AP-42
5th edition
Section 5.2
#10

R. A. Nichols Engineering

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March 23, 1977

H. B. Uhlig
Chevron U.S.A. Inc.
575 Market Street
San Francisco, CA 94120

Dear Mr. Uhlig:

Re: Tank Truck Leakage Calculations.

Enclosed on the accompanying Table and Graph are our most accurate predictions of the various truck leakage losses associated with vapor transfer. The graph shows the individual leakage versus diameter curves for the various loss modes associated with the truck. The upper curve is the additive loss curve. Our point is there is a knee in the loss curve and since the CARB criteria, either 1 inch or 2 inch probably will be more nearly 4 inches in practice, very little is lost in going above this point. There is also some indication from the refueling tests recently run that the vapor transit loss shown is high. Since we have not been able to analyze the test data in detail, we can only say that our knee will probably be lower.

Enclosed please find for transmittal to CARB:

1. "Comments on Proposed CARB Tank Truck Leakage Criteria". The comments shown there have been well documented by others. In addition terminal leakage and truck blowdown equations are given.

2. Section 2 - "Vapor Loss During Stage I Fuel Drops". The document discusses the factors affecting Stage I loss efficiency.

3. Appendix 2A - "Vapor Transfer Model and Quasi-Steady State Solution". This document discusses a rigourous approximation method of solution to the more detailed equations describing a Stage I transfer.

4. Appendix 3B - "Analytical Calculation of Fuel Transit Breathing Loss". The document discusses a conservative analytical approach to transit leakage.

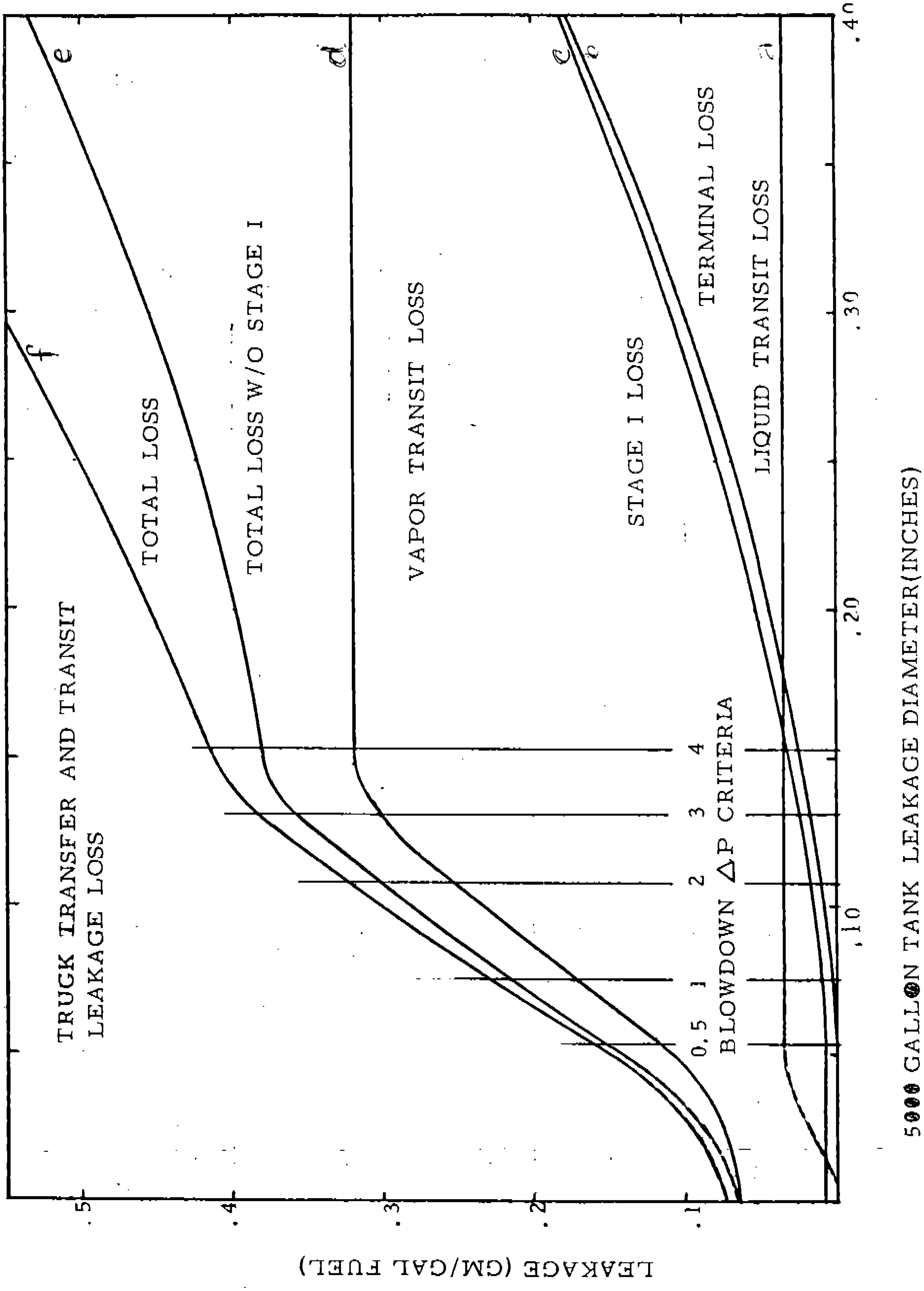
The above documents were to form a portion of the more complete analysis of the problem. Unfortunately time limitations have limited our effort to the above.

Very truly yours,

Richard A. Nichols, Ph.D.

RAN:sn
cc: J. E. Tuomy
Enc.

R. A. Nichols
Engineering



TRUCK TRANSFER AND TRANSIT LEAKAGE LOSS

ΔP Loss In. H_2O	Leak Dia 5000Gal In. Φ	Terminal Loss Gm/Gal	Terminal Vapor Vol%Loss	Liquid TransLoss Gm/Gal	Vapor TransLoss Gm/Gal	Loss S.S. Stage I Gm/Gal	S.S. Stage I Vol%Loss	TotLoss w/oStg I Gm/Gal	TotLoss w/Stg I Gm/Gal
0	-0-	0	0	0	.0641	.0083	0.20	.0641	.0724
0.5	.0528	.0031	.07	.0351	.1205	.0083	0.20	.1587	.1670
1	.0749	.0063	.15	.0351	.1743	.0124	0.30	.2157	.2281
2	.107	.0128	.31	.0351	.2521	.0186	0.45	.3000	.3186
3	.131	.0192	.46	.0351	.3025	.0253	0.61	.3568	.3821
4	.153	.0262	.63	.0351	.3195	.0336	0.81	.3808	.4144
	.200	.0445	1.1	.0351	.3195	.0547	1.32	.3991	.4538
	.250	.0696	1.7	.0351	.3195	.0808	1.95	.4242	.5050
	.300	.1002	2.4	.0351	.3195	.1077	2.60	.4548	.5555
	.400	.1781	4.3	.0351	.3195	.1822	4.40	.5327	.7149
	.500	.2782	6.7	.0351	.3195	.263	6.35	.6328	.8958

10% Vent Space - 5000 Gallon Tank

X b a c d

R. A. Nichols Engineering

COMMENTS ON PROPOSED CARB TANK TRUCK LEAKAGE CRITERIA

By

Richard A. Nichols, Ph.D.
R. A. Nichols Engineering

January 18, 1977

1.0 SUMMARY

Truck tightness restrictions should be designed to insure efficient vapor transfer conditions take place at service station drops and during truck refueling at terminals. Such restrictions will be tight enough to inhibit breathing losses caused by windage.

The maximum tank breathing loss conserved by the stringent tank leakage restriction is small (0.074 gm/gal)by any standard.. The proposed standard leads to tank drop efficiency standards far in excess of the 90% proposed for Stage I. Such tank tightness has not been maintainable on a working basis.

A discussion of tank relief vents and how they are used suggests that meaningful tank vacuum and pressure tests should be conducted on the truck tank hooked up in the normal drop or loading mode.

Testing at vacuums greater than 4.0 inches of water and pressures greater than 16.0 inches of water are shown unnecessary. Higher pressure and vacuum requirements increase valve complexity without improving effectiveness. Methods are shown to convert tank blowdown times between 4.0 and 1.0 inch of vacuum to an equivalent leak orifice diameter. Orifice diameters less than 0.75 inch correspond to drop efficiencies greater than 90%.

