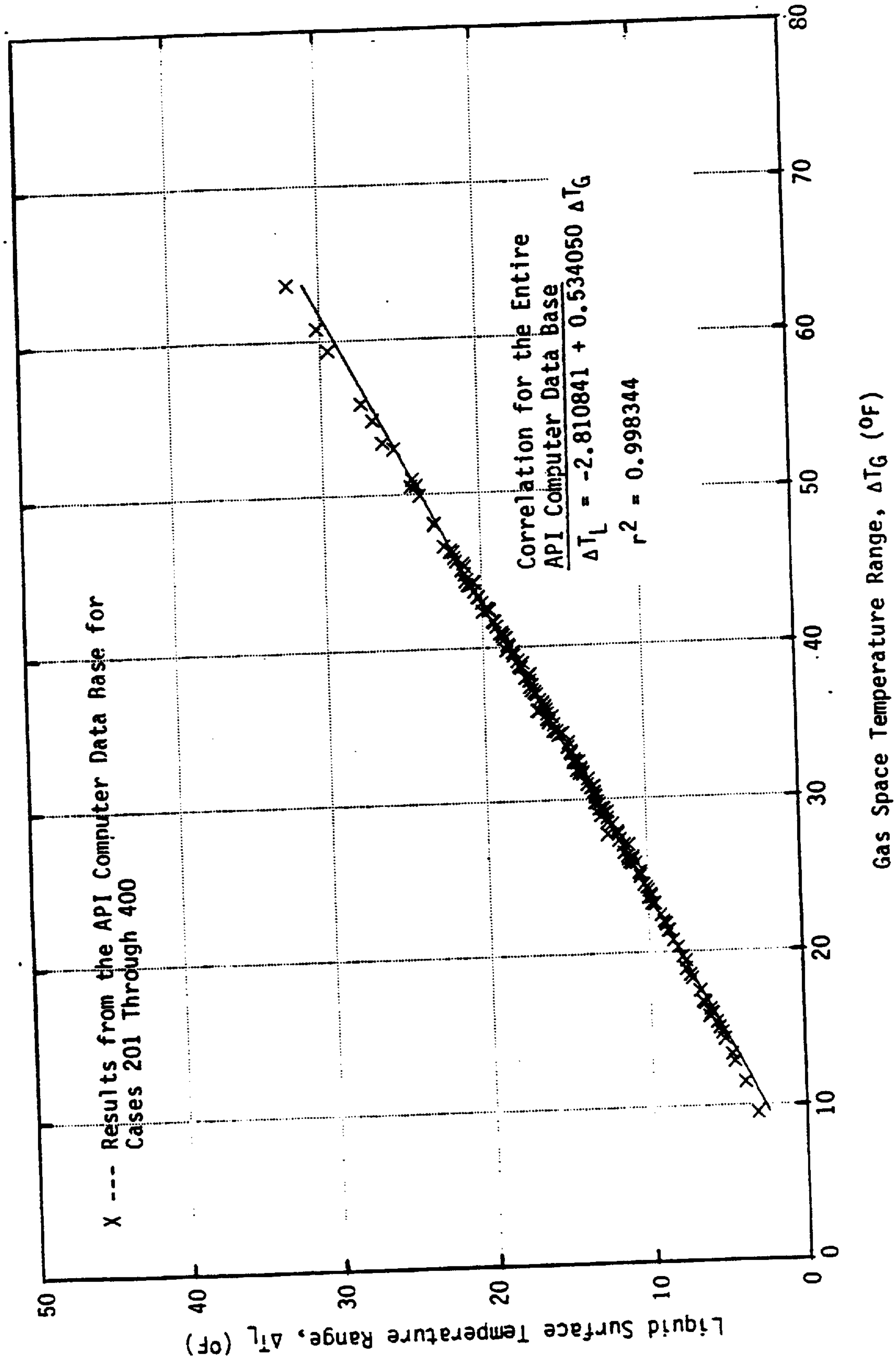

Figure F3 - Liquid Surface Temperature Range Versus Vapor Space Temperature Range for API Computer Data Base Cases 201 Through 400

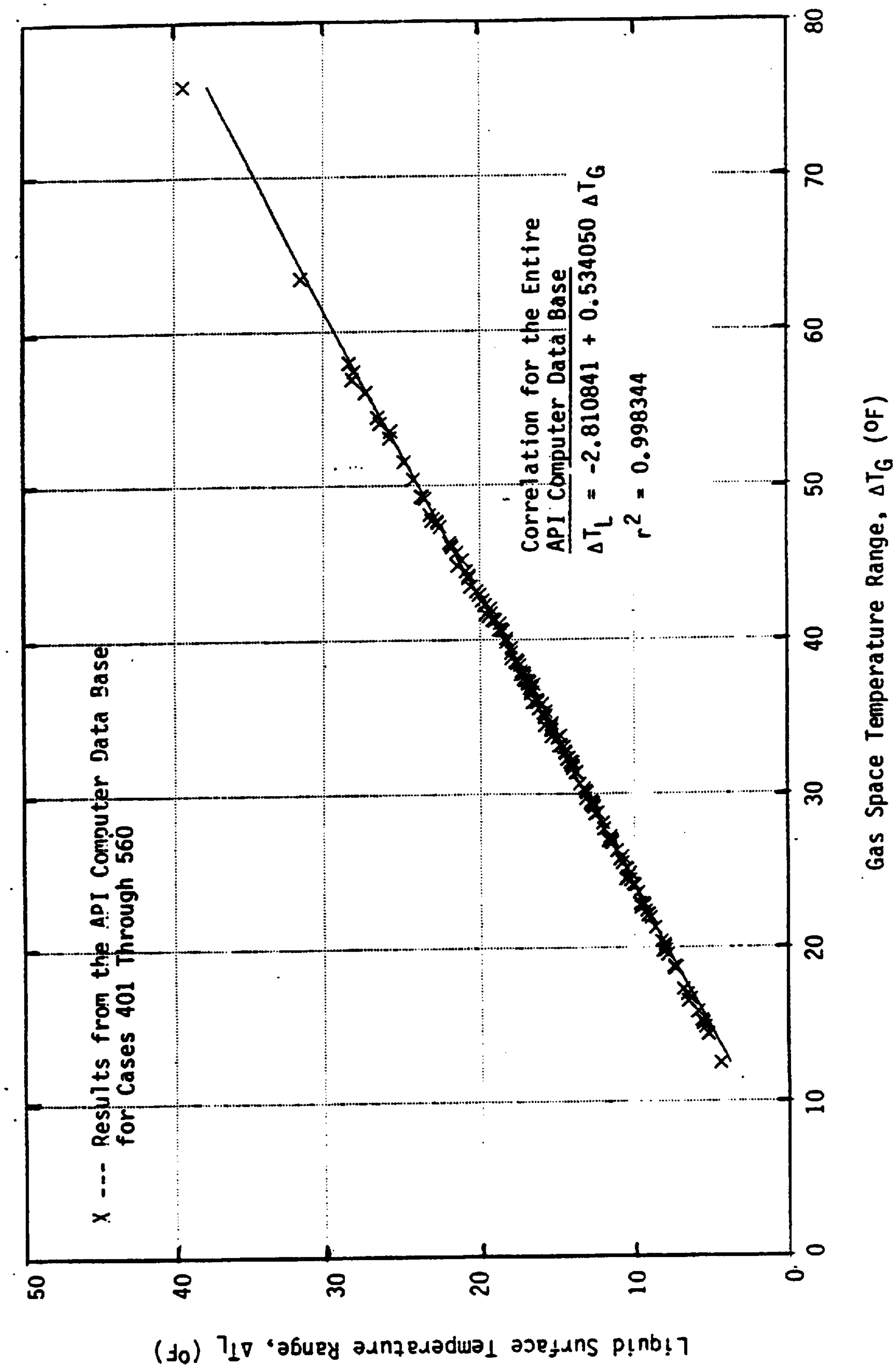

Figure F4 - Liquid Surface Temperature Range Versus Gas Space Temperature Range for API Computer Data Base Cases 401 Through 560

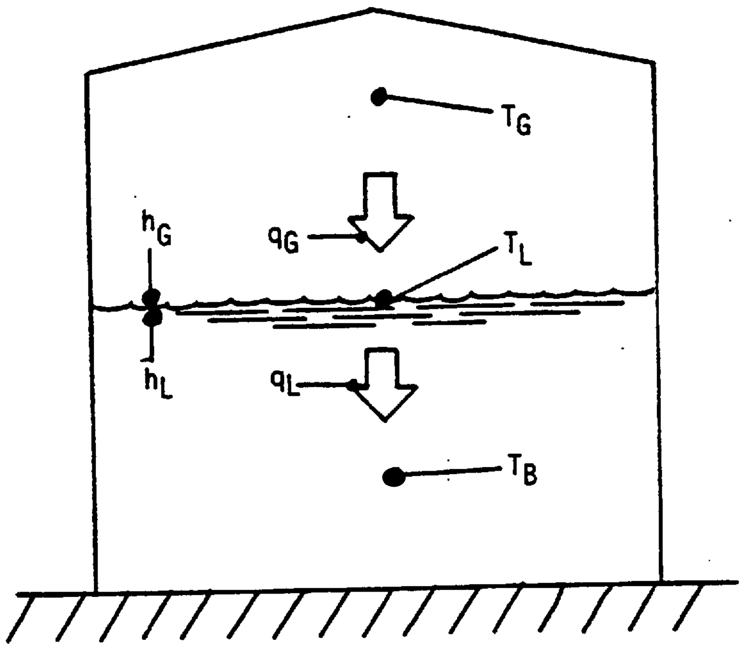

Figure F5 - Schematic of Energy Flows and Temperatures Near the Liquid Surface

API PUBLICATION 2518
DOCUMENTATION FILE

SECTION G

SENSITIVITY ANALYSIS OF STANDING STORAGE LOSS EQUATION

API PUBLICATION 2518
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SECTION G

CONTENTS

API PUBLICATION 2518
DOCUMENTATION FILE
SECTION G

NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
A	Constant in the vapor pressure equation	dimensionless
B	Constant in the vapor pressure equation	^{o}R
D	Tank diameter	ft
E_1	Daily standing storage loss calculated from API Publication 2518, First Edition [A6]	lb/day
E_2	Daily standing storage loss calculated from API Publication 2518, Second Edition [A7]	lb/day
H_{VO}	Vapor space outage	ft
I	Daily total solar insolation on a horizontal surface	Btu/ft^2 day
K_E	Vapor space volume expansion factor	dimensionless
K_S	Vented vapor saturation factor	dimensionless
L_S	Daily standing storage loss	lb/day
M_V	Stock vapor molecular weight	lb/lbmole
P_A	Atmospheric pressure	psia
P_{BP}	Breather vent pressure setting (always a positive value)	psig
P_{BV}	Breather vent vacuum setting (always a negative value)	psig
P_{VA}	Stock vapor pressure at the daily average liquid surface temperature	psia
P_{VN}	Stock vapor pressure at the daily minimum liquid surface temperature	psia
P_{VX}	Stock vapor pressure at the daily maximum liquid surface temperature	psia
ΔP_V	Stock daily vapor pressure range	psi
ΔP_B	Breather vent pressure setting range	psi
RVP	Reid vapor pressure	psi
T_{AA}	Daily average ambient temperature	^{o}R or ^{o}F
T_B	Liquid bulk temperature	^{o}R or ^{o}F
T_{LA}	Daily average liquid surface temperature	^{o}R or ^{o}F
ΔT_A	Daily ambient temperature range	^{o}R or ^{o}F
T_{LN}	Daily minimum liquid surface temperature	^{o}R or ^{o}F

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SECTION G

NOMENCLATURE (Continued)

SYMBOL	DESCRIPTION	UNITS
T_{LX}	Daily maximum liquid surface temperature	°R or °F
ΔT_V	Daily vapor temperature range	°R or °F
V_V	Tank vapor space volume	ft^3
W_V	Stock vapor density	lb/ft^3
α	Tank paint solar absorptance	dimensionless

G1.0 INTRODUCTION

This section of the Documentation File to API Publication 2518, Second Edition [A7]* contains a sensitivity analysis of the standing storage loss equation. The objective of this analysis is to determine the affect of the variables in the standing storage loss equation on the calculated loss over a range of conditions for each variable.

Section G2 summarizes the variables used in the sensitivity analysis.

Section G3 presents sample calculations for the Base Case conditons.

Section G4 presents the results of the sensitivity analysis.

Section G5 presents conclusions from the sensitivity analysis.

G2.0 VARIABLES USED IN THE SENSITIVITY ANALYSIS

Table G1 lists the input variables that were studied as part of the sensitivity analysis. For each input variable, a "Base Case" value and a range were selected.

In performing the sensitivity analysis, each of the input variables was kept at the Base Case value while the value of the input variable being studied was varied over the desired range. In this way, the sensitivity of the API standing storage loss model was evaluated around the Base Case conditions.

G3.0 SAMPLE CALCULATIONS FOR THE BASE CASE

This section summarizes sample calculations of the standing storage loss for the Base Case conditions.

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* Numbers in brackets refer to the numbered references listed at the end of this Documentation File.

