REFERENCES

Baldarano, J. M., Delgado, R. and Calbo, J. (1998). Applying receptor models to analyze urban/suburban VOCs air quality in Martorell (Spains). Environment Science Technology, 32(3), 405-412.

Beychok, M. R. (1983). Calculate tank losses easier. Hydrocarbon Processing. 62(3), 71-73

Crowl, D. A., and Louvar, J. F. (Eds.). (1990). Chemical process safety: fundamentals with applications. New Jersey: Prentice-Hall.

Department of Land Transport. (1998). Road transport statistics. Department of Land Transport Database, Bangkok, Thailand.

Department of Public and Municipal Works. (1999). Gas station in Bangkok information. Department of Public and Municipal Works Database, Bangkok, Thailand.

Emission Factor and Inventory Group. (1999a). Organic liquid storage tank. Ap 42 U.S. EPA Publication.

Emission Factor and Inventory Group. (1999b). Transportation and marketing of petroleum liquids. Ap 42 U.S. EPA Publication.

Faculty of Mechanical Engineering. (1995). Prediction of gasoline vaporization from depots and gas stations. Final Report. King Mongkut's Institute of Technology, Thonburi.

Geankoplis, C. J. (1993). Transport process and unit operations. 3rd ed. New Jersey: Prentice-Hall.

Lewis, R. J. and Sax, N. I. (Eds.). (1987). Hazardous chemical desk references. New York: Van Nostrand Reinhold.

Nevers, N. D. (1995). Air pollution control engineering. New York: McGraw-Hill.

Panich, S., Walsh, M. P. and Kishan, S. (1995). Vapor emission from gasoline transport, storage and refueling in Bangkok. Final Report. National Energy Policy Office.

Patnaik, P. (1992). A comprehensive guide to the hazard properties of chemical substances. New York: Van Nostrand Reinhold.

Perry, R. H. and Green, D. W. (1997). Perry's chemical engineers' handbook. 7th ed. New York: McGraw-Hill.

Quality Control Division. (1999). Gasoline properties. Petroleum Authority of Thailand.

Smith, J. M., Van Ness, H. C. and Abbott, M. M. (1996). Introduction to chemical engineering thermodynamics. 5th ed. Singapore: McGraw-Hill.

Thorpe, J. J. (1978). How much benzene causes cancer? Hydrocarbon Processing. 57(5), 172-174.

TI-3 Petroleum Committee of the Air Pollution Control Association. (1971). Control of atmospheric emissions from petroleum storage tanks. Journal of the Air Pollution Control Association. 21(5), 260-268.

APPENDICES

Appendix A : Determination of parameter in calculation

Determination of molecular weight of gasoline vapor

Molecular weight of gasoline vapor, M_V, can be calculated as follows

1) Molecular weight of gasoline vapor from U.S. EPA (1999a). Table A-1 shows properties of selected petroleum liquids.

Table A-1 Properties of selected petroleum liquids (U.S. EPA, 1999)

Petroleum liquid	**Vapor molecular weight at 60°F M_V (lb/lb-mole)**
Gasoline RVP 13	62
Gasoline RVP 10	66
Gasoline RVP 7	68
Gasoline RVP 5	50
Jet naphtha	80
Jet kerosene	130

2) Molecular weight of gasoline vapor from the Beychok's equation, (A-1).