Pressure versus time measurements can be taken and correlated with an equivalent tank orifice. If tank truck pressure versus loading rate is known then given any calculated equivalent orifice, percentage leakage can be found. In the absence of such data, the representative data presented shows that vapor transfer is more than 90% effective, if the equivalent pressure orifice leak diameter is less than about 0.60 inch in diameter.

In conclusion the testing methods outlined and limits shown conform to the 90% efficiency requirement generally supported by CARB. The procedure outlined can be used without removing trucks from service by fueling or defueling isolated tanks. By changing leakage requirements, criteria can be made more stringent as technology improves.

2.0 MAGNITUDE OF RECOVERABLE LOSS

Chevron, using specially prepared trucks, has monitored vent space pressure, following drops with vapor return, on the way back to the terminal. The highest pressure recorded was 9 in. of H_2O with about 6 in. of H_2O in the truck return to the terminal. Assuming that the entire amount trapped were otherwise lost, the loss would be

$$\frac{6}{407} \times 5000 \text{ gal} \times 4.172 \frac{\text{gm}}{\text{gal}} = 307.5 \text{ gm}$$

On leaving the terminal following refueling a pressure buildup of 22 in. of H_2O was found which decreased to between 16 and 17 in. of H_2O on reaching the service station. Assuming the entire amount trapped would otherwise be lost, we have

$$\frac{17}{407} \times .07 \times 5000 \text{ gal} \times 4.172 \frac{\text{gm}}{\text{gal}} = 61.0 \text{ gm}$$

This total amount divided by the gallons of fuel transferred is the maximum vent loss that can be gained by the proposed stringent leakage requirement

$$\frac{61 + 307.5}{5000} = .074 \text{ gm/gal}$$

This maximum loss is less than 20% of that allowed for automobile refueling at .4 gm/gal and 40% of the claim of the best secondary system. We would note that all vapor losses were assumed saturated and that relaxed standards were assumed to trap no vapor. Neither assumption is true.

3.0 STRINGENCY OF PROPOSED CRITERIA

Calculations were made assuming an isothermal blowdown of a 5000 gallon tanker from 22 to 19, 20 and 21 in. of H_2O in 5 minutes (See Appendix A). The equivalent sharp edged orifice diameter was calculated to be

final pressure (in. H_2O)	19	20	21
equivalent orifice (in.)	0.131	0.107	0.075

These equivalent orifice diameters were compared with those present on trucks and equivalent truck drop stage I efficiencies. Figure 8 of Reference 1 (Figure 1 attached) shows that equivalent orifice diameters approaching 0.750 in. with the required 3 inch drop equipment will still meet the stage I recovery requirement.

Chevron in the article "Vapor Control Concepts" by M. W. Leiferman (Reference 2) lists the average results of 18 tank truck drops as 95.6%. By assuming temperature difference effects average out, this result would correspond to an average truck leak equivalent to a 0.5 in. orifice or roughly between 15 and 44 times larger leakage flow area than proposed by the CARB test.

In view of the above, the stringency of the CARB proposed requirement appears unreasonable. From a practical standpoint one can then ask what is reasonable. To do this we propose to discuss truck design and operating configuration as well as efficiency versus measureable test parameters.

4.0 TANKER CONFIGURATION AND DESIGN PRESSURES

There are three types of vents on trucks

- o 1 - 1 1/4" pressure and vacuum over the road relief valves. Max relief pressure 1 psi, vacuum 6 oz. = 10.5" H_2O.
- o The 10" dome covers which additionally act as emergency relief valves. Relief pressure 3 psi.
- o If the trucks are not loaded through the dome covers then compartments usually have 5" mechanically, hydraulically or pneumatically operated vents. Relief pressure 3 psi.

With vapor recovery, the 5" vents are hooded over, piped to a rollover rail, and down to a vapor recovery fitting for transfering vapor during service station fuel drops and/or terminal truck refueling. Some companies, to prevent leakage during refueling, hood over the 1" over the road vents. In this case the rollover rail must be vented during times when refueling is not taking place.

Since truck tightness is of primary benefit on truck loading and unloading, it is in this flow configuration the truck should be pressure and vacuum tested. For example if the truck over the road vents are hooded over when the truck unloads at the service station then this should be the same condition for the vacuum test. Similarly if over the road vents are enclosed upon truck refueling then they should be for the pressure test.

On unloading with nominal 3" equipment vacuum should always be less than 4" of H_2O in the truck (see Figure 9, Reference 1, Figure 2 attached) consequently a test at that start point should be sufficient. The question then is what kind of pressure fall off during a period of time should be allowed. For accuracy of measurement the fall off should be as large as practical and still measureable with high accuracy. We suggest 1" of H_2O as a lower limit.

On loading with multiple connections in a terminal which is loading more than one truck at the same time, tank truck pressures may be as high as 12 in. of water. If the over the road vents are not enclosed in the vapor hood, maximum pressures should be designed for less than 16 in of water. According we suggest the pressure test start at 16 in of water and terminate at 6 to 10 in of water.

5.0 VACUUM LEAKAGE VERSUS DROP EFFICIENCY

It is assumed that approximately 4.5 in. H_2O vacuum is pulled on the truck and that time is measured from 4.0 inches of water vacuum until the tank reaches 1" of water vacuum. Efficiencies are interpolated from Figure 1. Times are for a 5000 gal tank. To correct measured times for volume differences, we use the formula below

$$t\ calc = \frac{5000\ (t\ meas)}{(tank\ size\ gal)}$$

t calc (sec)	816.8	204.2	90.8	51.1	32.7	22.7
t calc (min: sec)	13:37	3:24	1:31	0:51	0:33	0:23
orifice dia (in.)	0.125	0.250	0.375	0.500	0.625	0.750
efficiency	99.4	98.7	97.8	96.2	94.3	92.3

The above calculations are outlined in Appendix B.

6.0 PRESSURE LEAKAGE VERSUS REFUELING LOSSES

In order to equate loading efficiency to leakage we need to know tank truck pressure versus refueling rate. For our correspondence we use some Chevron reference data:at 1200 gpm loading rate tank truck pressure is about 12 in. of H_2O, at 600 gpm about 3 in of H_2O. By using these pressures, leakage and % of load rate can be calculated for various orifice sizes (See Appendix C).

dia orifice in	0.125	0.25	0.375	0.50	0.625	0.750
gpm leak, 3" H_2O	2.5	10.1	22.7	40.3	63.0	90.7
% of 600gpm	0.4	1.7	3.8	6.7	10.5	15.1
gpm leak, 12" H_2O	5.0	20.0	45.1	80.2	125.3	180.4
% of 1200gpm	0.4	1.7	3.8	6.7	10.4	15.0

For this example truck leaks with equivalent orifices less than 0.60 in. diameter are more than 90% efficient at transferring vapor at the terminal.

To pressure test the truck, we assume an empty truck full of saturated vapor is pressurized, probably by loading a small amount of fuel, to approximately 18 in of H_2O and that leak rate time is measured from the time the tank reaches 16.0 in of water until it reaches 10.0 inches of water. Calculation times shown below are for a 5000 gallon truck. To correct measured times to calculated times, the formula below can be used

$$t\ \text{calc} = \frac{5000 \quad (t\ \text{meas})}{(\text{tank size, gal})}$$

dia orifice(in)	0.125	0.250	0.375	0.500	0.625	0.750
t calc(sec)	840.9	210.2	93.4	52.6	33.6	23.4
t calc(min:sec)	14:01	3:30	1:33	0:53	0:34	0:23

The above calculations are outlined in Appendix D.

7.0 REFERENCES

1. Nichols, R.A. Hydrocarbon Emission Sources at Service Stations. Paper Vehicle Refueling Emissions Seminar. API 4222, American Petroleum Institute. Washington, D.C. pages 60-66. December, 1973.

2. Leiferman, M.W. Vapor Control Concepts. Paper Vehicle Refueling Emissions Seminar. API 4222. American Petroleum Institute. Washington, D.C. pages 32-37. December, 1973

3. Nichols, R.A. Comments on San Diego Air Pollution Control District Permit to Operate for the Clean Air Engineering-California Highway Patrol System. R. A. Nichols Engineering 519 Iris, Corona del Mar, CA 92625. January, 1976.