G3.1 Base Case Conditions

G3.1.1 Tank Conditions

$D = 100$ ft

$H_{VO} = 30$ ft

$\alpha = 0.50$

$P_{BP} = 0.03$ psig

$P_{BV} = -0.03$ psig

G3.1.2 Meteorological Conditions

$T_{AA} = 519.69^{o}R\ (60.00^{o}F)$

$\Delta T_A = 20.00^{o}R\ (20.00^{o}F)$

$I = 1500\ Btu/ft^2\ day$

$P_A = 14.696$ psia

G3.1.3 Stock Conditions

Type = Crude Oil

RVP = 2.0 psi

$M_V = 80$ lb/lbmole

G3.2 Calculated Results

G3.2.1 Determine T_B

$$T_B = T_{AA} + 6\alpha - 1 \qquad \text{(G-1)}$$

$$T_B = (519.69) + (6)(0.50) - (1)$$

$$T_B = 521.69^{o}R\ (62.00^{o}F)$$

G3.2.2 Determine T_{LA}

$$T_{LA} = 0.44T_{AA} + 0.56T_B + 0.0079\alpha I \quad \text{(G-2)}$$
$$T_{LA} = (0.44)(519.69) + (0.56)(521.69) + (0.0079)(0.50)(1500)$$
$$T_{LA} = 526.74^{o}R\ (67.05^{o}F)$$

G3.2.3 Determine ΔT_V

$$\Delta T_V = 0.72\Delta T_A + 0.028\alpha I \quad \text{(G-3)}$$
$$\Delta T_V = (0.72)(20.00) + (0.028)(0.50)(1500)$$
$$\Delta T_V = 35.40^{o}R\ (35.40^{o}F)$$

G3.2.4 Determine T_{LX}

$$T_{LX} = T_{LA} + 0.25\Delta T_V \quad \text{(G-4)}$$
$$T_{LX} = (526.74) + (0.25)(35.40)$$
$$T_{LX} = 535.59^{o}R\ (75.90^{o}F)$$

G3.2.5 Determine T_{LN}

$$T_{LN} = T_{LA} - 0.25\Delta T_V \quad \text{(G-5)}$$
$$T_{LN} = (526.74) - (0.25)(35.40)$$
$$T_{LN} = 517.89^{o}R\ (58.20^{o}F)$$

G3.2.6 Determine A

$$A = 12.82 - 0.9672 \ln (RVP) \quad \text{(G-6)}$$
$$A = (12.82) - (0.9672) \ln(2.0)$$
$$A = 12.15$$

G3.2.7 Determine B

$$B = 7261 - 1216 \ln(RVP) \quad \text{(G-7)}$$

$$B = (7261) - (1216) \ln(2.0)$$

$$B = 6418^{o}R$$

G3.2.8 Determine P_{VX}

$$P_{VX} = \exp\left[A - \frac{B}{T_{LX}}\right] \quad \text{(G-8)}$$

$$P_{VX} = \exp\left[(12.15) - \frac{(6418)}{(535.59)}\right]$$

$$= 1.1817 \text{ psia}$$

G3.2.9 Determine P_{VA}

$$P_{VA} = \exp\left[A - \frac{B}{T_{LA}}\right] \quad \text{(G-9)}$$

$$P_{VA} = \exp\left[(12.15) - \frac{(6418)}{(526.74)}\right]$$

$$= 0.9662 \text{ psia}$$

G3.2.10 Determine P_{VN}

$$P_{VN} = \exp\left[A - \frac{B}{T_{LN}}\right] \qquad \text{(G-9)}$$

$$P_{VN} = \exp\left[(12.15) - \frac{(6418)}{(517.89)}\right]$$

$$= 0.7846 \text{ psia}$$

G3.2.11 Determine ΔP_V

$$\Delta P_V = P_{VX} - P_{VN} \qquad \text{(G-11)}$$

$$\Delta P_V = (1.1817) - (0.7846)$$

$$\Delta P_V = 0.3971 \text{ psi}$$

G3.2.12 Determine ΔP_B

$$\Delta P_B = P_{BP} - P_{BV} \qquad \text{(G-12)}$$

$$\Delta P_B = (0.03) - (-0.03)$$

$$\Delta P_B = 0.06 \text{ psi}$$

G3.2.13 Determine V_V

$$V_V = \frac{\pi}{4} D^2 H_{VO} \qquad \text{(G-13)}$$

$$V_V = \frac{(3.1416)(100)^2(30)}{(4)}$$

$$V_V = 235{,}620 \text{ ft}^3$$

G3.2.14 Determine W_V

$$W_V = \frac{M_V P_{VA}}{R\ T_{LA}} \qquad \text{(G-14)}$$

$$W_V = \frac{(80.00)(0.9662)}{(10.731)(526.74)}$$

$$W_V = 0.01367 \text{ lb/ft}^3$$

G3.2.15 Determine K_E

$$K_E = \frac{\Delta T_V}{T_{LA}} + \frac{\Delta P_V - \Delta P_B}{P_A - P_{VA}} \qquad \text{(G-15)}$$

$$K_E = \frac{(35.40)}{(526.74)} + \frac{(0.3971) - (0.0600)}{(14.696) - (0.9662)}$$

$$K_E = 0.09176$$

G3.2.16 Determine K_S

$$K_S = \frac{1}{1 + 0.053\ P_{VA}\ H_{VO}} \qquad \text{(G-16)}$$

$$K_S = \frac{1}{1 + (0.053)(0.9662)(30)}$$

$$K_S = 0.3943$$

G3.2.17 Determine L_S

$$L_S = V_V\ W_V\ K_E\ K_S \qquad \text{(G-17)}$$

$$L_S = (235,620)(0.01367)(0.09176)(0.3943)$$

$$L_S = 116.5 \text{ lb/day}$$

G4.0 SENSITIVITY ANALYSIS RESULTS

Table G2 lists the input and output variables from the API standing storage loss equation for each of the 57 cases which were studied as part of the sensitivity analysis.

Figures G1 through G10 illustrate the effect of the input variables on the emissions calculated by the API standing storage loss equation. The Base Case condition is also indicated on each figure.

G4.1 Breather Vent Setting Sensitivity

Figure G8 indicates that the breather vent pressure and vacuum settings (up to ±0.05 psig) have little effect on the standing storage loss.

G4.2 Vapor Pressure Sensitivity

The sensitivity analysis also include an evaluation of the effect of vapor pressure on emissions. Vapor pressure is affected by stock type, Reid Vapor Pressure and temperature. Table G2 and Figures G9 and G10 show the effect of Reid Vapor Pressure and resulting true vapor pressure, respectively, on emissions for crude oil.

Even though the RVP was kept constant in most of the sensitivity analysis, the TVP varied from 0.3547 psia in Case No. 29 to 2.2815 psia in Case No. 33. This variation in TVP occurred implicitly as the calculated liquid surface temperature vaired due to varying the ambient temperature.

Currently, stocks with a TVP greater than 1.5 psia are not commonly stored in fixed-roof tanks.

G4.3 Comparison Between the First and Second Editions of API Publication 2518

A comparison was made between standing storage loss calculated from the First Edition [A6] and the Second Edition [A7] of API Publication 2518. The RVP was varied from 0.001 psi to 12.0 psi, while the other variables were kept at the Base Case conditions.

Table G3 summarizes the calculated results. The last column indicates the ratio of the standing storage loss calculated from the First Edition to that calculated from the Second Edition. It should be noted that the ratio equals about 1.0 when the RVP equals about 12 psi or the TVP equals about 10 psia.

Figures G9 and G10 graphically illustrate the effect of RVP and TVP on standing storage loss. It should be noted that the emissions predicted by the Second Edition are close to the emissions predicted by the First Edition when the vapor pressure is over about 2 psia. For low vapor pressures, the emissions calculated from the Second Edition are significantly less than those calculated from the First Edition, indicating that the First Edition overpredicts emissions for low vapor pressure stocks (less than 2.0 psia).

G5.0 CONCLUSIONS

The sensitivity analysis showed that the standing storage loss equation exhibits the same trends that were shown by a similar sensitivity analysis performed on the API Computer Model [39]. This similarily in sensitivity helps validate the standing storage loss equation.

The sensitivity analysis showed that the breather vent pressure and vacuum settings had little affect on the calculated loss.

The sensitivity analysis showed that for high vapor pressure stocks (greater than 2.0 psia) the evaporation losses calculated from the Second Edition are close to those calculated from the First Edition, and that for low vapor pressure stocks (less than 2.0 psia) the First Edition overpredictes the evaporation loss.

Table G1 - Range of Values and Base Case Value Used in Sensitivity Analysis

SYMBOL	DESCRIPTION	UNITS	BASE CASE VALUE	RANGE OF VALUES
D	Tank Diameter	ft	100	25, 50, 75, 100, 150, 200, 250, 300
H_{VO}	Vapor Space Outage	ft	30	10, 20, 30, 40, 50
I	Daily Total Solar Insolation on a Horizontal Surface	Btu/ft^2 day	1500	500, 1000, 1500, 2000, 2500
α	Tank Paint Solar Absorptance	dimensionless	0.5	0.1, 0.3, 0.5, 0.7, 0.9
M_V	Stock Vapor Molecular Weight	lb/lbmole	80	40, 60, 80, 100, 120
T_{AA}	Daily Average Ambient Temperature	^oF	60	20, 40, 60, 80, 100
ΔT_A	Daily Ambient Temperature Range	^oF	20	10, 15, 20, 25, 30
P_{BP}, P_{BV}	Breather Vent Pressure and Vacuum Settings	±psig	±0.03	0, ±0.1, ±0.2, ±0.3, ±0.4, ±0.5
RVP	Stock Reid Vapor Pressure	psi	2	0.001, 0.003, 0.01, 0.03, 0.1, 0.3, 1, 2, 3, 5, 8, 10, 12

Table G2 - Input and Output Variables for the Sensitivity Analysis

CASE NO.	D (ft)	H_{VO} (ft)	I (Btu/ft^2 day)	α (-)	M_V (lb/lbmole)	T_{AA} (^oF)	ΔT_A (^oF)	P_{BP} (psig)	P_{BV} (psig)	RVP (psi)	L_S (lb/day)
1	25	30	1500	0.5	80	60	20	0.03	-0.03	2.0	7.282
2	50	30	1500	0.5	80	60	20	0.03	-0.03	2.0	29.13
3	75	30	1500	0.5	80	60	20	0.03	-0.03	2.0	65.53
4	100	30	1500	0.5	80	60	20	0.03	-0.03	2.0	116.5
5	150	30	1500	0.5	80	60	20	0.03	-0.03	2.0	262.1
6	200	30	1500	0.5	80	60	20	0.03	-0.03	2.0	466.0
7	250	30	1500	0.5	80	60	20	0.03	-0.03	2.0	728.2
8	300	30	1500	0.5	80	60	20	0.03	-0.03	2.0	1048.6
9	100	10	1500	0.5	80	60	20	0.03	-0.03	2.0	65.13
10	100	20	1500	0.5	80	60	20	0.03	-0.03	2.0	97.31
11	100	30	1500	0.5	80	60	20	0.03	-0.03	2.0	116.5
12	100	40	1500	0.5	80	60	20	0.03	-0.03	2.0	129.3
13	100	50	1500	0.5	80	60	20	0.03	-0.03	2.0	138.3
14	100	30	500	0.5	80	60	20	0.03	-0.03	2.0	54.18
15	100	30	1000	0.5	80	60	20	0.03	-0.03	2.0	84.24
16	100	30	1500	0.5	80	60	20	0.03	-0.03	2.0	116.5
17	100	30	2000	0.5	80	60	20	0.03	-0.03	2.0	151.1
18	100	30	2500	0.5	80	60	20	0.03	-0.03	2.0	188.1
19	100	30	1500	0.1	80	60	20	0.03	-0.03	2.0	64.88
20	100	30	1500	0.3	80	60	20	0.03	-0.03	2.0	90.09
21	100	30	1500	0.5	80	60	20	0.03	-0.03	2.0	116.5
22	100	30	1500	0.7	80	60	20	0.03	-0.03	2.0	144.2
23	100	30	1500	0.9	80	60	20	0.03	-0.03	2.0	173.1
24	100	30	1500	0.5	40	60	20	0.03	-0.03	2.0	58.25
25	100	30	1500	0.5	60	60	20	0.03	-0.03	2.0	87.38
26	100	30	1500	0.5	80	60	20	0.03	-0.03	2.0	116.5
27	100	30	1500	0.5	100	60	20	0.03	-0.03	2.0	145.6
28	100	30	1500	0.5	120	60	20	0.03	-0.03	2.0	174.8

Table G2 - Input and Output Variables for the Sensitivity Analysis (Continued)

CASE NO.	D (ft)	H_{VO} (ft)	I (Btu/ft^2 day)	α (-)	M_V (lb/lbmole)	T_{AA} (°F)	ΔT_A (°F)	P_{BP} (psig)	P_{BV} (psig)	RVP (psi)	L_S (lb/day)
29	100	30	1500	0.5	80	20	20	0.03	-0.03	2.0	65.86
30	100	30	1500	0.5	80	40	20	0.03	-0.03	2.0	89.61
31	100	30	1500	0.5	80	60	20	0.03	-0.03	2.0	116.5
32	100	30	1500	0.5	80	80	20	0.03	-0.03	2.0	148.0
33	100	30	1500	0.5	80	100	20	0.03	-0.03	2.0	187.7
34	100	30	1500	0.5	80	60	10	0.03	-0.03	2.0	91.64
35	100	30	1500	0.5	80	60	15	0.03	-0.03	2.0	104.1
36	100	30	1500	0.5	80	60	20	0.03	-0.03	2.0	116.5
37	100	30	1500	0.5	80	60	25	0.03	-0.03	2.0	129.0
38	100	30	1500	0.5	80	60	30	0.03	-0.03	2.0	141.4
39	100	30	1500	0.5	80	60	20	0.00	-0.00	2.0	122.1
40	100	30	1500	0.5	80	60	20	0.01	-0.01	2.0	120.2
41	100	30	1500	0.5	80	60	20	0.02	-0.02	2.0	118.4
42	100	30	1500	0.5	80	60	20	0.03	-0.03	2.0	116.5
43	100	30	1500	0.5	80	60	20	0.04	-0.04	2.0	114.7
44	100	30	1500	0.5	80	60	20	0.05	-0.05	2.0	112.8
45	100	30	1500	0.5	80	60	20	0.03	-0.03	0.001	0.00759
46	100	30	1500	0.5	80	60	20	0.03	-0.03	0.003	0.03312
47	100	30	1500	0.5	80	60	20	0.03	-0.03	0.01	0.1664
48	100	30	1500	0.5	80	60	20	0.03	-0.03	0.03	0.7249
49	100	30	1500	0.5	80	60	20	0.03	-0.03	0.1	3.599
50	100	30	1500	0.5	80	60	20	0.03	-0.03	0.3	14.89
51	100	30	1500	0.5	80	60	20	0.03	-0.03	1.0	59.67
52	100	30	1500	0.5	80	60	20	0.03	-0.03	2.0	116.5
53	100	30	1500	0.5	80	60	20	0.03	-0.03	3.0	168.9
54	100	30	1500	0.5	80	60	20	0.03	-0.03	5.0	282.1
55	100	30	1500	0.5	80	60	20	0.03	-0.03	8.0	534.5
56	100	30	1500	0.5	80	60	20	0.03	-0.03	10.0	846.4
57	100	30	1500	0.5	80	60	20	0.03	-0.03	12.0	1529.