$$M_V = 72.833-1.3183(RVP)+0.15079(RVP)^2-0.0087302(RVP)^3 \quad \text{(A-1)}$$

RVP = Reid vapor pressure, psi

Determination of liquid surface temperature

Daily average liquid surface temperature (T_{LA}) can be calculated as follows

$$T_{LA} = 0.44T_{AA} + 0.56T_B + 0.0079\alpha_A I \quad \text{(A-2)}$$

Daily temperature range (ΔT_V) can calculated as follows

$$\Delta T_V = 0.72\Delta T_A + 0.028\alpha_A I \quad \text{(A-3)}$$

where

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

ΔT_V = daily temperature range, R

T_{AA} = daily average ambient temperature, R

$$T_{AA} = \frac{(T_{AX} + T_{AN})}{2} \quad \text{(A-4)}$$

$$\Delta T_A = T_{AX} - T_{AN} \quad \text{(A-5)}$$

ΔT_A = daily ambient temperature range, R

T_{AX} = daily maximum ambient temperature, R

T_{AN} = daily minimum ambient temperature, R

T_B = liquid bulk temperature, R

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

α_A = tank paint solar absorbance, dimensionless

and I = daily total solar insolation factor, btu/ft^2.d

Determination of true vapor pressure

True vapor pressure of gasoline (P_{VA}) in this work was measured with a Setavap analyzer. Table A-2 shows true vapor pressure of gasoline at different temperatures.

Table A-2 True vapor pressure of gasoline at different temperatures

Temperature (°C)	Pressure (atm)			
	Data 1	Data 2	Data 3	Average
30	0.3099	0.2941	0.3069	0.3036
35	0.4283	0.4283	0.4204	0.4257
40	0.5004	0.4806	0.4579	0.4796

Appendix B : Determination of expansion coefficient and molar diffusivity

Determination of liquid expansion coefficient

Liquid expansion coefficient (α_L) can calculated as follows:

$$\alpha_L = 5\times10^{-6}T_{LA}^2 + 0.0013T_{LA} - 0.0102 \quad \text{(B-1)}$$

where

α_L = liquid expansion coefficient

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

Determination of vapor expansion coefficient

Vapor expansion coefficient (α_V) is calculated as follows:

$$\alpha_V = \frac{\Delta T_A}{T_{AN}} \quad \text{(B-2)}$$

where

α_V = vapor expansion coefficient

ΔT_A = daily ambient temperature range, K

T_{AN} = daily minimum ambient temperature, K

Determination of molar diffusivity

1) Molar diffusivity of gasoline determined by using a mathematical equation as follows

$$\frac{D_G}{D_W} = \sqrt{\frac{M_W}{M_G}} \tag{B-3}$$

where

D_G = molar diffusivity of gasoline to air, cm^2/s

D_W = molar diffusivity of water to air, cm^2/s

M_G = molecular weight of gasoline

M_W = molecular weight of water

Molecular diffusivity of water (D_{Water}) can be calculated from

$$D_W = \frac{0.1013 T_{LA}^{1.75}\left(\frac{1}{M_A} + \frac{1}{M_W}\right)^{0.5}}{P_A\left[\left(\sum v_A\right)^{1/3} + \left(\sum v_W\right)^{1/3}\right]^2} \tag{B-4}$$

where

M_A = molecular weight of air

T_{LA} = daily average liquid surface temperature, K

P_A = atmospheric pressure, Pa

Σv_A = group contribution value for air, 20.1

Σv_W = group contribution value for water, 12.7

Table B-1 Molar diffusivity of gasoline from calculation

T (°C)	M_{water}	M_{air}	Σv_{water}	Σv_{air}	Molar diffusivity (cm^2/s)	
					Water	Gasoline
30	18	29	12.7	20.1	0.2587	0.1339
35	18	29	12.7	20.1	0.2662	0.1378
40	18	29	12.7	20.1	0.2738	0.1417

2) Determination of molar diffusivity of gasoline from experimental results. Equation (2.25) was used to determine the molar diffusivity,

$$L_D = \frac{D_G A}{\Delta z} W_V \qquad (2.25)$$

From this equation, loss from diffusion, L_D, can be determined from experiment by starting with loading liquid gasoline until the storage was full and the liquid level exceeded the bottom of the release vent. Then, the same procedure as mentioned in experimental part was carried out. Vent height, Δz, was measured from the top to liquid level inside the release vent. Cross-sectional area of the release vent was 0.1963 cm^2 (vent diameter = 0.5 cm). Vapor density of gasoline can be determined by Equation (2.11). Table B-2 reports of gasoline molar diffusivity from the experiment.

Table B-2 Molar diffusivity of gasoline from experimental

Temperature (°C)	Area (cm^2)	Vent height (cm)	Emission rate $x10^6$ (g/s)	Diffusivity (cm^2/s)
30	0.1963	26.7	1.1111	0.18379
35	0.1963	25.3	1.6667	0.18939
40	0.1963	24.5	2.0833	0.20679

Table B-3 shows the comparison of the molar diffusivity from the model and experiment.