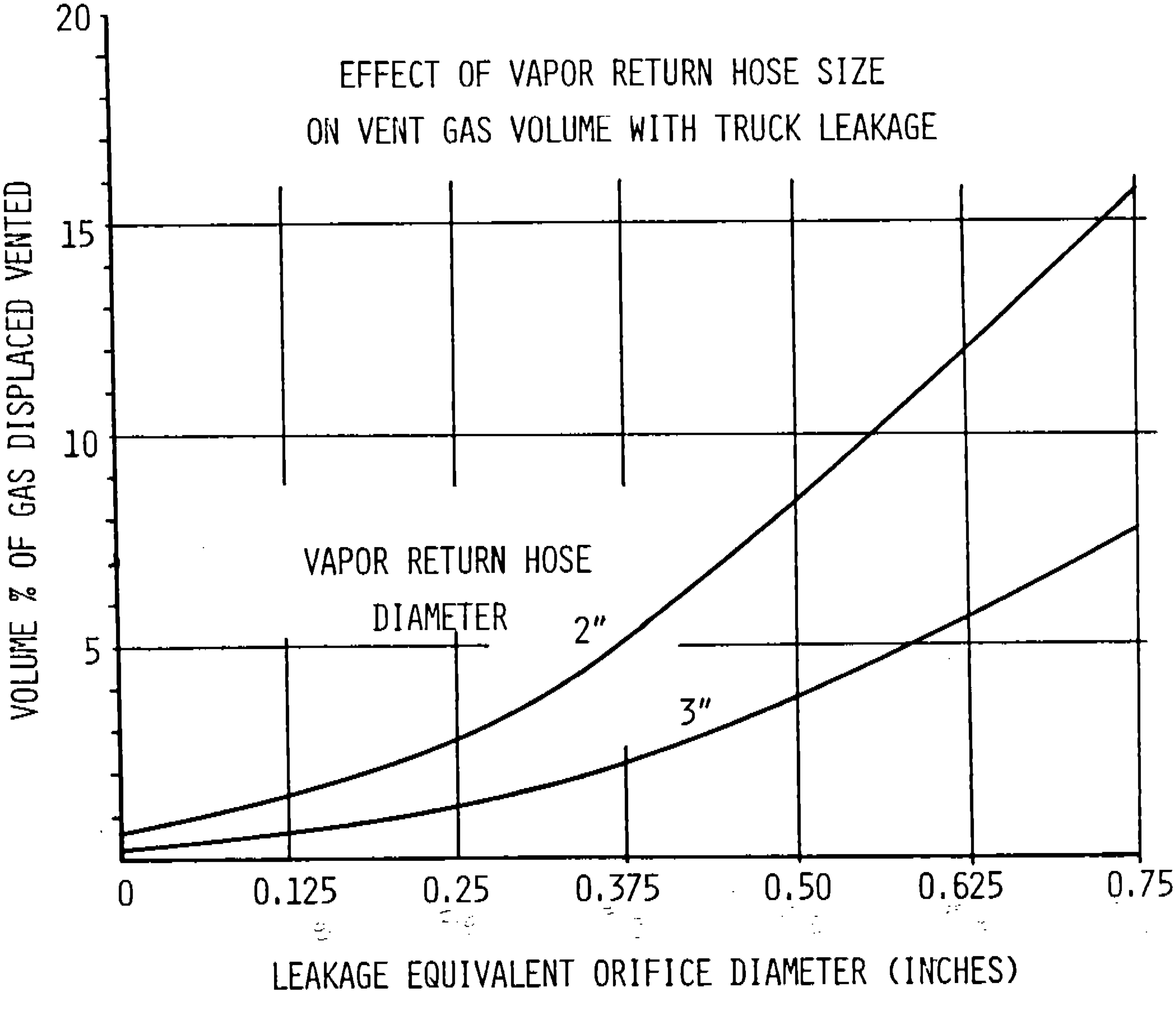
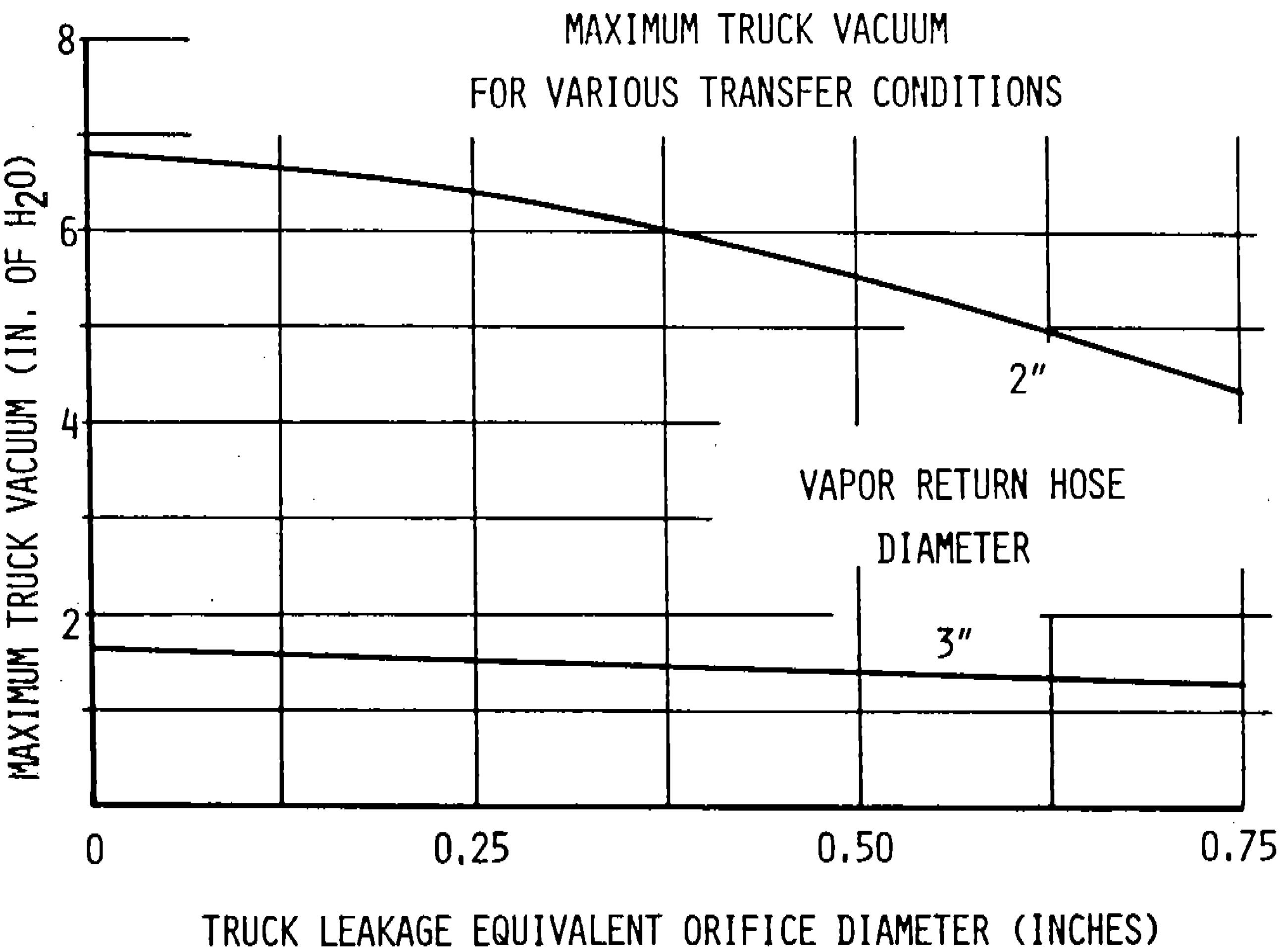

EFFECT OF VAPOR RETURN HOSE SIZE
ON VENT GAS VOLUME WITH TRUCK LEAKAGE
VOLUME % OF GAS DISPLACED VENTED
20
15
10
5
VAPOR RETURN HOSE
DIAMETER
2"
3"
0
0.125
0.25
0.375
0.50
0.625
0.75
LEAKAGE EQUIVALENT ORIFICE DIAMETER (INCHES)

Figure 1

MAXIMUM TRUCK VACUUM FOR VARIOUS TRANSFER CONDITIONS

Figure 9 presents a graph of maximum truck vacuum versus truck leakage for both 2- and 3-inch equivalent vapor return hose sizes. The smaller leakage and truck vacuums with the 3-inch vapor return piping indicates why the Los Angeles and Orange County laws were written around such equipment.

The question of how a driver can be encouraged to hook up was investigated by running trade-offs on the effect of various diameter vent line orifices.



~~Figure 2~~ Figure 9

EFFECT OF VENT LINE ORIFICE ON FUEL DROPS AT SERVICE STATIONS

Figure 10 is a plot of Service Station tank pressures versus time for present day fuel drops in stations that have variously sized vent line orifices. We have assumed in these trade-offs that the transport compartments are vented to ambient through the equivalent of a 2-1/2-inch orifice.