Table G3 - Effect of Reid Vapor Pressure on Emissions Calculated From From Both the First and Second Edition of API Publication 2518

RVP (psi)	A (1) (-)	B (2) (^oR)	P_B (3) (psia)	P_{VA} (4) (psia)	E_1 (5) (lb/day)	E_2 (6) (lb/day)	$\left(\frac{E_1}{E_2}\right)$ (-)
0.001	19.50	15,660	0.00002705	0.00003607	0.1217	0.00759	16.03
0.003	18.44	14,320	0.0001223	0.0001591	0.3396	0.03312	10.25
0.01	17.27	12,860	0.0006232	0.0007893	1.0277	0.1664	6.176
0.03	16.21	11,520	0.002817	0.003481	2.867	0.7249	3.955
0.1	15.05	10,060	0.01450	0.01745	8.740	3.599	2.428
0.3	13.98	8,725	0.06428	0.07546	24.12	14.89	1.620
1.0	12.82	7,261	0.3335	0.3811	74.82	59.67	1.254
2.0	12.15	6,418	0.8587	0.9662	146.0	116.5	1.253
3.0	11.76	5,925	1.496	1.668	219.9	168.9	1.302
5.0	11.26	5,304	2.983	3.289	381.3	282.1	1.352
8.0	10.81	4,732	5.694	6.212	707.9	534.5	1.324
10.0	10.59	4,461	7.682	8.339	1028.	846.4	1.215
12.0	10.42	4,239	9.919	10.723	1589.	1529.	1.039

Notes:
(1) Calculated from: $A = 12.82 - 0.9672 \ln(RVP)$.
(2) Calculated from: $B = 7261 - 1216 \ln(RVP)$.
(3) Calculated from: $P_B = \exp[A - (B/T_B)$, where $T_B = 521.69^oR$ (62.00^oF).
(4) Calculated from: $P_{VA} = \exp[A - (B/T_{LA})]$, where $T_{LA} = 526.74$ (67.05^oF).
(5) Calculated from API Publication 2518, First Edition [A6] for the Base Case Conditions listed in Table G1 and for the RVP listed in this table.
(6) Calculated from API Publication 2518, Second Edition [A7] for the Base Case Conditions listed in Table G1 and for the RVP listed in this table.

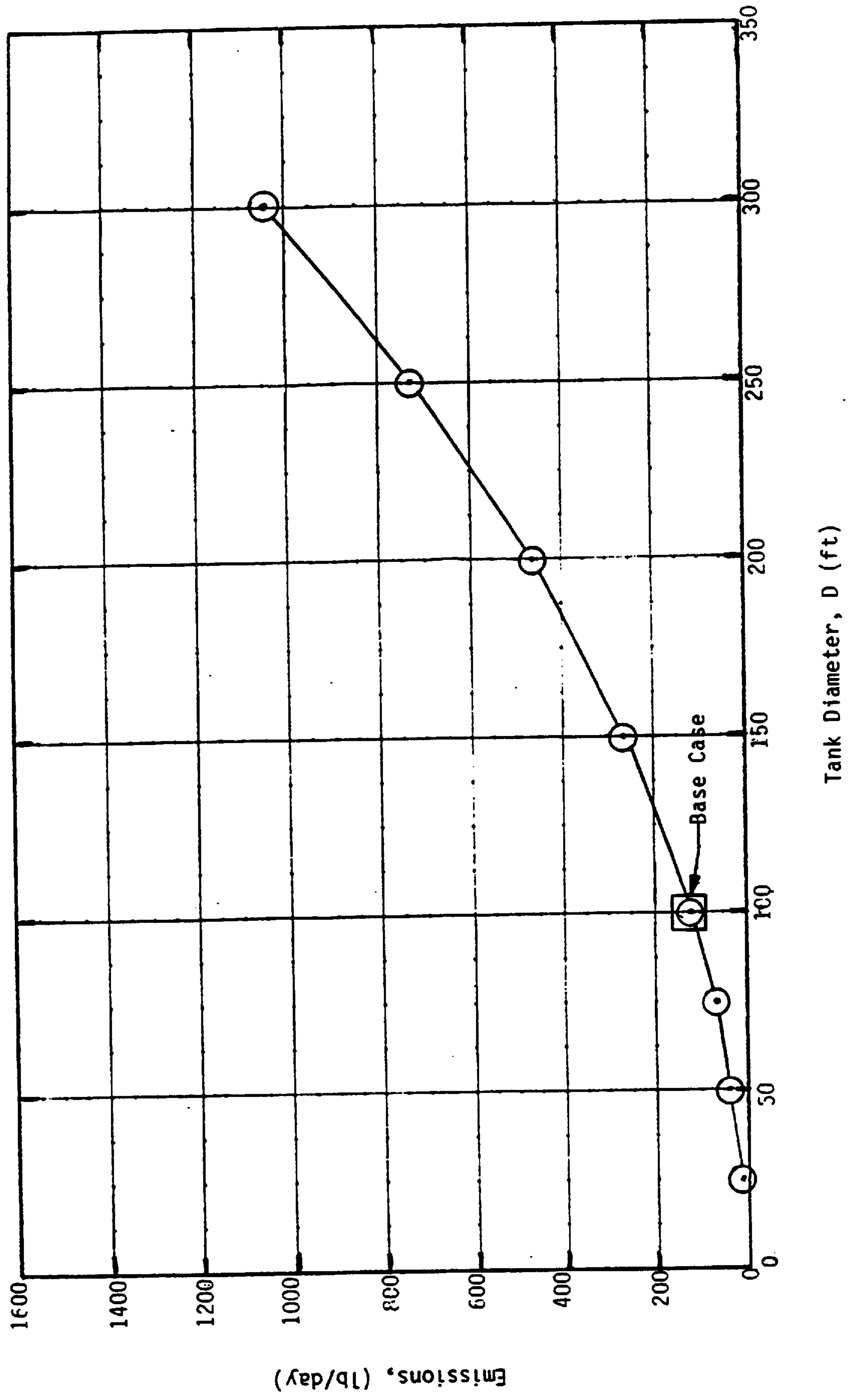

Figure G1 - Effect of Tank Diameter, D, on Emissions

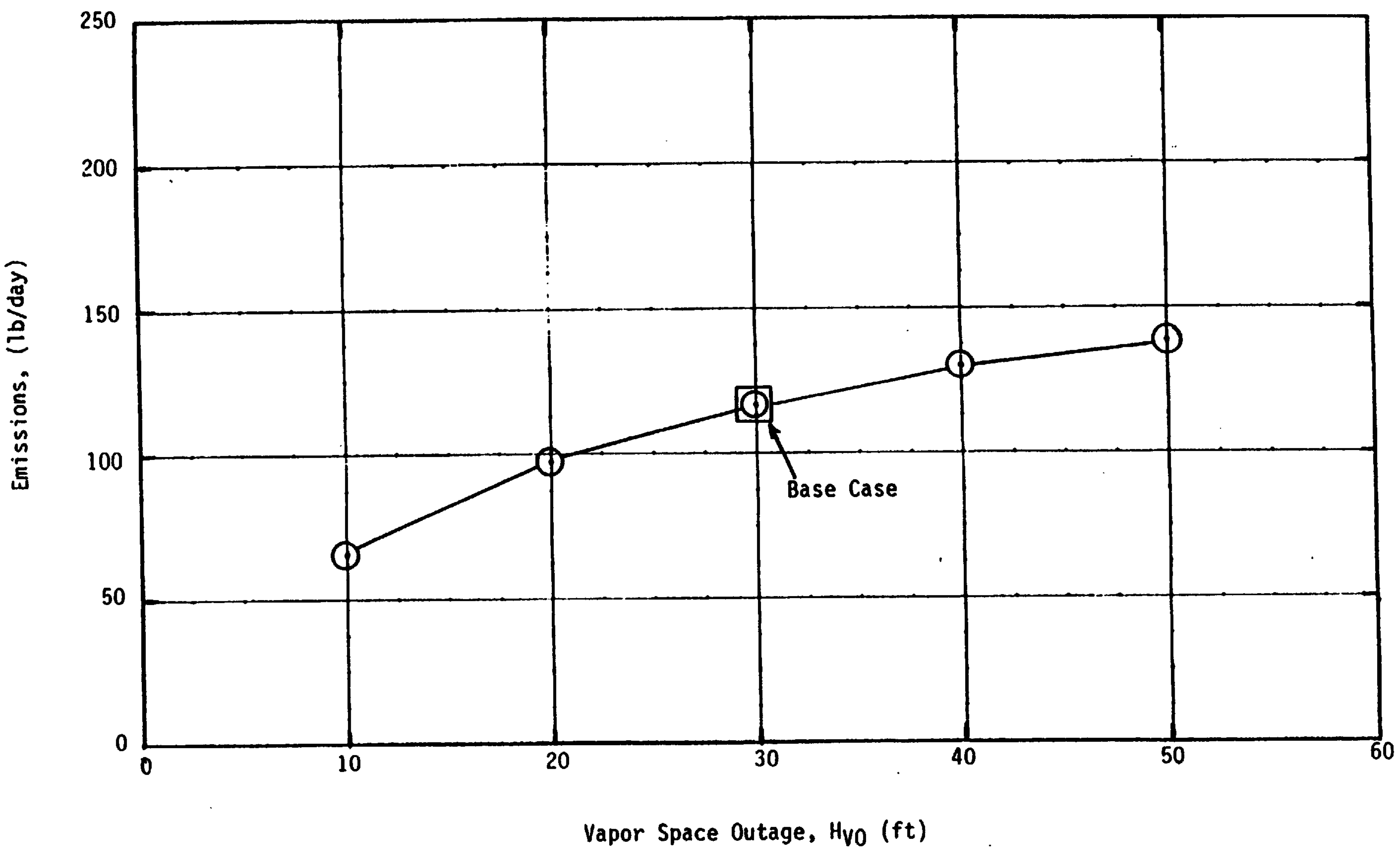

Figure G2 - Effect of Vapor Space Outage, H_{VO}, on Emissions

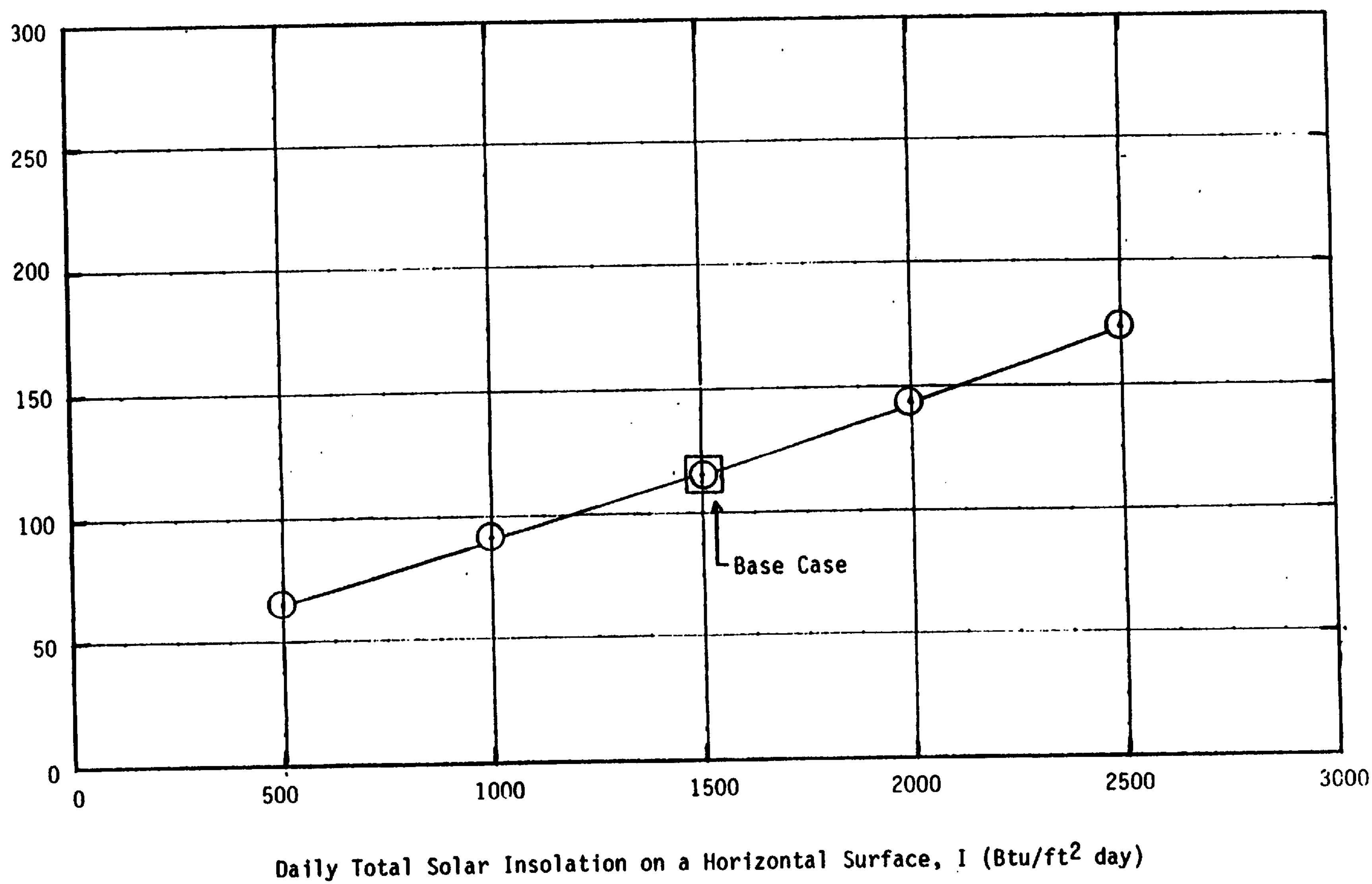

Figure G3 - Effect of Daily Total Solar Insolation on a Horizontal Surface, I, on Emissions