Table B-3 Comparison of molar diffusivity from the calculation and experiment

Temperature (°C)	Volume (ml)	Molar diffusivity (cm^2/s)		Deviation %
		Calculation	Experiment	
30	300	0.1339	0.18379	37.26
35	300	0.1378	0.18939	37.45
40	300	0.1417	0.20679	45.91

Appendix C : Summarized experimental results and modeling results

Table C-1 Experiment results

Day	Weight (g/day)											
	Vent height 15 cm & Gasoline volume of 300 ml			Vent height 30 cm & Gasoline volume of 300 ml			Vent height 45 cm & Gasoline volume of 300 ml			Vent height 30 cm & Temperature of 40°C		
	Temperature (°C)			Temperature (°C)			Temperature (°C)			Volume (ml)		
	30	35	40	30	35	40	30	35	40	250	300	350
1	0.21	0.29	0.47	0.155	0.230	0.320	0.130	0.180	0.320	0.370	0.320	0.270
2	0.18	0.23	0.32	0.120	0.130	0.165	0.090	0.090	0.090	0.160	0.165	0.185
3	0.19	0.25	0.31	0.125	0.135	0.180	0.100	0.095	0.120	0.160	0.180	0.195
4	0.18	0.23	0.34	0.100	0.145	0.175	0.080	0.105	0.110	0.200	0.175	0.165
5	0.20	0.23	0.32	0.130	0.130	0.180	0.090	0.085	0.120	0.185	0.180	0.185
6	0.19	0.19	0.33	0.100	0.145	0.215	0.085	0.110	0.120	0.180	0.215	0.200
7	0.20	0.23	0.28	0.110	0.145	0.195	0.080	0.100	0.120	0.200	0.195	0.165

Table C-2 Comparison of modeling results with different conditions

Model	Model results (g/day)											
	Vent height 15 cm & Gasoline volume of 300 ml			Vent height 30 cm & Gasoline volume of 300 ml			Vent height 45 cm & Gasoline volume of 300 ml			Vent height 30 cm & Temperature of 40°C		
	Temperature (°C)			Temperature (°C)			Temperature (°C)			Volume (ml)		
	30	35	40	30	35	40	30	35	40	250	300	350
Thesis	0.182	0.261	0.321	0.097	0.140	0.176	0.068	0.098	0.125	0.177	0.176	0.174
U.S. EPA	0.004	0.011	0.022	0.005	0.013	0.026	0.004	0.011	0.022	0.036	0.026	0.015
Nevers	0.011	0.018	0.027	0.011	0.018	0.029	0.011	0.017	0.027	0.030	0.029	0.027

Table C-3 Deviations of the models from the experimental results

Model	Deviation (%)											
	Vent height 15 cm & Gasoline volume of 300 ml			Vent height 30 cm & Gasoline volume of 300 ml			Vent height 45 cm & Gasoline volume of 300 ml			Vent height 30 cm & Temperature of 40°C		
	Temperature (°C)			Temperature (°C)			Temperature (°C)			Volume (ml)		
	30	35	40	30	35	40	30	35	40	250	300	350
Thesis	4.36	14.86	4.44	14.31	4.90	6.66	22.16	7.84	11.50	8.39	6.66	7.69
U.S. EPA	97.86	94.95	92.89	95.88	90.48	86.02	95.52	88.61	80.79	79.87	86.02	91.74
Nevers	94.25	92.29	91.36	90.00	86.81	84.48	87.70	82.12	76.00	83.38	84.48	84.90

Appendix D : Experimental data

Table D-1 Experimental data at 25°C, 15 cm release vent height and 300 ml gasoline volume