Bob Murray of the LAAPCD suggested the orifice in the vent line with the idea that if the unloading time were doubled, drivers would be encouraged to hook up the return hose.

Our results show that by restricting the standard vent line (80 feet of 2-inch pipe) with either a 1-inch or 3/4-inch orifice that, although tank back pressure is increased, drop time is not appreciably affected. Drop time is shown by the break in the pressure curve. The fast dropping curve following the break represents blowdown of the underground tank through the vent line.

The 1/2- and 3/8-inch orifices approach and exceed the criteria of doubling the drop time. Compared to the original five minutes and 400 gpm drop time, the 1/2- and 3/8-inch orifices take 9.5 and 14.8 minutes corresponding to respective drop rates of 218 and 138 gpm.

The 1/4-inch orifice takes 30.9 minutes to unload at a corresponding flow rate of 67 gpm. The tank maximum pressure level is 3.3 psig and the vacuum level that can be drawn on the tank at a 50-gpm defueling rate is -1.8 psig. Both these values exceed tank pressure limits.

The tank blowdown time after defueling until the liquid hose could be drained and disconnected without spilling fluid from the hose and pumping gasoline from the tank is also an excessive 5.1 minutes. Here we have considered the minimum disconnect pressure without discharge to be 1.5 psig or 4.5 feet of head. This value will vary, of course, depending on the tank burial level and fuel level in the underground tank.

A. EQUIVALENT LEAKAGE ORIFICE FOR CARB PROPOSED STANDARD

By using the proposed CARB test procedure and by making some assumptions regarding ambient conditions, it is possible to calculate the equivalent orifice by using methods of Reference 3 (See Appendix E, Equation 3). Representative and ambient conditions are

V_G = 5000 gal = 668.45 cf
t = 5 min = 300 sec
T_G = 80°F = 540°R
M = .6(28.97) + .4(68) = 44.58 lbm/lbmol
P_A = 14.7 psia = 407 in. H_2O
P_{Gi} = 22 in. H_2O gage = 429 in. H_2O
$A = (0.7 \times \pi \times D^2)/4$

Orifices are calculated for the three phased pressures given by CARB (P_G = 19, 20, and 21 in. H_2O)

P_G(in. H_2O gage)	19	20	21
P_G in. H_2O	426	427	428
equiv. orifice in.	0.131	0.107	0.075

B. VACUUM TEST ORIFICE CALCULATION

The equation for a vacuum leak differ slightly from Equation 4, Appendix E since the sign of W_V is reversed in Equation 1; and, the term $(P_G - P_A)$ in Equation 3 is $(P_A - P_G)$. On integration the solution becomes

$$\sin^{-1}\left(\frac{P_G}{P_A}\right) - \sin^{-1}\left(\frac{P_{Gi}}{P_A}\right) = \frac{A\,t}{12V_G}\sqrt{\frac{32.2\ RT_G}{M}} \qquad (1)$$

where all symbols have the same units as in Appendix E.

By using the same initial volume and temperature, by using suggested values of pressure, and by using the molecular weight of air, the injested gas, an orifice diameter versus pressurization time can be calculated. The initial conditions are

P_{Gi} = 403 in. H_2O	V_G = 668.5 cf
P_G = 406 in. H_2O	T_G = 540°R
P_A = 407 in. H_2O	M = 28.97 lbm/lbmol
$A = (0.7 \times \pi \times D^2)/4$	

Calculated pressurization times for various orifices are

eff. orifice (in)	0.125	0.250	0.375	0.500	0.625	0.750
t (sec)	816.8	204.2	90.8	51.1	32.7	22.7
t (min:sec)	13:37	3:24	1:31	0:51	0:33	0:23

C. REFUELING LEAK RATE ORIFICE SIZE

By using Equation 5, Appendix E, vapor leakage in gpm was calculated for various orifice sizes and back pressures proportional to 600 and 1200 gpm refueling rates. These conditions are

P_A = 407 in. H_2O T = 540°R

M = 44.58 lbm/lbmol

$A = (0.7 \times \pi \times D^2)/4$

and

P_G = 3 in. H_2O gage = 410 in. H_2O at 600 gpm

P_G = 12 in. H_2O gage = 419 in. H_2O at 1200 gpm

Leakage flows for various equivalent orifices are calculated as well as leakage percentage of the refueling rate.

eff. orifice (in.)	0.125	0.250	0.375	0.500	0.625	0.750
Q gpm at 3"	2.5	10.1	22.7	40.3	63.0	90.7
% 600 gpm	0.4	1.7	3.8	6.7	10.5	15.1
Q gpm at 12"	5.0	20.0	45.1	80.2	125.3	180.4
% 1200 gpm	0.4	1.7	3.8	6.7	10.4	15.0

D. PRESSURE TEST ORIFICE CALCULATION

By using our example initial volume, temperature and molecular weight, and by using the suggested test conditions, effective orifice versus pressure blowdown times are calculated using Equation (4), Appendix E. The initial values are shown below

V_G = 668.45 cf M = 44.58 lbm/lbmol = [illegible] Satura[illegible] vapor-air [illegible]ure

P_A = 407 in. H_2O T_G = 540°R

P_{Gi} = 16 in. H_2O gage = 423 in. H_2O

P_G = 10 in. H_2O gage = 417 in. H_2O

$A = (0.7 \times \pi \times D^2)/4$

Calculated values of blowdown time versus orifice diameter are

eff. orifice (in)	0.125	0.250	0.375	0.500	0.625	0.750
t (sec)	840.9	210.2	93.4	52.6	33.6	23.4
t (min:sec)	14:01	3:30	1:33	0:53	0:34	0:23

E. LEAKAGE CALCULATION METHODS

Often it is necessary to find system leaks and to determine whether drops in pressure observable over a period of time are equivalent to an appreciable leak. In relatively ambient pressure systems where the leakage pressure difference is small compared to ambient and where the system temperature is not affected because of blowdown, it is possible to estimate leakage in terms of an equivalent orifice using ideal gas laws. The derivation basis is shown below.

A mass balance of the system can be written as

$$\frac{dW_G}{d_t} = -\dot{W}_v \qquad (1)$$

$$W_G = \frac{V_G P_G M}{R T_G} \qquad (2)$$

$$\dot{W}_v = \frac{A}{12} \sqrt{\frac{64.4(P_G + P_A)M}{2\, R T_G} \quad (P_G - P_A)} \qquad (3)$$

On substitution and integration between initial conditions $P = P_{Gi}$, $t = o$ and $P = P$, $t = t$ we have

$$n\left[\frac{P_G + \sqrt{P_G^2 - P_A^2}}{P_{Gi} + \sqrt{P_{Gi}^2 - P_A^2}}\right] = -\frac{A}{12}\,\frac{t}{V_G}\sqrt{\frac{32.2\ R\ T_G}{M}} \qquad (4)$$

where

P_G = final absolute system pressure, psia

P_{Gi} = initial absolute system pressure, psia

A = equivalent leakage orifice area, in.^{2}

t = leakage time, sec.

V_G = system vapor space volume, ft^3

R = universal gas constant 10.731psia ft^3/(lbmol°R)

T_G = system vapor temperature, °R

M = vapor molecular weight, lbm/lbmol

W_G = mass of vapor in system, lbm

$\dot{W}_v$ = mass leakage rate, lbm/sec

Since most systems are refueled in units gpm it is useful to find the equivalent leakage in gpm of vapor; to do this we use a modification of Equation 3

$$Q(\text{gpm}) = 37.40\, A \sqrt{\frac{128.8\,(P_G - P_A)\,R\,T}{(P_G + P_A)\;M}} \qquad (5)$$

where Q is the vapor leakage in gpm. All other symbols and units are given above.

SECTION 2.0

VAPOR LOSS DURING STAGE I FUEL DROPS

by

Richard A. Nichols, Ph.D.

R. A. Nichols Engineering

February 21, 1977

2.1 SUMMARY

A symplified model is developed to explain the basic effects involved in a tank truck fuel drop into an underground service station tank. It is concluded that vapor vented is related almost entirely to the ratio of the equivalent truck leakage area divided by the equivalent area of the vapor return path piping from the underground tank to the truck. Percentage of vapor volume vented is almost entirely a function of truck leakage for a given vapor return piping.

Percentages of vapor volume vented versus the equivalent truck leakage orifice is shown for typical 3 inch diameter return piping; leakage versus 2 inch diameter return lines is shown for historical comparison. Figure 2 is a graph of average truck vacuum and underground tank pressures for 2 and 3 inch return lines.