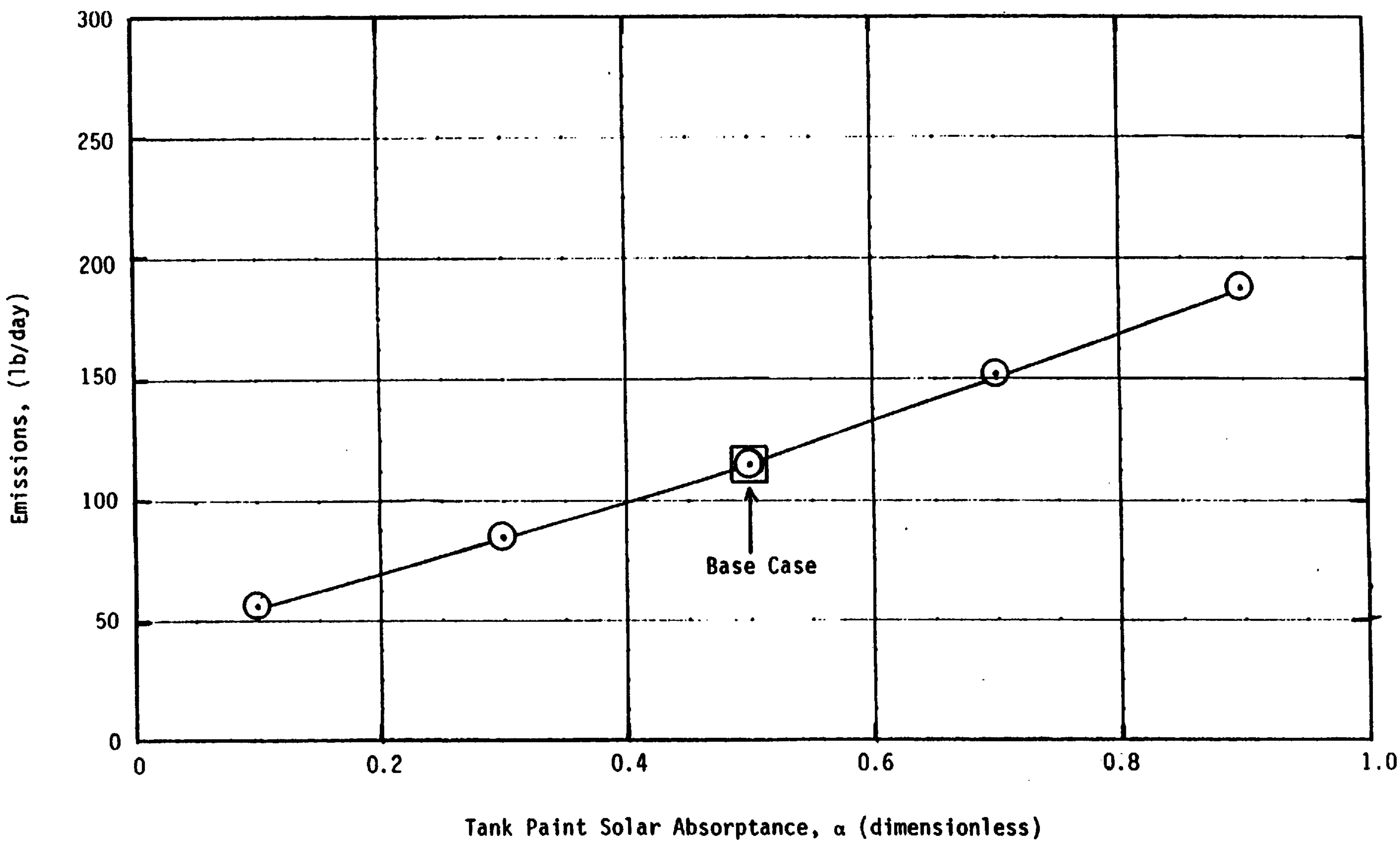

Figure G4 - Effect of Tank Paint Solar Absorptance, α, on Emissions

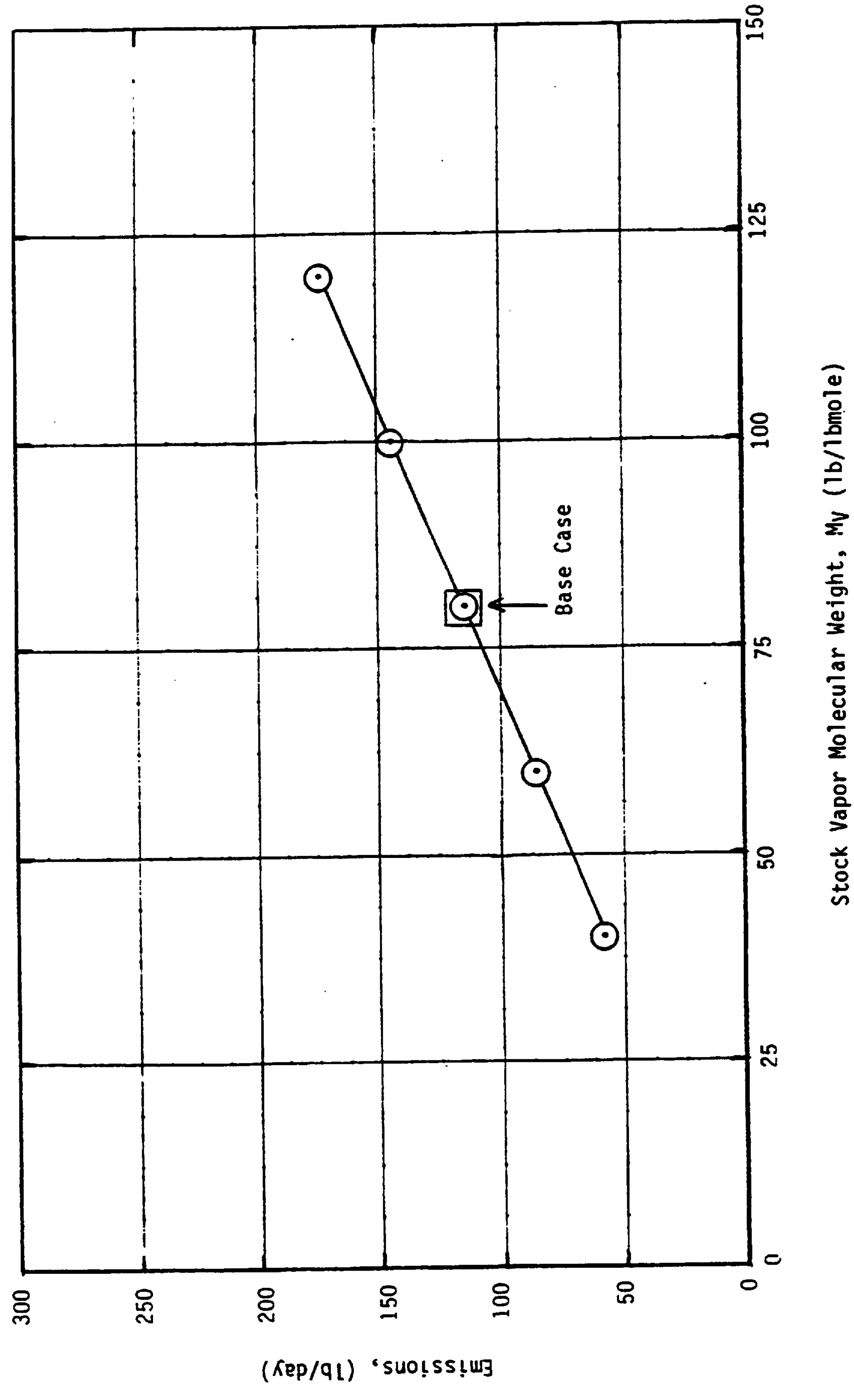

Figure G5 - Effect of Stock Vapor Molecular Weight, M_V, on Emissions

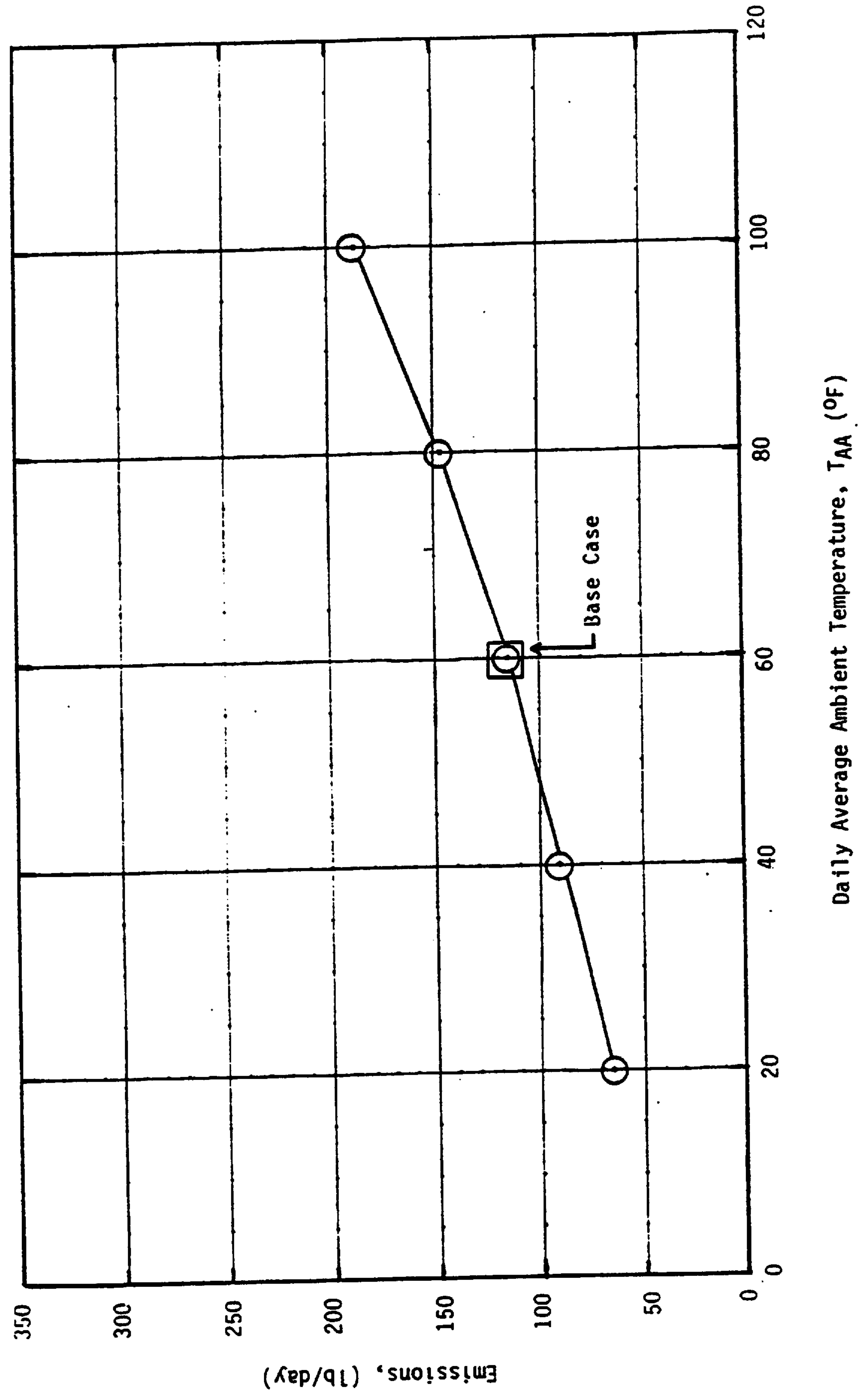

Figure G6 - Effect of Daily Average Ambient Temperature, T_{AA}, on Emissions

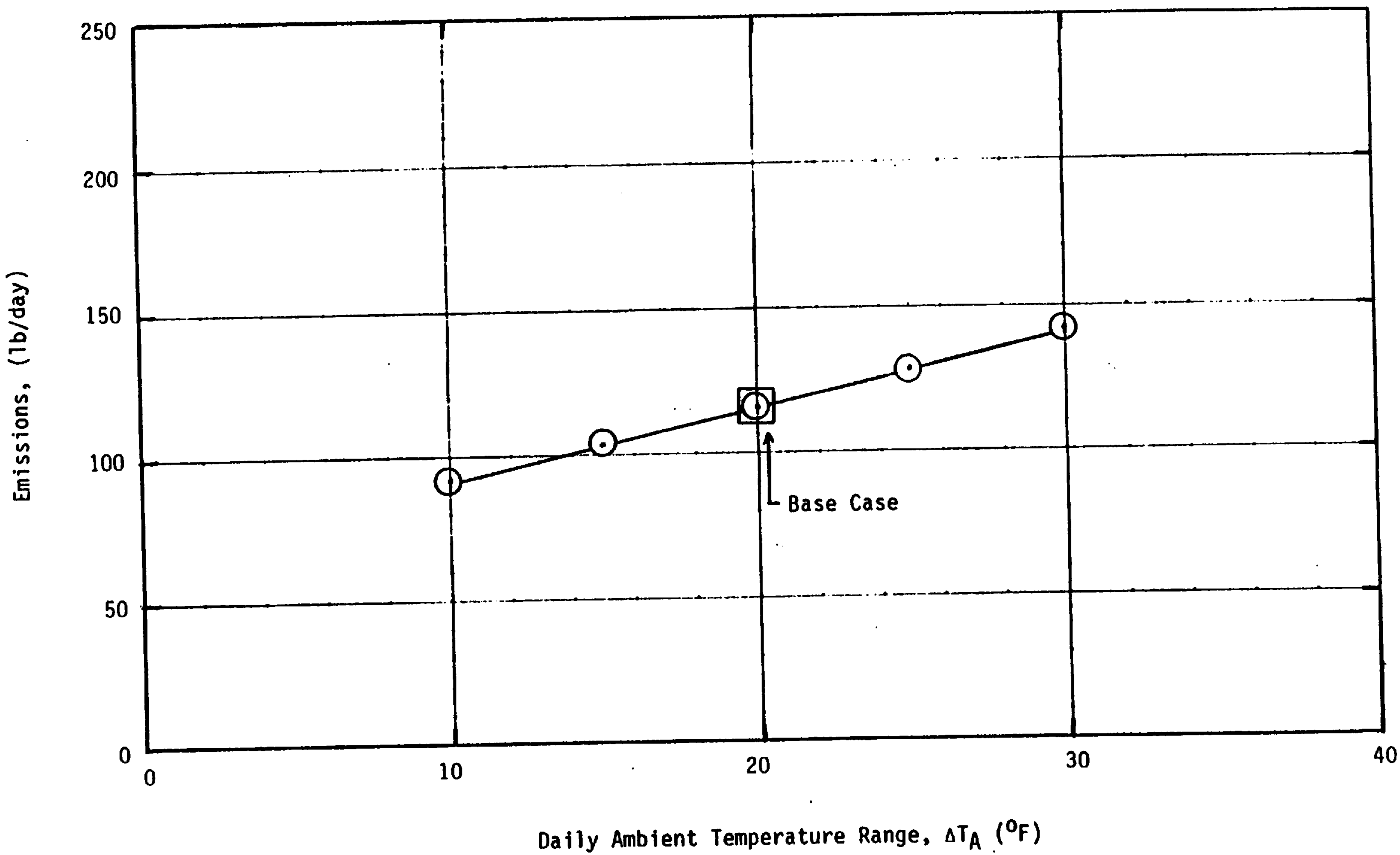

Figure G7 - Effect of Daily Ambient Temperature Range, ΔT_A, on Emissions

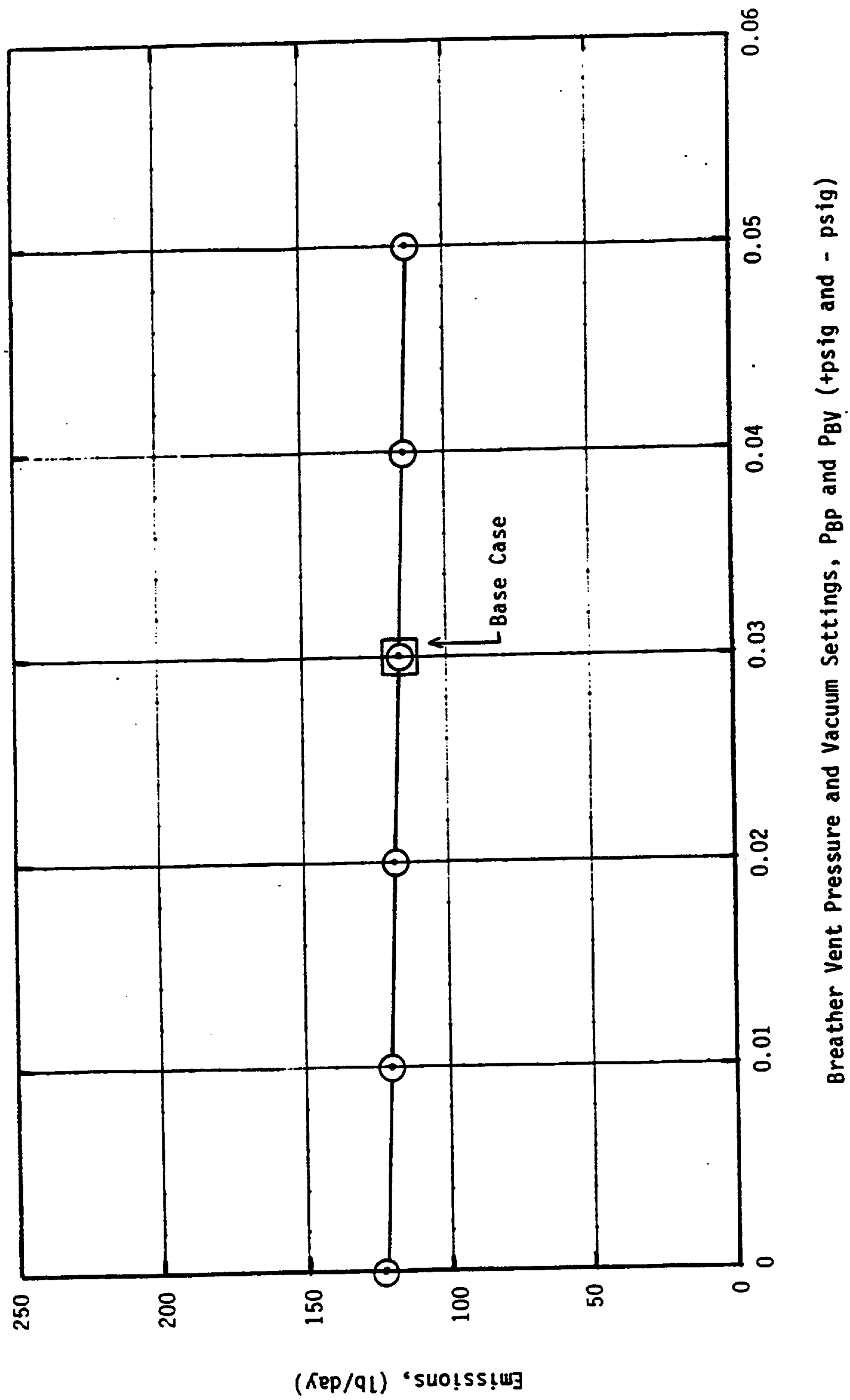

Figure G8 - Effect of Breather Vent Pressure and Vacuum Settings, P_{BP} and P_{BV}, on Emissions

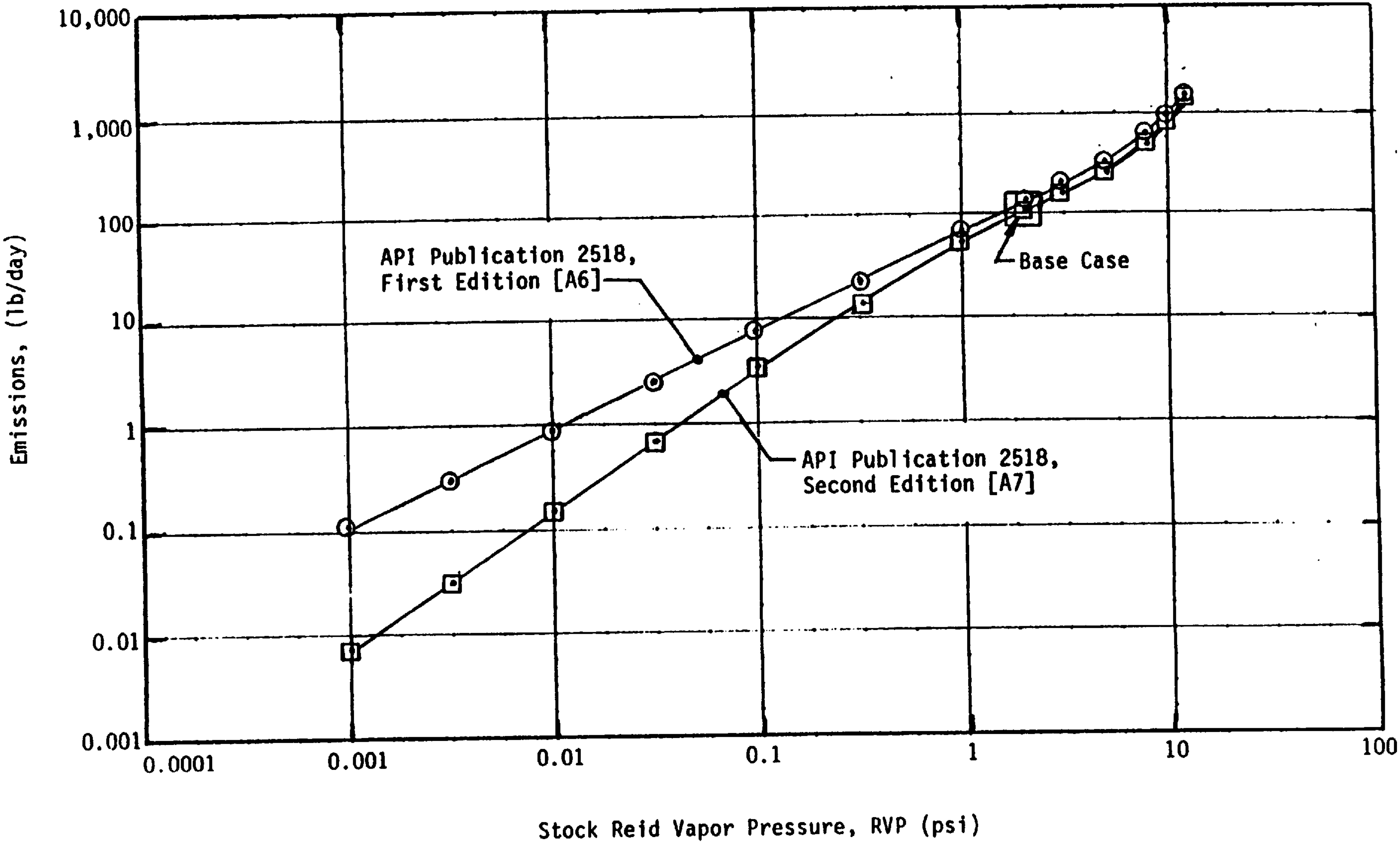

Figure G9 - Effect of Stock Reid Vapor Pressure, RVP, on Emissions

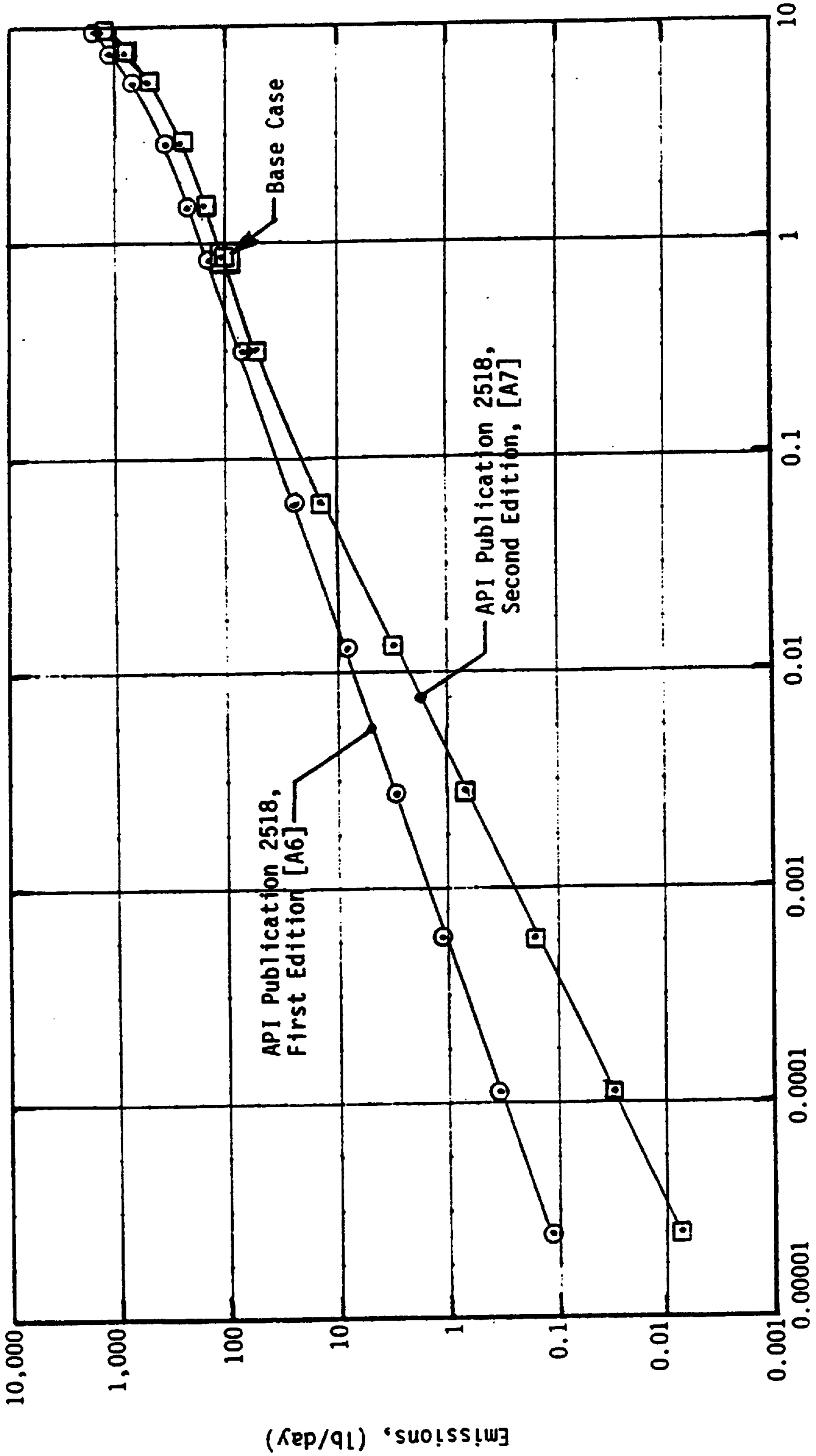

Figure G10 - Effect of Stock Vapor Pressure, P_{VA}, on Emissions

API PUBLICATION 2518
DOCUMENTATION FILE

SECTION H

COMPARISON OF STANDING STORAGE LOSS EQUATION WITH TEST DATA

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NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
A	Constant in the vapor pressure equation	dimensionless
B	Constant in the vapor pressure equation	^oR
D	Tank diameter	ft
H_{VO}	Vapor space outage	ft
I	Daily total solar insolation on a horizontal surface	Btu/ft^2 day
K_E	Vapor space expansion factor	dimensionless
L_S	Daily standing storage loss	lb/day
M_V	Stock vapor molecular weight	lb/lbmole
P_A	Atmospheric pressure	psia
P_{BP}	Breather vent pressure setting (always a positive value)	psig
P_{BV}	Breather vent vacuum setting (always a negative value)	psig
Q	Vented gas volume outflow	ft^3/day
T_{AX}	Daily maximum ambient temperature	^oR
T_{AN}	Daily minimum ambient temperature	^oR
T_B	Stock liquid bulk temperature	^oR
ΔT_V	Daily vapor temperature range	^oR
V_V	Tank vapor space volume	ft^3
α	Tank point solar absorptance	dimensionless

H1.0 INTRODUCTION