Data	Gasoline weights (g)			Gasoline losses (g)		
	Batch 1	Batch 2	Batch 3	Batch 1	Batch 2	Batch 3
Initial	500.19	502.61	491.35	-	-	-
1	500.04	502.47	491.21	0.15	0.14	0.14
2	499.89	502.36	491.08	0.15	0.11	0.13
3	499.75	502.22	490.95	0.14	0.14	0.13
4	499.59	502.08	490.81	0.16	0.14	0.14
5	499.45	501.96	490.69	0.14	0.12	0.12
6	499.31	501.83	490.56	0.14	0.13	0.13
7	499.17	501.70	490.43	0.14	0.13	0.13
8	499.02	501.56	490.28	0.15	0.14	0.15
9	498.88	501.44	490.16	0.14	0.12	0.12

Table D-2 Experimental data at 30°C, 15 cm release vent height and 300 ml gasoline volume

Data	Gasoline weights (g)			Gasoline losses (g)		
	Batch 1	Batch 2	Batch 3	Batch 1	Batch 2	Batch 3
Initial	501.40	504.37	492.65	-	-	-
1	501.20	504.16	492.43	0.20	0.21	0.22
2	500.90	503.91	492.20	0.30	0.25	0.23
3	500.71	503.74	492.02	0.19	0.17	0.18
4	500.51	503.56	491.83	0.20	0.18	0.19
5	500.31	503.39	491.65	0.20	0.17	0.18
6	500.09	503.21	491.44	0.22	0.18	0.21
7	499.88	503.03	491.25	0.21	0.18	0.19
8	499.67	502.84	491.05	0.21	0.19	0.20
9	499.46	502.67	490.86	0.21	0.17	0.19
10	499.26	502.50	490.67	0.20	0.17	0.19
11	499.06	502.33	490.49	0.20	0.17	0.18

Table D-3 Experimental data at 35°C, 15 cm release vent height and 300 ml gasoline volume

Data	Gasoline weights (g)			Gasoline losses (g)		
	Batch 1	**Batch 2**	**Batch 3**	**Batch 1**	**Batch 2**	**Batch 3**
Initial	499.73	502.62	492.55	-	-	-
1	499.42	502.34	492.27	0.31	0.28	0.28
2	499.17	502.11	492.05	0.25	0.23	0.22
3	498.90	501.86	491.81	0.27	0.25	0.24
4	498.65	501.48	491.59	0.24	0.38	0.22
5	498.40	501.25	491.38	0.25	0.23	0.21
6	498.19	501.07	491.19	0.21	0.18	0.19
7	497.94	500.84	490.98	0.25	0.23	0.21

Table D-4 Experimental data at 40°C, 15 cm release vent height and 300 ml gasoline volume

Data	Gasoline weights (g)			Gasoline losses (g)		
	Batch 1	**Batch 2**	**Batch 3**	**Batch 1**	**Batch 2**	**Batch 3**
Initial	501.60	504.07	492.62	-	-	-
1	501.24	503.71	492.25	0.48	0.47	0.47
2	500.90	503.38	491.93	0.34	0.33	0.32
3	500.57	503.06	491.62	0.33	0.32	0.31
4	500.24	502.70	491.30	0.33	0.36	0.32
5	500.19	502.60	491.24	-	-	-
6	499.71	502.14	490.81	0.48	0.46	0.43
7	499.38	501.83	490.50	0.33	0.31	0.31
8	499.03	501.51	490.17	0.35	0.32	0.33
9	498.73	501.25	489.89	0.30	0.26	0.28
10	498.40	500.94	489.59	0.33	0.31	0.30

Data 5 restart experiment cause of electrical problem in college

Table D-5 Experimental data at 30°C, 30 cm release vent height and 300 ml gasoline volume

Data	Gasoline weights (g)		Gasoline losses (g)	
	Batch 1	Batch 2	Batch 1	Batch 2
Initial	509.19	532.38	-	-
1	509.05	532.21	0.14	0.17
2	508.93	532.09	0.12	0.12
3	508.82	531.95	0.11	0.14
4	508.72	531.85	0.10	0.10
5	508.60	531.71	0.12	0.10
6	508.50	531.61	0.10	0.10
7	508.40	531.49	0.10	0.12
8	508.28	431.37	0.12	0.12

Table D-6 Experimental data at 30°C, 45 cm release vent height and 300 ml gasoline volume