Figure 1 differs from Figure 8 of Reference 1 and Figure 1 of Reference 2. The latter figures were drawn by applying an adjustment factor to computer results which were derived assuming saturated vapor instead of air was drawn in the truck tanks. Unfortunately the factor was misapplied. If the figure "Volume % of Gas Displaced Vented" is multiplied by 1.58, correct leakage for any equivalent truck leakage area having an orifice coefficient of 0.65 will result. The maximum truck vacuum curves shown in Figure 9 Reference 1 and Figure 2 Reference 2 remain correct.

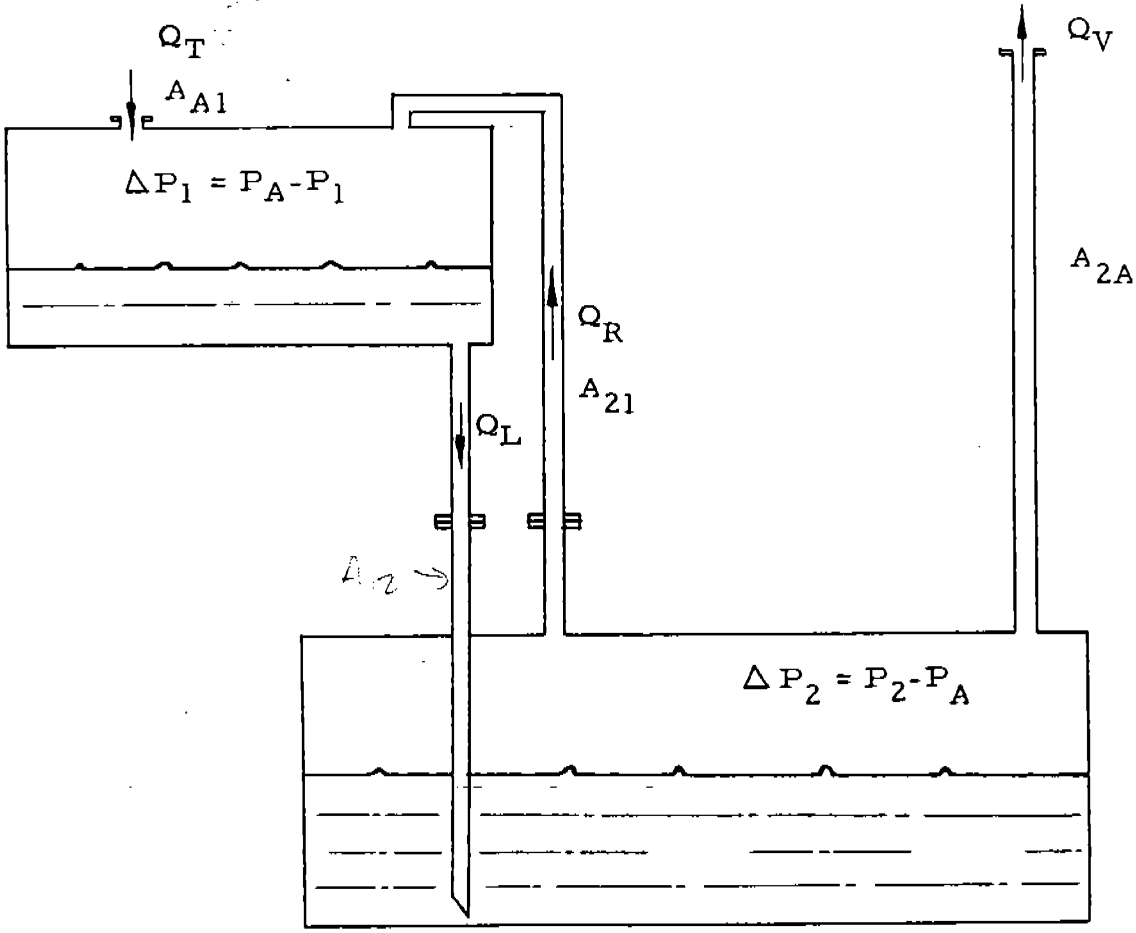
Appendix 2A presents the quasi-steady state solution to the more sophisticated unsteady state equations governing our mathematical model. The model was calculated rather than simply correctly redrawing the figure because conditions slightly more representative of real life could be approximated. The quasi-steady state model -- was checked against the original computer integrations using the same assumptions to check our solution accuracy; it was found to be

within 0.02 percent of the computer solution.

The validity of the model assumptions which assume the refueling to be isothermal and that diffusion effects are negligible are discussed first logically and then by comparison with theoretical diffusion calculations and experimental worst case testing. Both analytical and worst case test results seem to indicate the maximum vapor growth we would see during a normal, submerged, drop tube fill is $\pm 2\%$ of the liquid drop volume.

2.2 A SYMPLIFIED MODEL

From a logic stand point a Stage I truck drop can be visualized rather simply. Consider two tanks in flow communication as shown below



By assuming ΔP_2 and ΔP_1 are small with regard to P_A, we can write

$$Q_V = 983.2\ A_{2A}\sqrt{\frac{T_G\ \Delta P_2}{M_2 P_A}} \qquad (1)$$

Knowing A_{2A}, T_G, M_2, and P_A for any Q_V we can calculate ΔP_2. Now Q_R the return flow to the truck must equal the flow of liquid into the tank Q_L minus the vent flow

$$Q_R = Q_L - Q_V = 983.2\ A_{21}\sqrt{\frac{T_G(\Delta P_2 + \Delta P_1)}{M_2 P_A}} \qquad (2)$$

Since Q_L is measured and ΔP_2 calculated from Equation 1, if A_{21} is known, ΔP_1 can be calculated.

Since $Q_T + Q_R$ must again equal Q_L, neglecting small absolute pressure differences, we can write

$$Q_T = Q_L - Q_R = Q_V \qquad (3)$$

and

$$Q_T = 983.2\ A_{A1}\sqrt{\frac{T_G \Delta P_1}{M_A P_A}} \qquad (4)$$

Knowing ΔP_1 from Equation 2 and $Q_T = Q_V$ from Equation 3, A_{A1} can be solved for in Equation 4.

For high efficiency Stage I drops Q_V is small and since vent line flow area (A_{2A}) is large, ΔP_2 is very small. Since underground tank pressure is also difficult to measure, Q_V is difficult to characterize through the parameters of Equation 1. However Q_V can be characterized approximately through Equation 4. Truck vacuums are larger and more easily measured and the equivalent truck leakage orifice can be found by doing a truck blowdown test. Similarly the equivalent return flow orifice can be determined for a given equipment configuration

by prior correlation. Consequently the percentage leak Q_V over the percentage return becomes

$$\frac{Q_V}{Q_R} \doteq \frac{Q_V}{Q_L - Q_V} = \frac{A_{A1}}{A_{21}}\sqrt{\frac{M_2}{M_A}\frac{\Delta P_1}{(\Delta P_1 + \Delta P_2)}} \tag{5}$$

Since for small leaks ΔP_2 is much smaller than ΔP_1, it can be neglected and

$$\frac{Q_V}{Q_L - Q_V} = \frac{A_{A1}}{A_{21}}\sqrt{\frac{M_2}{M_A}} = \frac{D_{A1}^2}{D_{21}^2}\sqrt{\frac{M_2}{M_A}} \tag{6}$$

Practically we have correlated the typical flow area for a 3 inch drop configuration to be A_{21} = 2.475 in.^{2} or D_{21} = 2.12 in. diameter with an orifice flow coefficient C_{Re} = 0.7; i.e.

$$A_{21} = C_{Re}\frac{\pi D_{21}^2}{4} \tag{7}$$

Since the molecular weight of a saturated vapor-air mixture is typically about $M_2 \doteq 44$. For a 2% leak

$$\frac{.02}{1.0 - .02} = \frac{D_{A1}^2}{D_{21}^2}\sqrt{\frac{44}{29}} \tag{8}$$

$$D_{A1} = 0.129\ D_{21}$$

If D_{21} = 2.12, D_{A1} = 0.273 in. diameter with C_{Re} = 0.7. Note this approximate solution corresponds rather closely to the more accurate solution shown in Figure 1. Truck vacuum and underground tank pressure correlations are shown in Figure 2.

Note our entire development has been independent of tank sizes and head heighths. Leakage to a first order approximation is a function only of the ratio of truck leakage orifice diameter to vapor return

piping leakage diameter.