This section of the Documentation File to API Publication 2518, Second Edition [A7]* contains a comparison of the standing storage loss equation with the API test data [38], EPA test data [20] and WOGA test data [17].

H2.0 COMPARISON WITH THE API TEST DATA [38]

Table H1 summarizes the input information from Tests API-1 through API-10 which was used to calculate the standing storage loss. This table also compares the measured and calculated results.

All of the 10 API tests [38] continued sufficient information to make a comparison between the measured and calculated results for ΔT_V, Q and L_S.

Table H1 summarizes a comparison between the measured and calculated vapor space temperature range, ΔT_V. The average difference is -17.5%. Figure H1 illustrates this comparison graphically.

Table H1 summarizes a comparison between the measured and calculated vented gas volume outlfow, Q, which was calculated from $Q = V_V K_E$. The average difference is -11.3%. Figure H2 illustrates this comparison graphically.

Table H1 summarizes a comparison between the measured and calculated daily standing storage loss, L_S. The average difference is -14.3%. Figure H3 illustrates this comparison graphically.

In general, the comparison between the API test data and the predictions made by the standing storage loss equation are excellent.

* Numbers in brackets refer to the numbered references listed at the end of this Documentation File.

H3.0 COMPARISON WITH THE EPA TEST DATA [20]

Table H2 summarizes the input information from the EPA tests which was used to calculate the standing storage loss. This table also compares the measured and calculated results.

Only 12 of the 15 EPA tests [20] were suitable for making a comparison between the measured and calculated results for ΔT_V, Q and L_S.

Table H1 summarizes a comparison between the measured and calculated vapor space temperature range, ΔT_V. The average difference is 10.7%. Figure H4 illustrates this comparison graphically.