Data	Gasoline weights (g)		Gasoline losses (g)	
	Batch 1	Batch 2	Batch 1	Batch 2
Initial	515.79	505.31	-	-
1	515.65	505.19	0.14	0.12
2	515.56	505.10	0.09	0.09
3	515.46	505.00	0.10	0.10
4	515.39	504.91	0.07	0.09
5	515.29	504.83	0.10	0.08
6	515.21	504.74	0.08	0.09
7	515.13	504.66	0.08	0.08
8	515.05	504.57	0.08	0.09

Table D-7 Experimental data at 35°C, 30 cm release vent height and 300 ml gasoline volume

Data	Gasoline weights (g)		Gasoline losses (g)	
	Batch 1	**Batch 2**	**Batch 1**	**Batch 2**
Initial	508.94	533.33	-	-
1	508.71	533.10	0.23	0.23
2	508.58	532.97	0.13	0.13
3	508.44	532.84	0.14	0.13
4	508.30	532.69	0.14	0.15
5	508.17	532.56	0.13	0.13
6	508.02	532.42	0.15	0.14
7	507.87	532.28	0.15	0.14

Table D-8 Experimental data at 35°C, 45 cm release vent height and 300 ml gasoline volume

Data	Gasoline weights (g)		Gasoline losses (g)	
	Batch 1	**Batch 2**	**Batch 1**	**Batch 2**
Initial	516.00	505.24	-	-
1	515.82	505.06	0.18	0.18
2	515.74	504.96	0.08	0.10
3	515.65	504.86	0.09	0.10
4	515.55	504.75	0.10	0.11
5	515.47	504.66	0.08	0.09
6	515.37	504.54	0.10	0.12
7	515.27	504.44	0.10	0.10

Table D-9 Experimental data at 40°C, 30 cm release vent height and 300 ml gasoline volume

Data	Gasoline weights (g)		Gasoline losses (g)	
	Batch 1	Batch 2	Batch 1	Batch 2
Initial	507.96	532.87	-	-
1	507.64	532.55	0.32	0.32
2	507.47	532.39	0.17	0.16
3	507.30	532.20	0.17	0.19
4	507.12	532.03	0.18	0.17
5	506.94	531.85	0.18	0.18
6	506.73	531.63	0.21	0.22
7	506.54	531.43	0.19	0.20

Table D-10 Experimental data at 40°C, 45 cm release vent height and 300 ml gasoline volume

Data	Gasoline weights (g)		Gasoline losses (g)	
	Batch 1	Batch 2	Batch 1	Batch 2
Initial	515.87	516.46	-	-
1	515.55	516.21	0.32	0.25
2	515.46	516.05	0.09	0.16
3	515.34	515.90	0.12	0.15
4	515.23	515.77	0.11	0.13
5	515.11	515.61	0.12	0.16
6	514.99	515.44	0.12	0.17
7	514.87	515.27	0.12	0.17

Table D-11 Experimental data at 40°C, 30 cm release vent height and 250 ml gasoline volume

Data	Gasoline weights (g)		Gasoline losses (g)	
	Batch 1	Batch 2	Batch 1	Batch 2
Initial	472.18	495.45	-	-
1	471.83	495.06	0.35	0.39
2	471.69	494.88	0.14	0.18
3	471.54	494.71	0.15	0.17
4	471.34	494.51	0.20	0.20
5	471.16	494.32	0.18	0.19
6	470.98	494.14	0.18	0.18
7	470.80	493.92	0.18	0.22

Table D-12 Experimental data at 40°C, 30 cm release vent height and 350 ml gasoline volume

Data	Gasoline weights (g)		Gasoline losses (g)	
	Batch 1	Batch 2	Batch 1	Batch 2
Initial	546.33	569.75	-	-
1	546.07	569.47	0.26	0.28
2	545.89	569.28	0.18	0.19
3	545.69	569.09	0.20	0.19
4	545.53	568.92	0.16	0.17
5	545.35	568.73	0.18	0.19
6	545.15	568.53	0.20	0.20
7	544.99	568.36	0.16	0.17

Appendix E: Stainless storage tank experiment

The other experiment carried out involved a simulated storage tank which was made from stainless steel. This storage tank configuration was based on the underground storage tank as shown in Figure E.1 The experiment was set up at room temperautre and with 10 litre initial gasoline volume. Results from this experiment were shown in Table E.1 and Figure E.2.