That this is true can be shown by considering the effect of greatly increasing ΔP_2 with regard to ΔP_1 by restricting the underground tank vent. For example the addition of a 0.5 inch orifice to the vent line will cause $\Delta P_2 = 0.2 \Delta P_1$ at a 2% nominal leak. Equation 5 shows this would cause approximately a 9% decrease in venting or allow a truck leakage orifice to be about 5% larger. Since venting varies almost linearly with truck leakage area and since this is about the greatest allowable vent restriction, other effects are quite small.

2.3 PREVIOUS CALCULATIONS

An effort was made to verify Figure 8 of Reference 1, Figure 1 of Reference 2. The original computer results were for gases having the same molecular weight injected into the truck tank as expelled from the service station vent. Both were assumed saturated. Since air enters the leak at the tank truck a correction factor was used to derive the referenced figure. Unfortunately the correction factor was applied in the wrong direction. To correct the mistake, losses shown in Figure 8 of Reference 1 and Figure 1 of Reference 2 should be multiplied by the factor 1.58. For example instead of vapor loss with 3 in. return hose and a 0.75 in. diameter truck hole being 8% they should really be about 12.7%.

The truck vacuums shown in Figure 9 of Reference 1 and Figure 2 of Reference 2 are correct for the piping configuration shown.

In addition to the above, our calculations included several approximations appeared worth updating. Most vent lines enter the tank directly rather than the vapor transfer line between the tank and truck; this has been assumed. Previous calculations assumed a short vent line which could be approximated by a single orifice. For these updated calculations the vent line is assumed to be 100 ft. of 2 in.

diameter schedule 40 pipe having 7 standard elbows. At very low venting rates, flow becomes laminar. This has been taken into account by calculating the equivalent vent line orifice for a given vent line flow. Since the time of the original calculation, truck drawings have been obtained. They have been used to estimate the various liquid head heights to the surface. Finally maximum truck vacuums are shown in Figure 9 of Reference 1 and Figure 2 of Reference 2; it is more convenient to deal with average underground tank pressures and truck vacuums so these are shown in Figure 2.

The above assumptions were used in the recalculation performed in Appendix A. There the time dependent quantities and differentials were approximated by average rates of change. The techniques authenticity depends upon the results of the computer numerical integration for its basis. Results using previous computer program assumptions were verified against the previous computer results.

2.4 MODEL VALIDITY

Stage I truck dops occur by bottom loading into a partially full tank whose vapor space has had time to be at least partially saturated by the already present fuel. In the case of vapor balancing at the island during vehicle dispensing most of the vapor being introduced into the tank during fuel removal will be nearly saturated. Under these conditions we can expect that nearly the entire vapor space and not just the region adjacent the fuel surface will be saturated.

To cause either vapor growth or vapor contraction the entering fuel must be appreciably different from the resident fuel in temperature and/or vapor pressure and this added fuel must come into sufficient contact with the vapor space gases to cause appreciable heat transfer and diffusion to take place.

Drop tubes are specifically designed to introduce the incoming fuel smoothly beneath the present fuels surface. Some surface waves may be caused but no general mixing will be caused. Further the hydrocarbon concentration present in the vapor space tends to reduce natural convection.

Calculations by Nichols, Reference 3 show that with typical truck drop times less than 10% of the vapor space would be affected by diffusion only 4% being affected as much as 40% of the way to a new equilibrium. Since this new equilibrium in most cases differs only by a slight amount from the present fuel interface situation very little vapor growth is expected.

Although we know of no measurements taken to correlate vapor growth during fueling of underground tanks, we are aware of vapor growth and vapor layer saturation measurements which have been conducted during truck refueling. Since in bottom loading there is some splashing until the loading valve is covered and since there is only liquid layer to establish a vapor rich layer near the entering fuel, we are sure service station covered drop tube refueling will have less vapor growth and saturate a smaller fuel layer than in the best bottom loading. British Petroleum (Reference 3) shows the fraction of tank volume saturated during bottom loading to be between 0.016 and 0.083 on 14 tests. Accordinly it seems reasonable to postulate that except in the refueling of empty tanks or the like, vapor growth should be less than 2%.

2.5 NOMENCLATURE

A_{A1}	tank truck equivalent leakage area, $in.^2$
A_{21}	vapor return path equivalent flow area, $in.^2$
A_{2A}	S.S. tank vent line equivalent leakage area, $in.^2$
C_{Re}	orifice flow coefficient, demensionless = 0.7
D_{A1}	tank truck leak equivalent orifice, C_{Re} = 0.7, in.
D_{21}	vapor return path equivalent orifice, C_{Re} = 0.7, in.
M_A	molecular weight air, 28.97 lbm/lbmol
M_2	vapor-air mixture mole weight, Tank 2, $\doteq$ 44 lbm/lbmol
P_A	ambient pressure, 407 in H_2O
P_1	absolute tank truck vapor space pressure, in. H_2O
P_2	absolute S.S. tank vapor space pressure, in. H_2O
ΔP_1	$P_A - P_1$, in. H_2O
ΔP_2	$P_2 - P_A$, in. H_2O
Q_L	average liquid drop rate, gpm
Q_R	vapor return flow rate, gpm
Q_T	truck vapor leakage flow rate, gpm
Q_V	S.S. tank vapor leakage flow rate, gpm
T_G	absolute temperature, °R

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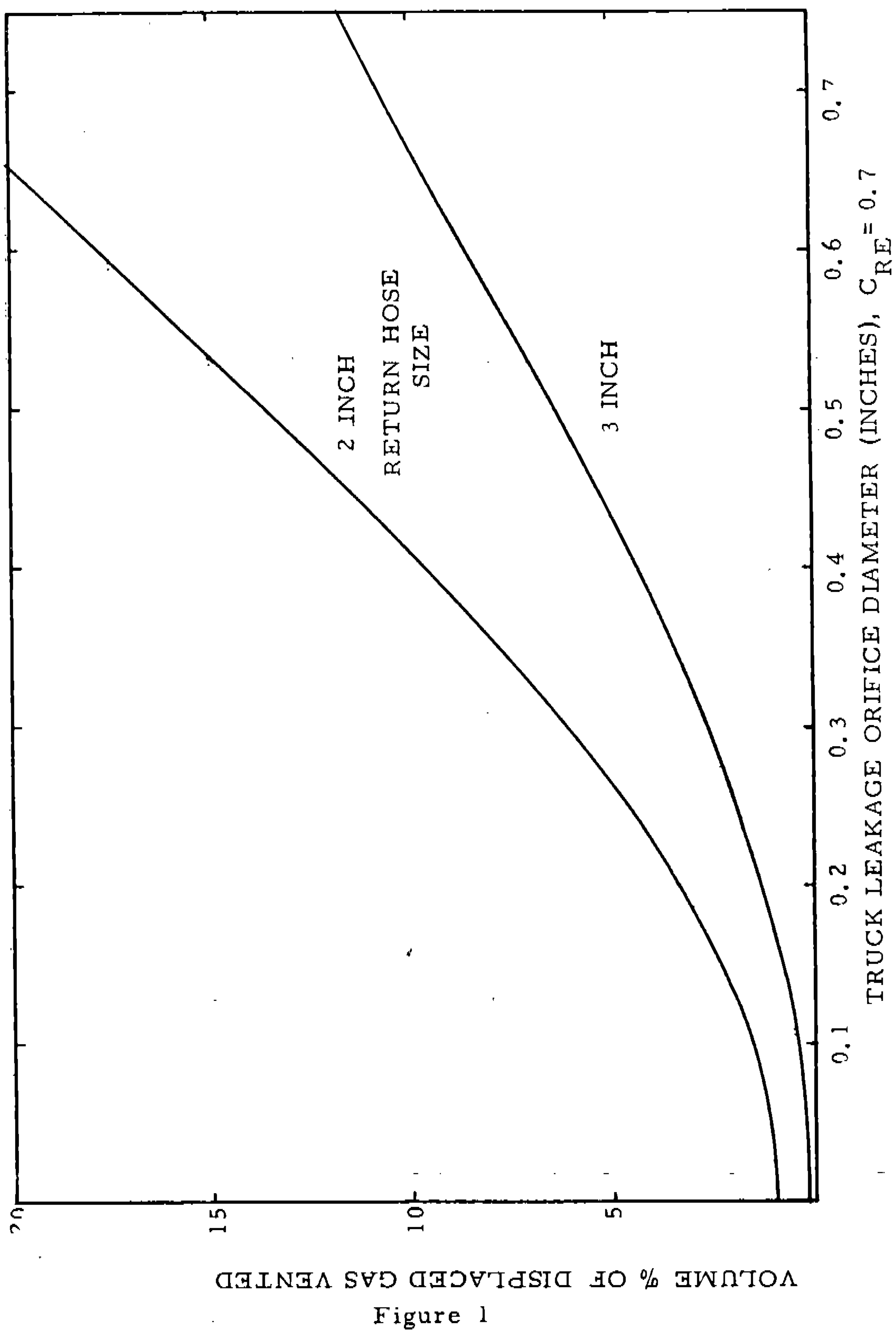
2 INCH
RETURN HOSE
SIZE
3 INCH
TRUCK LEAKAGE ORIFICE DIAMETER (INCHES), $C_{RE} = 0.7$
0.1
0.2
0.3
0.4
0.5
0.6
0.7
VOLUME % OF DISPLACED GAS VENTED
5
10
15
20