Table H1 summarizes a comparison between the measured and calculated vented gas volume outflow, Q. The average difference is 77.3%. Figure H5 illustrates this comparison graphically.

Table H1 summarizes a comparison between the measured and calculated daily standing storage loss, L_S. The average difference is 111.3%. Figure H6 illustrates this comparison graphically.

In general, the thermal response of the tank vapor space is predicted quite well, thus indicating that the heat transfer aspects of the standing storage loss model compare well with actual measurements.

H4.0 COMPARISON WITH THE WOGA TEST DATA [17]

Table H3 summarizes the input information from the WOGA tests which was used to calculate the standing storage loss. This table also compares the measured and calculated results.

During the WOGA tests, measurements were not made of the vapor space temperature, T_V. Thus, it is not possible to compare the predicted values with the measured values for this variable.

Only 8 of the 44 WOGA tests [17] were suitable for making a comparison between the measured and calculated results for Q and L_S.

Table H3 summarizes a comparison between the measured and calculated vented gas volume outflow, Q. The average difference is 79.3%. Figure H7 illustrates this comparison graphically.

Table H3 summarizes a comparison between the measured and calculated daily standing storage loss, L_S. The average difference is 28.1%. Figure H8 illustrates this comparison graphically.

In general, the comparison between the measured and calculated vented gas volume outflow, Q, for the WOGA tests is about as good as that for the EPA tests. Again, this illustrates that the standing-storage loss model incorporates a good charaterization of the tank vapor space thermal response.

H5.0 CONCLUSIONS

The comparison with the API test data [38], EPA test data [20] and WOGA test data [17] validated the suitability of the standing storage loss equation.

The API tests provided a more accurate and extensive set of test data for comparison with the API standing storage loss equation. The average difference between the calculated and measured standing storage loss is 14.3%.

The EPA and WOGA test data, although of lesser suitability for an accurate validation, also confirmed the suitability of the standing storage loss equation. The average difference between the calculated and measured standing storage loss is 111.3% for the EPA tests and 28.1 for the WOGA tests.

Table H1 - Summary of Calculated and Measured Variables for the API Tests [38]

VARIABLE	UNITS	API-1	API-2	API-3	API-4	API-5	API-6	API-7	API-8	API-9	API-10	AVERAGE
Reference:												
Test Date	---	11-25-84	11-29-84	11-30-84	12-01-84	12-02-84	12-03-84	03-30-85	04-03-85	04-04-85	04-25-85	
Product Type	---	Fuel Oil No. 2	Fuel Oil No. 2	Fuel Oil No. 2	Fuel Oil, No. 2	Fuel Oil No. 2	Fuel Oil No. 2	Fuel Oil No. 2	Fuel Oil No. 2	Fuel Oil No. 2	Fuel Oil No. 2	
Calculation Input:												
D	ft.	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	
H_{VO}	ft.	8.85	8.85	8.85	8.85	8.85	8.85	8.85	8.85	8.85	8.85	
α	---	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	
P_{BP}	in. H_2O	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	
P_{BV}	in. H_2O	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	
T_{AX}	^oF	53.0	62.0	64.4	64.1	62.0	52.7	67.0	80.3	69.2	69.1	
T_{AN}	^oF	39.8	46.0	40.3	41.2	39.5	44.4	46.3	49.7	46.7	54.5	
I	Btu/ft^2 day	1,028	1,142	1,072	1,095	981	448	2,136	2,021	1,818	2,047	
M_V	lb/lbmole	110	110	110	110	110	110	110	110	110	110	
A	---	14.348	14.348	14.348	14.348	14.348	14.348	9.260	9.260	9.260	9.260	
B	^oR	10,082	10,082	10,082	10,082	10,082	10,082	7,287.2	7,287.2	7,287.2	7,287.2	
T_B	^oR	52.8	52.7	53.2	53.8	53.8	53.7	55.0	66.1	65.9	65.5	
P_A	psia	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	
Calculation Output:												
ΔT_V	^oF	21.59	24.95	29.96	29.37	27.74	11.24	40.02	45.80	37.58	34.58	
Q	ft^3/day	110.6	127.9	155.2	151.8	143.3	54.35	207.1	233.8	192.0	175.4	
L_S	lb/day	0.0110	0.0145	0.0172	0.0171	0.0155	0.00531	0.0374	0.0530	0.0397	0.0382	
Measured:												
ΔT_V	^oF	29.1	32.8	39.4	38.7	33.0	17.3	42.1	44.0	43.5	39.1	
Q	ft^3/day	139	157	188	185	159	78	202	210	207	185	
L_S	lb/day	0.0152	0.0170	0.0216	0.0219	0.0179	0.0079	0.0334	0.0502	0.0478	0.0441	
Difference: (1)												
ΔT_V	%	-25.8	-23.9	-24.0	-24.1	-15.9	-35.0	- 4.9	4.1	-13.6	-11.6	-17.5
Q	%	-20.4	-18.5	-17.4	-17.9	- 9.9	-30.3	2.5	11.3	- 7.2	- 5.2	-11.3
L_S	%	-27.6	-14.7	-20.4	-21.9	-13.4	-32.8	12.0	5.6	-16.9	-13.2	-14.3

Notes: (1) Difference = [(Calculated - Measured) x 100]/Measured, (%)

Table H2 - Summary of Calculated and Measured Variables for the EPA Tests [20]

VARIABLE	UNITS	EPA-1A	EPA-1B	EPA-2A	EPA-2B	EPA-2C	EPA-3A	EPA-3B	EPA-5A	EPA-5B	EPA-6A	EPA-6B	EPA-6C	AVERAGE
Reference:														
Test Date	---	04-13-78	04-14-78	04-18-78	04-19-78	04-20-78	04-20-78	04-21-78	05-09-78	05-10-78	05-16-78	05-17-78	05-18-78	
Product Type	---	Iso-propanol	Iso-propanol	Ethanol	Ethanol	Ethanol	Glacial Acetic Acid	Glacial Acetic Acid	Ethyl Benzene	Ethyl Benzene	Cyclo-hexane	Cyclo-hexane	Cyclo-hexane	
Calculation Input:														
D	ft.	54.0	54.0	70.0	70.0	70.0	120.0	120.0	95.0	95.0	73.0	73.0	73.0	
H_{VO}	ft.	27.1	27.1	11.4	11.4	11.4	26.7	26.7	11.9	11.9	17.8	17.8	17.8	
α	---	0.17	0.17	0.17	0.17	0.17	0.54	0.54	0.17	0.17	0.17	0.17	0.17	
P_{BP}	in. H_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.25	0.25	0.25	
P_{BV}	in. H_2O	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.50	-0.50	-0.25	-0.25	-0.25	
T_{AX}	^oF	72.0	73.0	85.0	83.0	71.0	67.0	71.0	88.0	83.0	89.0	84.0	87.0	
T_{AN}	^oF	57.0	60.0	69.0	63.0	57.0	56.0	53.0	71.0	61.0	74.0	74.0	75.0	
I	Btu/ft^2 day	2,470	2,290	1,700	2,320	1,730	1,730	2,400	2,140	2,540	1,730	2,510	2,160(1)	
M_V	lb/lbmole	60.10	60.10	46.02	46.02	46.02	60.05	60.05	106.11	106.11	84.16	84.16	84.16	
A	---	16.7687	16.7687	16.3801	16.3801	16.3801	14.8028	14.8028	14.0362	14.0362	13.6969	13.6969	13.6969	
B	^oR	9113.6	9113.6	8760.7	8760.7	8760.7	8591.1	8591.1	8423.3	8423.3	7091.7	7091.7	7091.7	
T_B	^oF	70.0	70.0	70.3	71.4	70.4	69.9	69.8	81.7	80.0	79.0	78.7	78.7	
P_A	psia	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	
Calculation Output:														
ΔT_V	^oF	22.56	20.26	19.61	25.44	18.31	34.08	49.25	22.43	27.93	19.03	19.15	18.92	
Q	ft^3/day	3,717	3,354	2,583	3,343	2,290	22,230	32,370	3,702	4,645	4,979	4,997	4,949	
L_S	lb/day	13.35	12.15	12.99	16.73	10.42	45.64	70.50	13.56	15.59	48.64	48.64	48.41	
Measured:														
ΔT_V	^oF	NA	NA	35.0	31.0	28.0	30.0	39.0	17.0	24.0	NA	13.0	12.0	
Q	Δ	3,824	4,248	1,313	790	1,435	9.508	18,934	2,526	3,740	2,965	3,094	2,980	
L_S	lb/day	15.0	17.2	5.91	3.41	5.15	21.2	45.3	11.4	14.4	20.0	17.0	14.4	
Difference: (2)														
ΔT_V	%	---	---	-44.0	-17.9	-34.6	13.6	26.3	31.9	16.4	---	47.3	57.7	10.7
Q	%	-2.8	-21.0	96.7	323.2	59.6	133.8	71.0	46.6	24.2	67.9	61.5	66.4	77.3
L_S	%	-11.0	-29.4	119.8	390.6	102.3	115.3	55.6	18.9	8.3	142.7	186.1	236.2	111.3

Notes: (1) Assumed value. Based on the average of the I values for the other EPA tests.

(2) Difference = [(Calculated - Measured) x 100]/Calculated, (%).

Table H3 - Summary of Calculated and Measured Input Variables for the WOGA Tests [17]

VARIABLE	UNITS	WOGA-7B	WOGA-8A	WOGA-13A	WOGA-13B	WOGA-16A	WOGA-16B	WOGA-17A	WOGA-17B	AVERAGE
Reference:										
Test Date	---	02-19-77	05-13-77	05-10-77	05-11-77	02-11-77	02-12-77	05-18-77	05-19-77	
Product Type	---	Crude	Crude	Crude	Crude	Crude	Crude	Crude	Crude	
Calculation Input:										
D	ft.	120.0	120.0	120.0	120.0	175.8	175.8	175.8	175.8	
H_{VO}	ft.	39.6	37.3	35.8	35.8	2.3	2.3	6.9	6.9	
α	---	0.68	0.68	0.17	0.17	0.36	0.36	0.36	0.36	
P_{BP}	in. H_2O	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	
P_{BV}	in. H_2O	-0.86	-0.86	-0.86	-0.86	-0.86	-0.86	-0.86	-0.86	
T_{AX}	°F	79	72	69	67	90	91	75	79	
T_{AN}	°F	53	52	54	54	47	49	56	58	
I	Btu/ft^{2}day	933	1,780	1,400	1,610	1,020	984	2,050	1,850	
M_V	lb/lbmole	69.0	66.7	63.9	64.4	63.9	63.9	52.4	52.4	
A	---	11.64	12.64	13.49	13.49	11.23	11.23	11.17	11.17	
B	°R	5773	7039	8104	8104	5257	5257	5189	5189	
T_B	°F	56	65	92	83	56	56	65	65	
P_A	psia	14.696	14.696	14.696	14.696	14.696	14.696	14.696	14.696	
Calculation Output:										
ΔT_V	°F	36.48	48.29	17.46	17.02	41.24	40.16	34.34	33.77	
Q	ft^3/day	54,540	46,580	12,850	12,430	10,530	10,320	29,900	29,680	
L_S	lb/day	254.6	145.2	22.0	19.5	282.7	278.7	448.0	446.6	
Measured:										
ΔT_V	°F	NA	NA	NA	NA	NA	NA	NA	NA	
Q	ft^3/day	29,200	14,930	18,300	18,320	4,029	5,857	17,058	16,059	
L_S	lb/day	148	80.3	129	143	98.7	143	578	544	
Difference: (1)										
ΔT_V	%	---	---	---	---	---	---	---	---	---
Q	%	86.8	212.0	-29.8	-32.2	161.4	76.0	75.3	84.8	79.3
L_S	%	72.0	80.8	-82.9	-86.4	186.4	94.9	-22.5	-17.9	28.1

Notes: (1) Difference = [(Calculated - Measured) x 100]/Measured, (%).

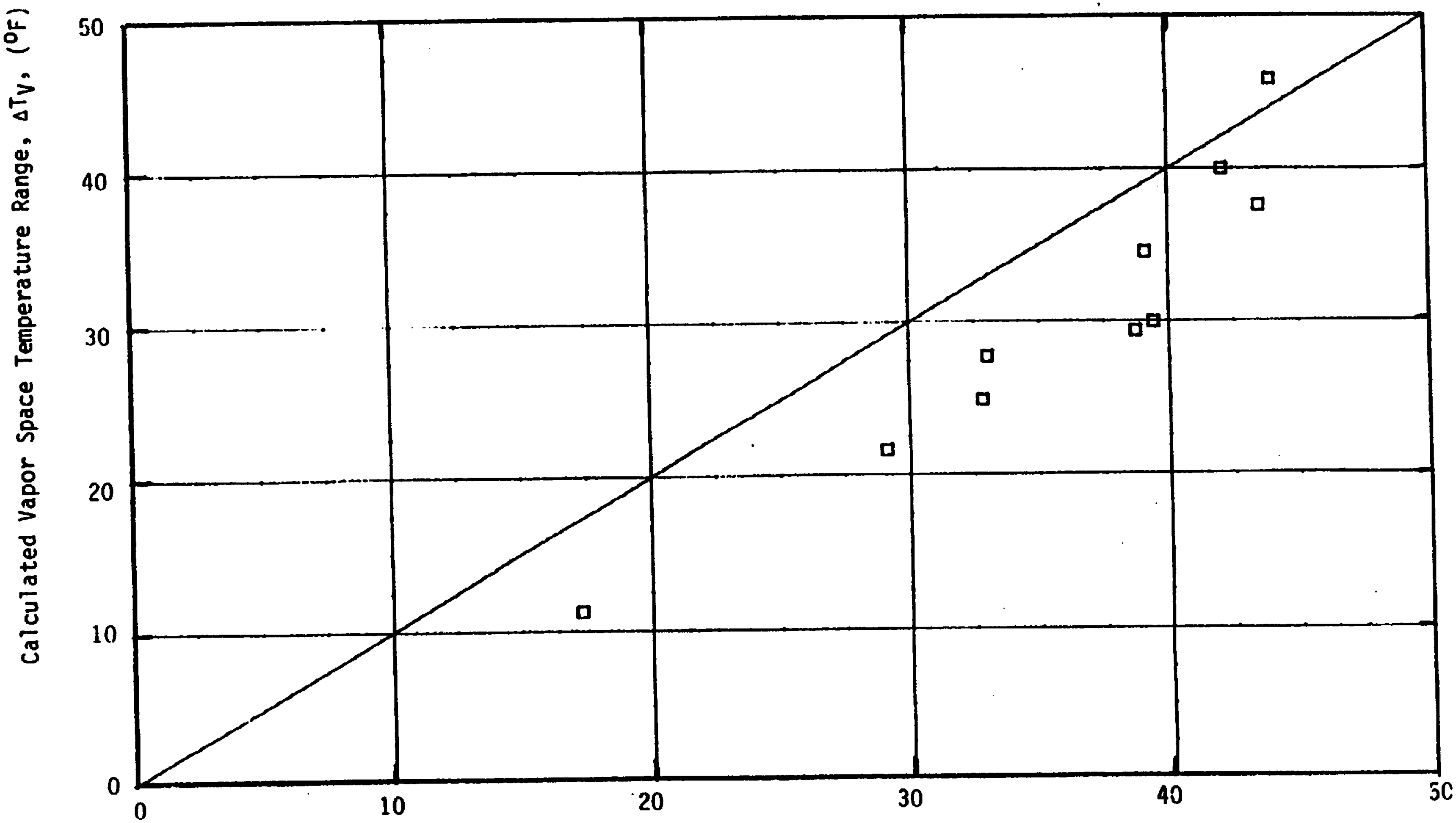

Figure H1 - Calculated Versus Measured Vapor Space Temperature Range, ΔT_V, for the API Tests [38]