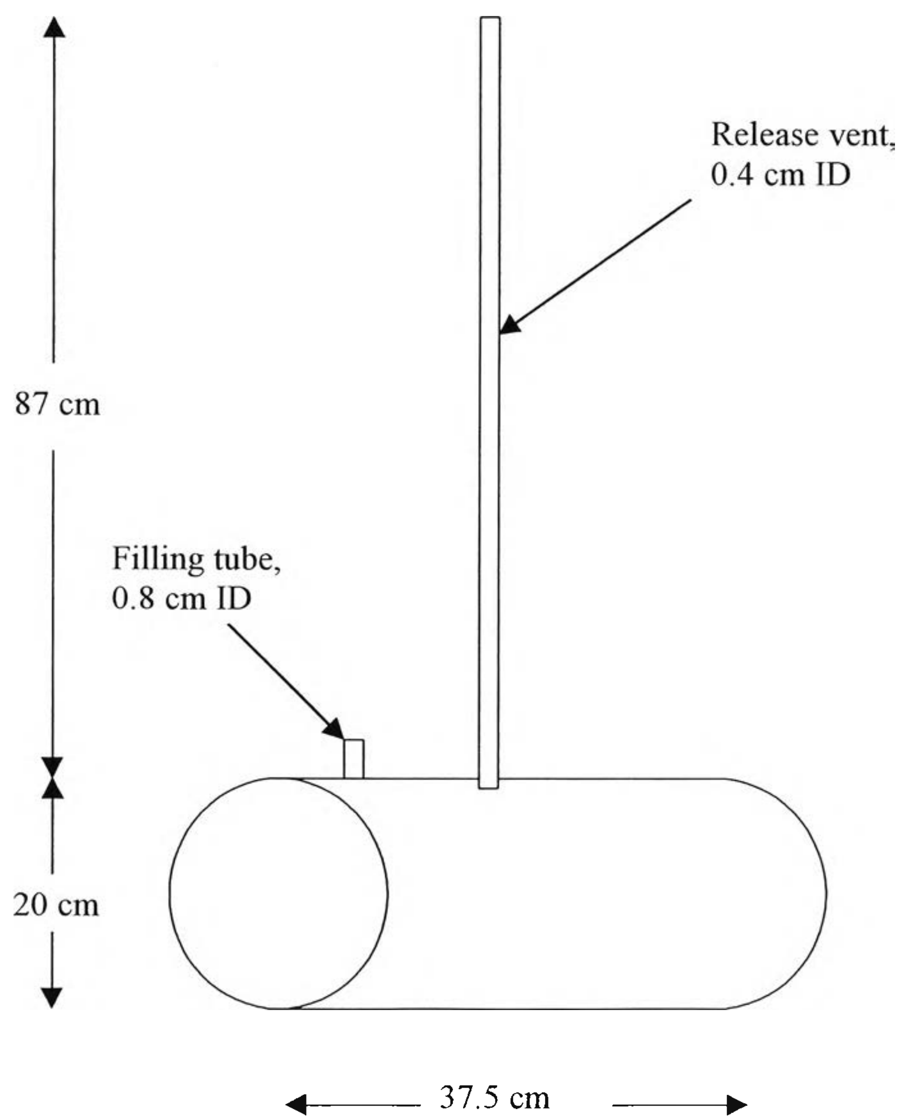

Figure E.1 Stainless steel storage tank

Table E.1 Experimental data at room temperature, 10 litre gasoline volume and 87 cm vent height

Data	Gasoline weight (g)	Data	Gasoline weight (g)
1	10626.0	26	10565.0
2	10623.8	28	10562.8
3	10621.7	31	10558.5
5	10620.0	32	10556.9
8	10617.6	40	10552.8
9	10616.7	41	10549.5
10	10615.7	42	10548.8
11	10614.9	43	10544.9
12	10614.2	44	10547.3
13	10613.2	45	10547.7
15	10610.2	46	10551.7
16	10588.9	47	10552.5
17	10587.7	49	10542.1
23	10583.8	50	10538.6

From this table, the results from the experiment were unreliable. This may be due to the unproportional size of the storage tank and the digital balance used. Therefore, the proposed model was not used with these results.