Figure 1

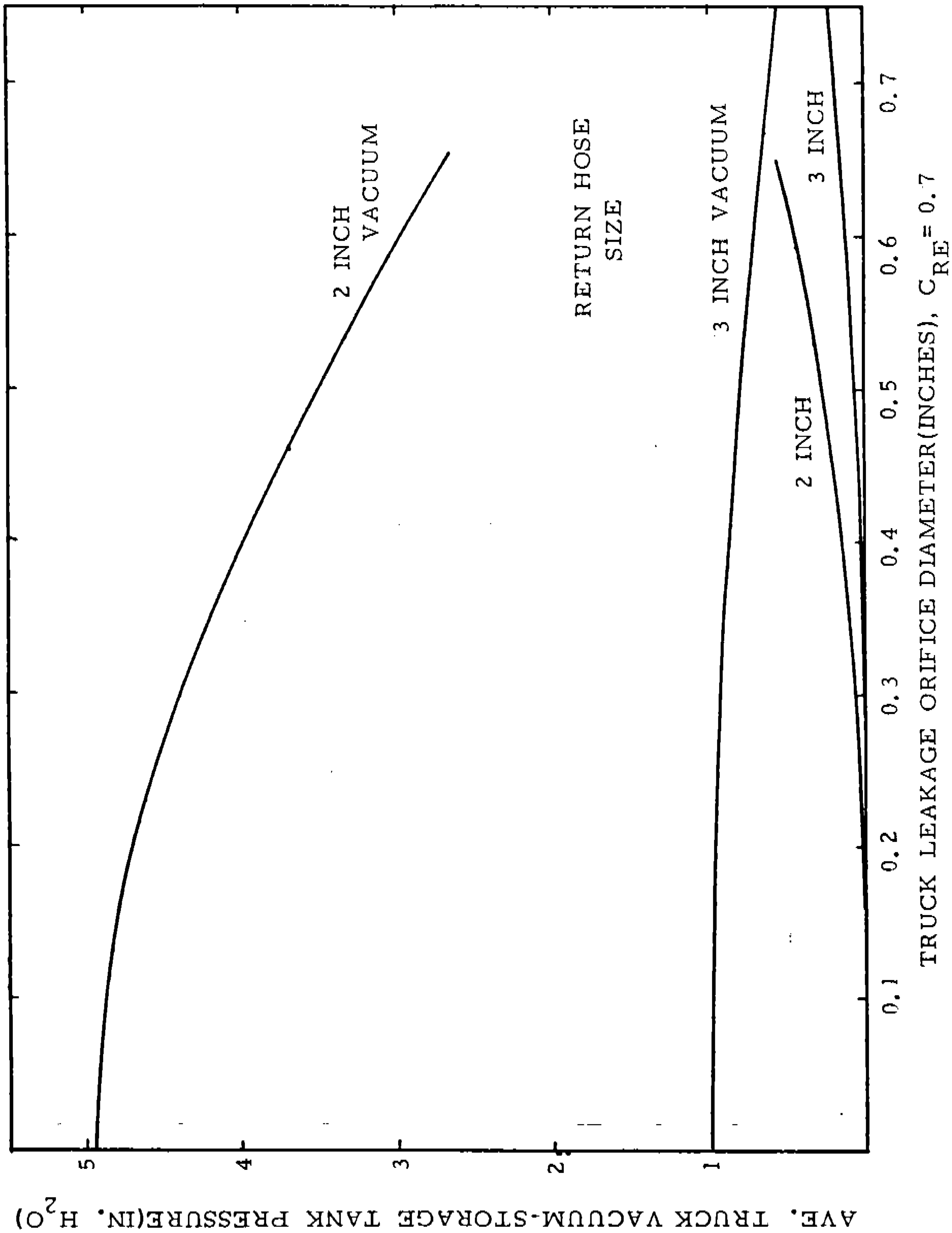
2 INCH VACUUM
RETURN HOSE SIZE
3 INCH VACUUM
2 INCH
3 INCH
0.1
0.2
0.3
0.4
0.5
0.6
0.7
TRUCK LEAKAGE ORIFICE DIAMETER(INCHES), $C_{RE} = 0.7$
1
2
3
4
5
AVE. TRUCK VACUUM-STORAGE TANK PRESSURE(IN. H_2O)

Figure 2

APPENDIX 2A

VAPOR TRANSFER MODEL

AND

QUASI STEADY STATE SOLUTION

by

Richard A. Nichols, Ph.D.

March 17, 1977

A.1 MODEL DESCRIPTION

An isothermal vapor transfer model for flow between a higher and lower tank by gravity when each tank has an external vent is described in Figure A.1. Liquid flows by gravity under head H_L from Tank 1 to Tank 2. Symbols A_{A1}, A_{21}, and A_{2A} are the designations for the effective flow areas for vapor flows Q_T, Q_R and Q_V. Absolute pressures are designated by the capital letter and gauge pressures by the Δ symbol. Capital N stands for moles of vapor, $\dot{N}$ for moles of vapor per unit time.

A.2 MODEL EQUATIONS

The vapor space molar balance for compartments 1 and 2 can be expressed as

$$\frac{dN_{V1}}{dt} = \dot{N}_{V21} + \dot{N}_{VA1} \qquad (A.1)$$

$$\frac{dN_{V2}}{dt} = -\dot{N}_{V2A} - \dot{N}_{V21} \qquad (A.2)$$

The equations for the flows expressed on the right hand side of Equations 1 and 2 are

$$\dot{N}_{V21} = \frac{A_{21}}{12}\sqrt{\frac{64.4\ P_2(P_2-P_1)}{M_2\ R\ T_G}} \qquad (A.3)$$

$$\dot{N}_{VA1} = \frac{A_{A1}}{12}\sqrt{\frac{64.4\ P_A(P_A-P_1)}{M_A\ R\ T_G}} \qquad (A.4)$$

$$\dot{N}_{V2A} = \frac{A_{2A}}{12}\sqrt{\frac{64.4\ P_2(P_2-P_A)}{M_2\ R\ T_G}} \qquad (A.5)$$

The number of moles of gas in vapor spaces V_{G1} and V_{G2} is given by the ideal gas law

$$N_{V1} = \frac{P_1 V_{G1}}{R\ T_G} \qquad (A.6)$$

$$N_{V2} = \frac{P_2 V_{G2}}{R\ T_G} \qquad (A.7)$$

Gauge pressures of Tanks 1 and 2 are expressed as

$$\Delta P_1 = P_A - P_1 \qquad (A.8)$$

$$\Delta P_2 = P_2 - P_A \qquad (A.9)$$

Vapor Space Volumes 1 and 2 can be expressed in terms of initial volumes and liquid flow rate as

$$V_{G1} = V_{T1} - V_{L1I} + Q_L t \qquad (A.10)$$

$$V_{G2} = V_{T2} - V_{L2I} - Q_L t \qquad (A.11)$$

In addition the time it takes to empty V_{L1I} at flow rate Q_L is defined as

$$t_F = \frac{V_{L1I}}{Q_L} \qquad (A.12)$$

It can also be surmised that the rate of differential pressure change in Vapor Spaces 1 and 2 necessary to induce vapor flow will be in proportion to the liquid head heights

$$\frac{\Delta P_1}{\Delta t} = \frac{P_{2F} - P_{2I}}{t_F - 0} = \frac{P_1 Q_L}{V_{L1I}} \left(\frac{H_{LF} - H_{LI}}{H_{LA}} \right) \qquad (A.13)$$

$$\frac{\Delta P_2}{\Delta t} = \frac{P_{2F} - P_{2I}}{t_F - 0} = \frac{P_2 Q_L}{V_{L1I}} \left(\frac{H_{LF} - H_{LI}}{H_{LA}} \right) \qquad (A.14)$$

where H_{LF}, H_{LI} and H_{LA} are the final, initial and average liquid head heights of liquid levels in the two tanks.