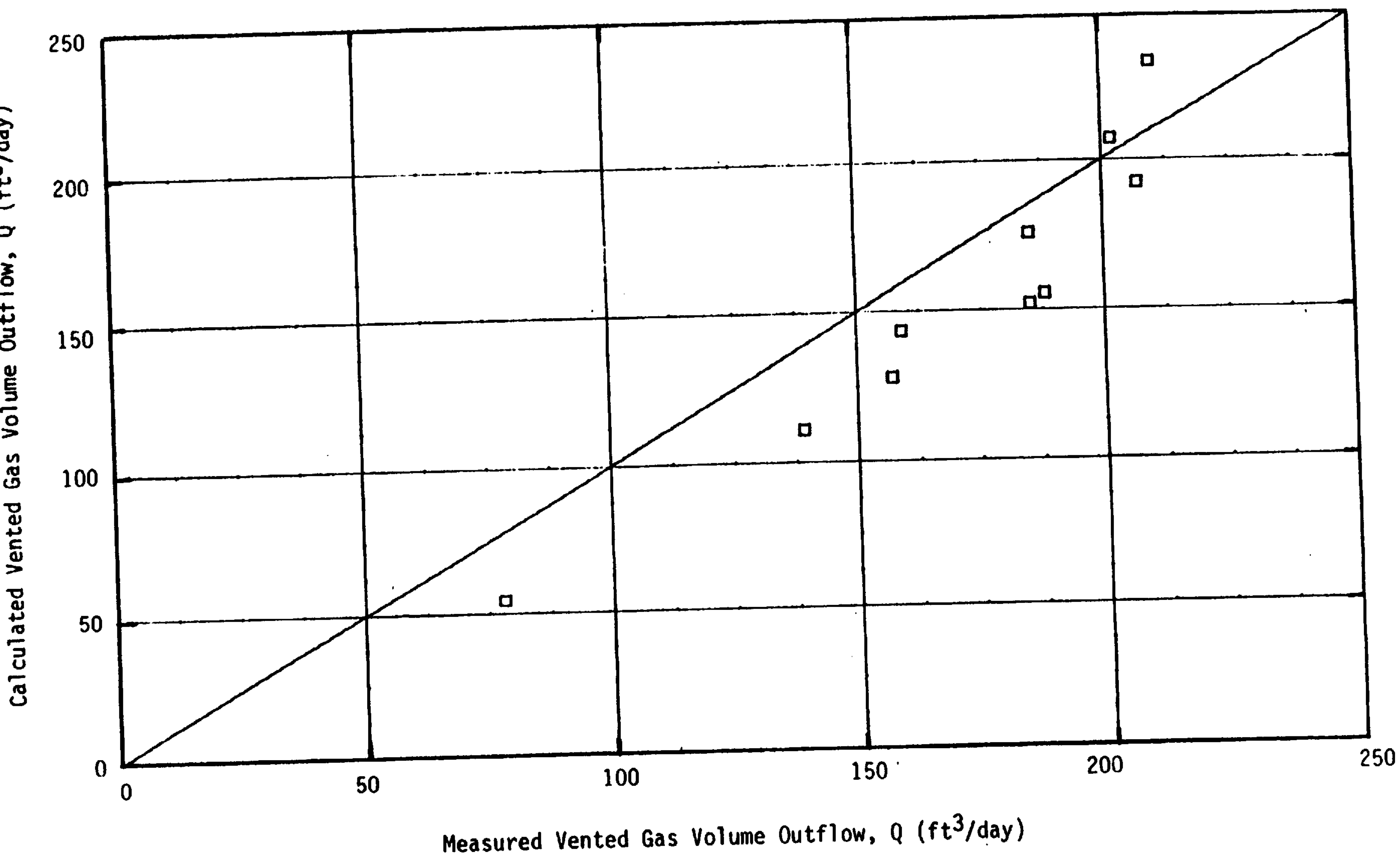

Figure H2 - Calculated Versus Measured Vented Gas Volume Outflow, Q, for the API Tests [38]

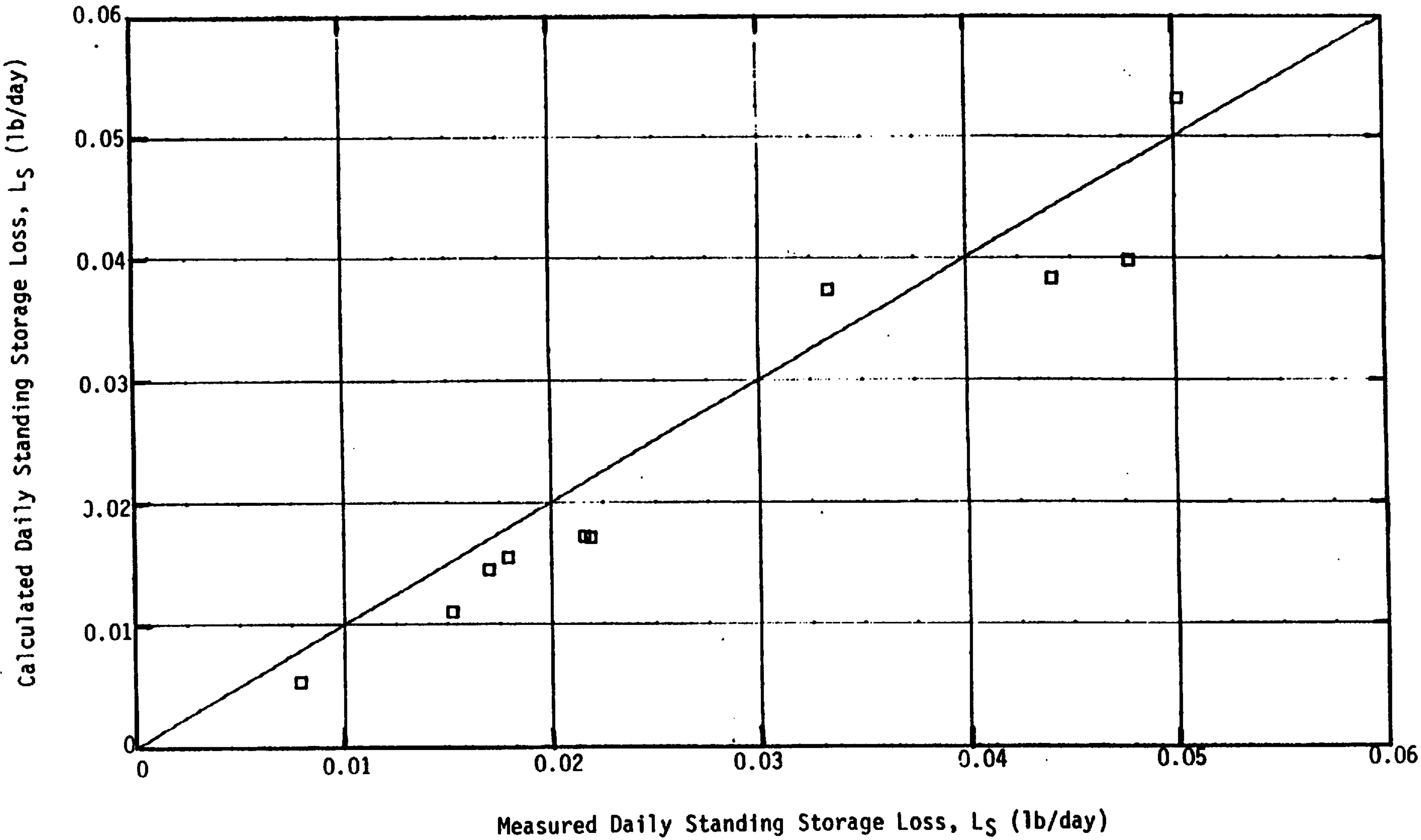

Figure H3 - Calculated Versus Measured Daily Standing Storage Loss, L_S, For The API Tests [38]

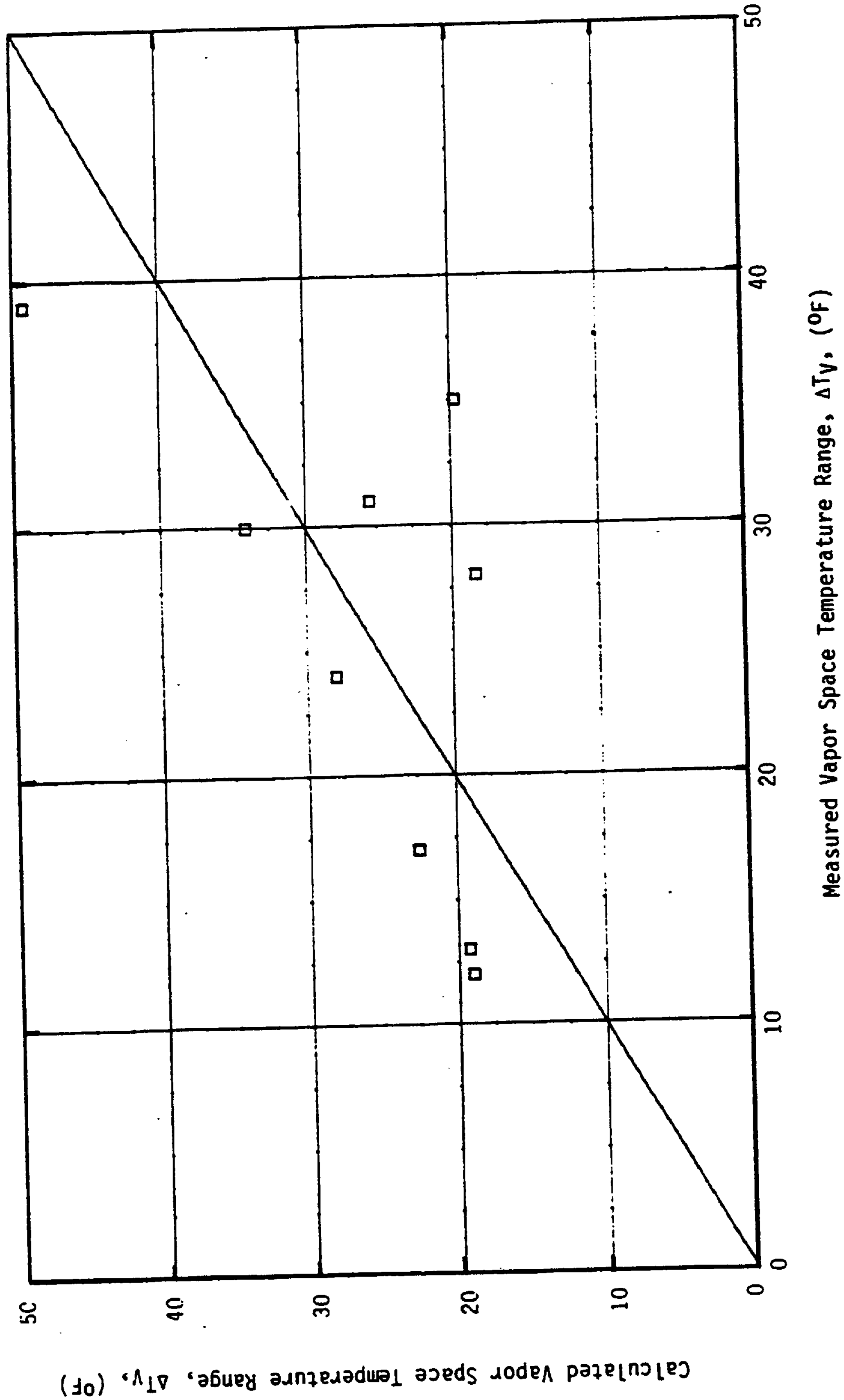

Figure H4 - Calculated Versus Measured Vapor Space Temperature Range, ΔT_V, for the EPA Tests [20]