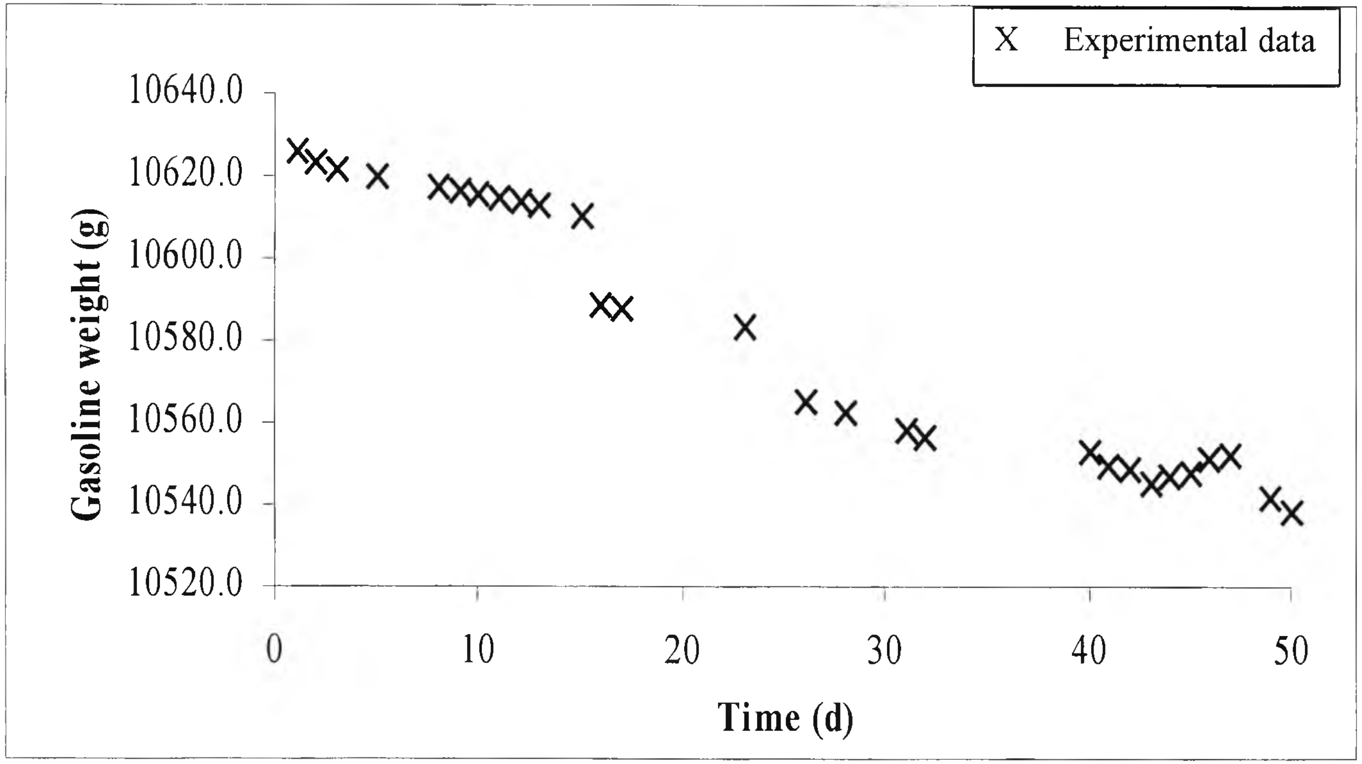

Figure E.2 Stainless steel storage tank experimental data

CURRICULUM VITAE

Name: Mr. Sawin Kulchanyavivat

Date of Birth: April 26, 1975

Nationality: Thai

University Education:

1994-1997 Bachelor Degree of Chemical Engineering,
Mahidol University