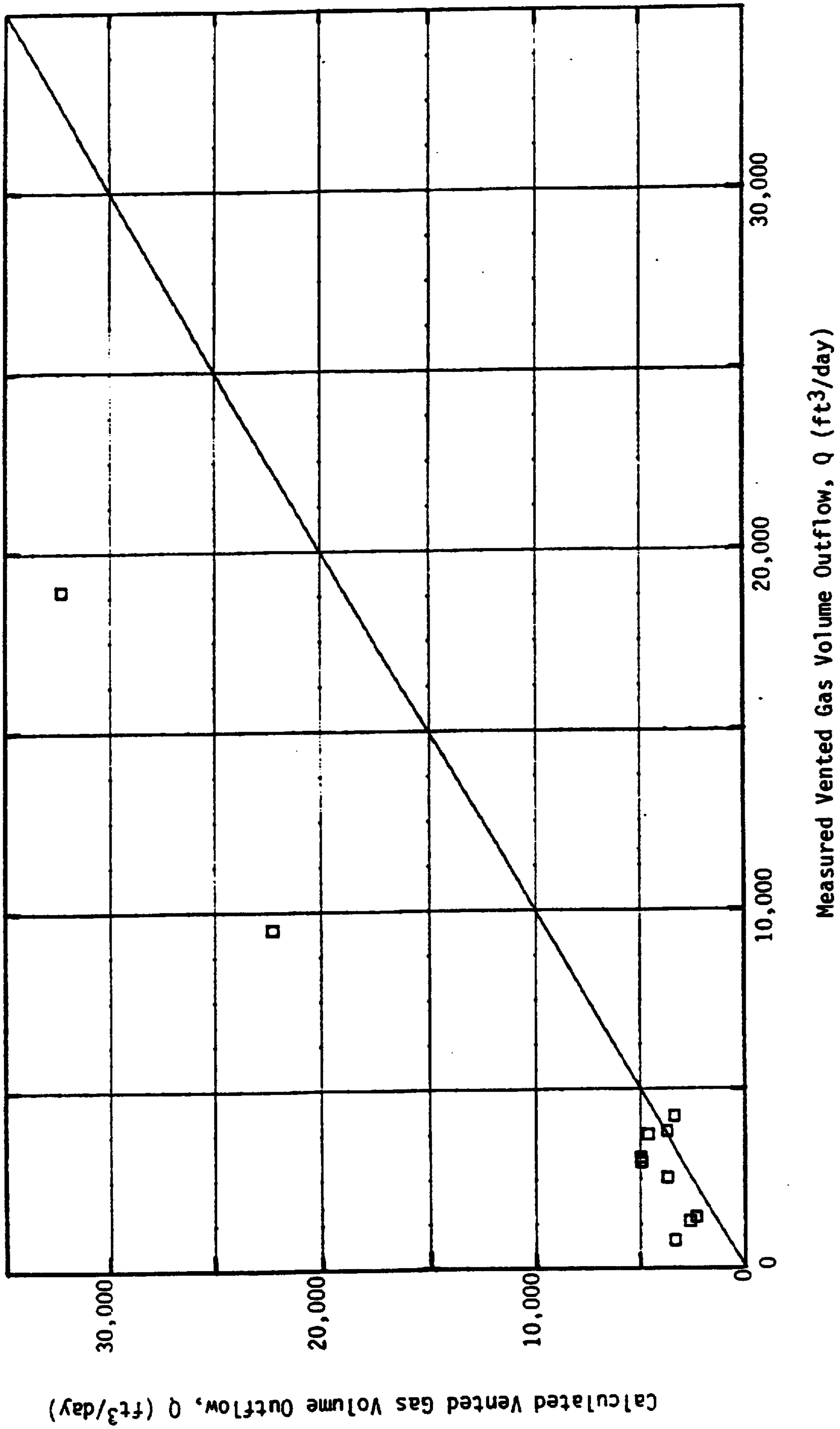

Figure H5 - Calculated Versus Measured Vented Gas Volume Outflow, Q, for the EPA Tests [20].

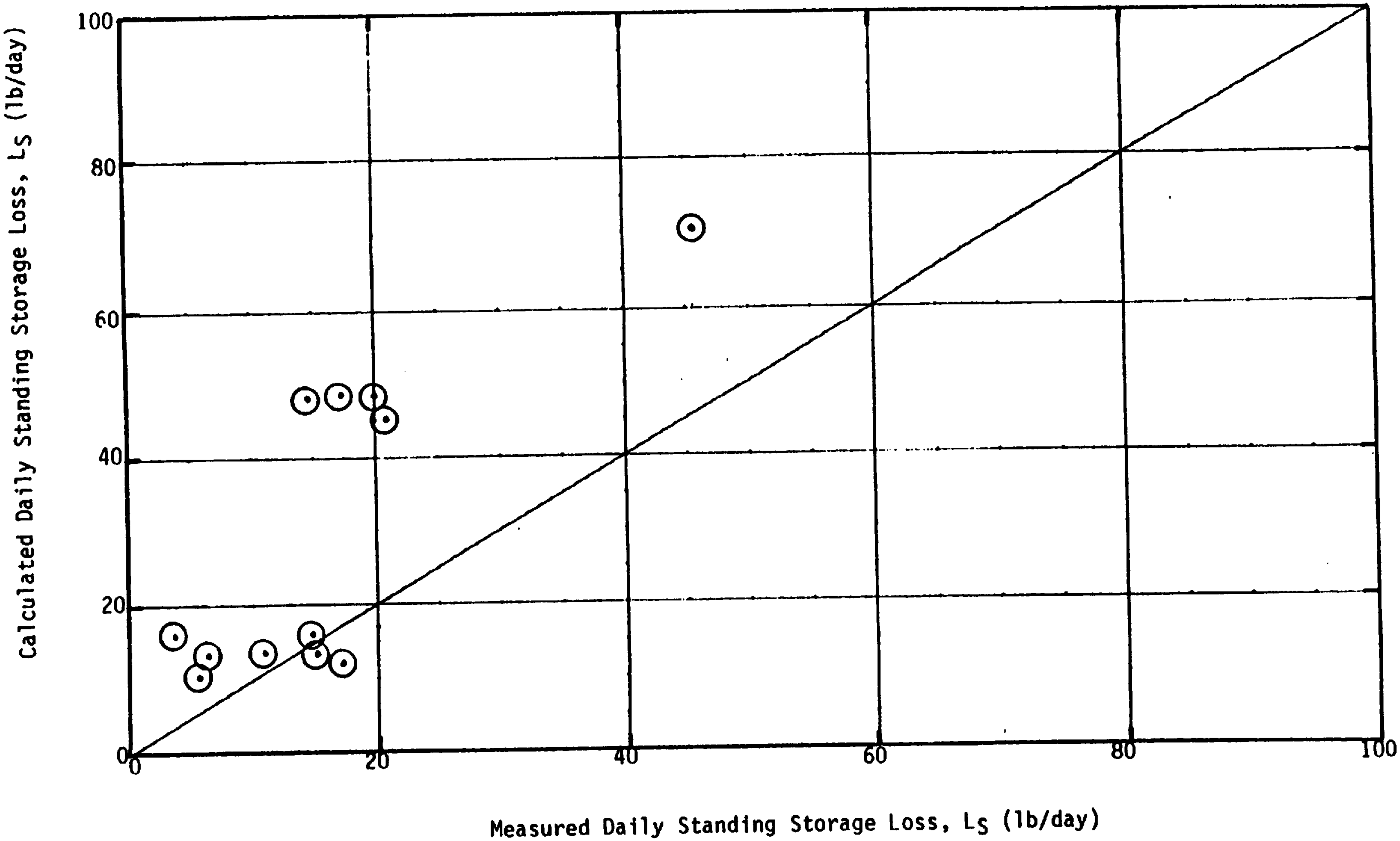

Figure H6 - Calculated Versus Measured Daily Standing Storage Loss, L_S, for the EPA Tests [20]

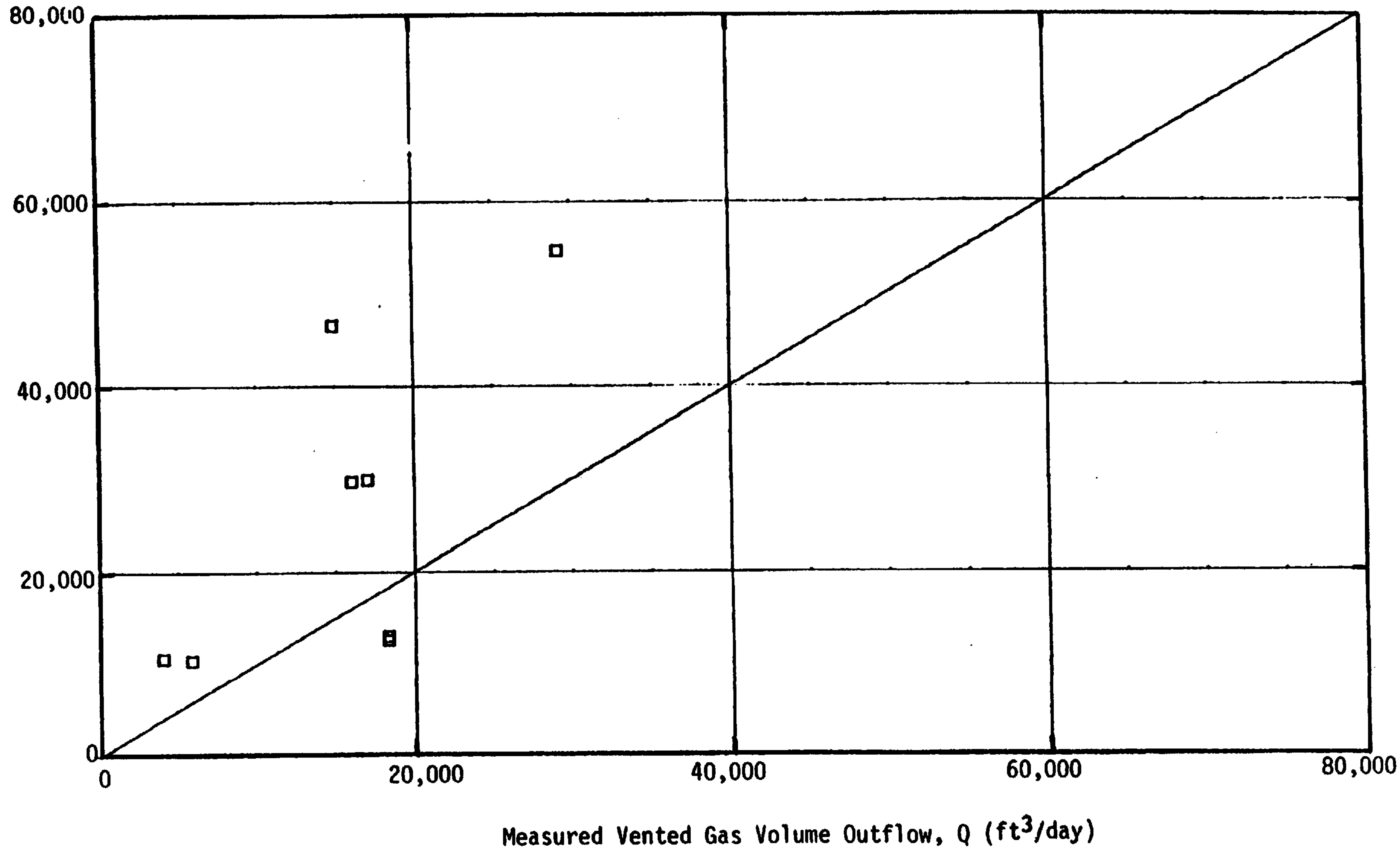

Figure H7 - Calculated Versus Measured Vented Gas Volume Outflow, Q, for the WOGA Tests [17]

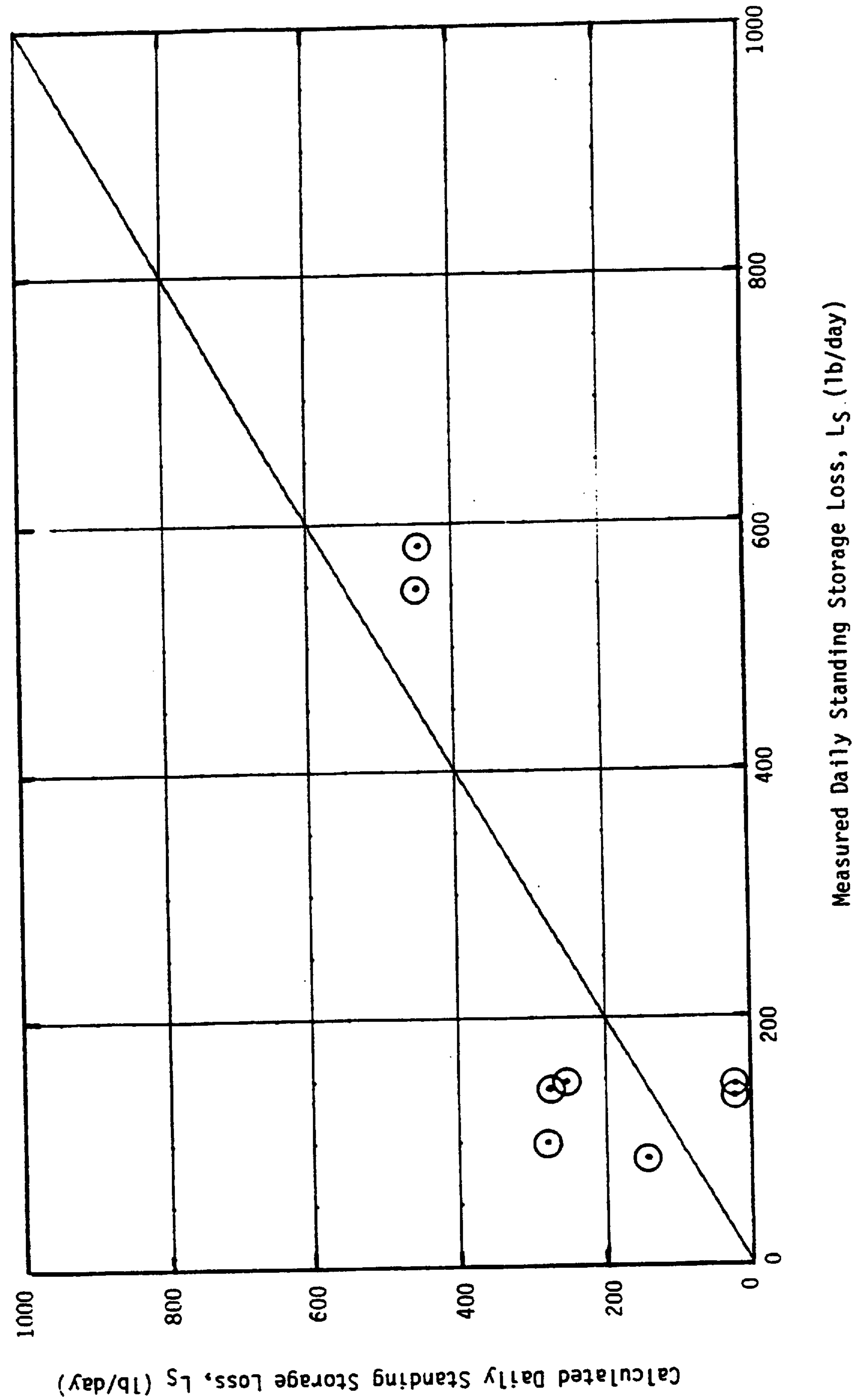

Figure H8 - Calculated Versus Measured Daily Standing Storage Loss, L_S, for the WOGA Tests [17]

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R1 INTRODUCTION

This section of the Documentation File to API Publication 2518, Second Edition, contains a list of the references that are cited in this Documentation File. In addition to those that are cited, the list also contains references that were reviewed as part of preparing the Second Edition to API Publication 2518.

Section R2 contains a list of API publications that relate to atmospheric storage tanks. These are arranged in numerical order according to their API publication number.

Section R3 contains a list of literature references. These are arranged in chronological order according to their publication date.

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