A.3 EQUATION SOLUTION

Introducing gauge pressure variables as defined in Equations A.8 and A.9 and using the ideal gas law Expressions A.6 and A.7 the left hand sides of Equations A.1 and A.2 can be expressed as

$$\frac{dN_{V1}}{dt} = \frac{(P_A - \Delta P_1)}{R\ T_G} \frac{dV_{G1}}{dt} - \frac{V_{G1}}{R\ T_G} \frac{d\Delta P_1}{dt} \qquad \text{(A.15)}$$

$$\frac{dN_{V2}}{dt} = \frac{(P_A + \Delta P_2)}{R\ T_G} \frac{dV_{G2}}{dt} + \frac{V_{G2}}{R\ T_G} \frac{d\Delta P_2}{dt} \qquad \text{(A.16)}$$

By substituting expressions developed in Equations A.10, A.11, A.12, A.13, and A.14, we have

$$\frac{dN_{V1}}{dt} = \frac{(P_A - \Delta P_1)}{R\ T_G} Q_L + \frac{\Delta P_1 Q_L}{R\ T_G} \frac{(2V_{T1} - V_{L1I})}{2V_{L1I}} \frac{(H_{LI} - H_{LF})}{H_{LA}} \qquad \text{(A.17)}$$

$$\frac{dN_{V2}}{dt} = -\frac{(P_A + \Delta P_2)}{R\ T_G} Q_L - \frac{\Delta P_2 Q_L}{R\ T_G} \frac{[2(V_{T2} - V_{L2I}) - V_{L1I}]}{2V_{L1I}} \frac{(H_{LI} - H_{LF})}{H_{LA}} \qquad \text{(A.18)}$$

Combining Equations A.18, A.2 and A.5, we have

$$Q_L\left[1 + \frac{\Delta P_2\ [2\ (V_{T2} - V_{L2I}) - V_{L1I}]\ (H_{LI} - H_{LF})}{(P_A + \Delta P_2)\ 2V_{L1I}\ \ H_{LA}}\right] =$$

$$Q_V + 983.2\ A_{21}\sqrt{\frac{T_G(\Delta P_2 + \Delta P_1)}{M_2(P_A + \Delta P_2)}} \qquad \text{(A.19)}$$

where

$$Q_V = 983.2\ A_{2A}\sqrt{\frac{T_G\ \Delta P_2}{M_2(P_A + \Delta P_2)}} \qquad \text{(A.20)}$$

By adding Equations A.1 and A.2 with substitution of Expressions A.17 and A.18, we have

$$Q_T = \left(\frac{P_A + \Delta P_2}{P_A}\right) Q_V - Q_L \frac{\Delta P_1}{P_A} \left[1 - \frac{(2V_{T1} - V_{L1I})}{2V_{L1I}} \frac{(H_{LI} - H_{LF})}{H_{LA}} \right]$$

$$- Q_L \frac{\Delta P_2}{P_A} \left[1 + \frac{[2(V_{T2} - V_{L2I}) - V_{L1I}]}{2V_{L1I}} \frac{(H_{LI} - H_{LF})}{H_{LA}} \right] \qquad (A.21)$$

where

$$Q_T = 983.2\ A_{A1} \sqrt{\frac{T_G \Delta P_1}{M_A P_A}} \qquad (A.22)$$

Specifically the equations are solved as follows. Let

$$C_1 = \frac{(2V_{T1} - V_{L1I})}{2\ V_{L1I}} \frac{(H_{LI} - H_{LF})}{H_{LA}} \qquad (A.23)$$

$$C_2 = \frac{[2(V_{T2} - V_{L2I}) - V_{L1I}]}{2V_{L1I}} \frac{(H_{LI} - H_{LF})}{H_{LA}} \qquad (A.24)$$

Given Q_V, Equation A.20 is solved for ΔP_2

$$\Delta P_2 = \frac{\dfrac{P_A M_2}{T_G} \left(\dfrac{Q_V}{983.2\ A_{2A}} \right)^2}{\left[1 - \dfrac{M_2}{T_G} \left(\dfrac{Q_V}{983.2\ A_{2A}} \right)^2 \right]} \qquad (A.25)$$

Equation A.19 is solved for ΔP_1

$$\Delta P_1 = \frac{(P_A + \Delta P_2) M_2}{T_G} \left[\frac{Q_L \dfrac{[P_A + \Delta P_2 (1 + C_2)]}{(P_A + \Delta P_2)} - Q_V}{983.2\ A_{21}} \right]^2 - \Delta P_2 \qquad (A.26)$$

Equation A.21 is solved for Q_T

$$Q_T = \frac{(P_A + \Delta P_2)\, Q_V}{P_A} - \frac{Q_L}{P_A}[\Delta P_1(1-C_1) + \Delta P_2(1 + C_2)] \qquad (A.27)$$

Finally, Equation A.22 is solved for A_{A1}

$$A_{A1} = \frac{Q_T}{983.2\sqrt{\frac{T_G \Delta P_1}{M_A P_A}}} \qquad (A.28)$$

A.4 COMPUTER CHECK CASE

Parameters of the computer solution (Reference 1) were fed into the equations

H_{LI} = 68.4 + 60 + 96 - 42.9 = 181.5"

H_{LF} = 0 + 60 + 96 - 62.7 = 93.3"

H_{LA} = 34.2 + 60 + 96 - 52.8 = 137.4"

V_{T1} = 2174 gal

V_{L1I} = 2065 gal

V_{T2} = 10,000 gal

V_{L2I} = 4,465 gal

P_A = 407 in.H_2O

M_2 = 45.69 lbm/lbmol

T_G = 540°R

A_{A2} = 1.2275 in.^{2}

A_{21} = 1.1 in.^{2} for 2 in. hose, 2.475 in.^{2} for 3 in. hose

Q_L = 420 gpm

M_A = 45.69 lbm/lbmol

$$C_1 = \left(\frac{2(2174) - 2065}{2(2065)}\right)\left(\frac{181.5 - 93.3}{137.4}\right) = .355 \qquad 1 - C_1 = .645$$

$$C_2 = \left(\frac{2(10) - 4.465}{2(2.065)}\right)\left(\frac{181.5 - 93.3}{137.4}\right) = 2.415 \quad 1 + C_2 = 3.415$$

Case 1 2" Hose - $A_{21} = 1.1$

Computer result:

$A_{A1} = 0.0$ in.^{2}, $Q_V/Q_L = 0.659\%$, $\Delta P_1 = 4.9$ in. H_2O

Steady State results:

$Q_V/Q_L = 0.810\%$, $Q_V = 3.4027$gpm, $\Delta P_2 = 2.737E\text{-}4$ in. H_2O

$\Delta P_1 = 5.107$ in. H_2O, $Q_T = 0.001$gpm, $A_{A1} = 2.645E\text{-}6$ in.^{2}

$D_{A1} = 0.0022$ in at $C_{Re} = 0.7$

Case 2 3" Hose - $A_{21} = 2.475$

Computer Result:

$A_{A1} = 0.07179$ in.^{2}, $Q_V/Q_L = 2.93\%$, $\Delta P_1 = 1.04$ in. H_2O

Steady State result:

$A_{A1} = 0.07179$ in.^{2}, $Q_V/Q_L = 2.965\%$, $Q_V = 12.45$gpm

$\Delta P_2 = 3.66E\text{-}3$ in. H_2O, $\Delta P_1 = 0.9623$ in. H_2O, $Q_T = 11.80$gpm

$D_{A1} = 0.375$ in. at $C_{Re} = 0.65$

A.5 ACTUAL CALCULATIONS

Assume a 2000 gallon drop into a 10,000 gallon service station tank with 4000 gallons of fuel in it. The tank is assumed to be buried 3 feet deep and be 8 feet in diameter. Truck compartments are assumed to be 5 feet above ground and 60 inches high. A 10% truck vapor space is assumed. The vent line is assumed to be 100 feet of 2 inch diameter schedule 40 pipe having 7 standard elbows.

The area of a segment of a circle (A(sector) - A (triangle)) is related to the included angle of a triangle by the following relations from Reference 2.

$A(\text{sector}) = 1/2\ R^2(\Theta - \sin\Theta)$ (A.29)

$d(\text{distance to chord of sector}) = R\ \cos\frac{\Theta}{2}$ (A.30)

By assuming a flat ended tank 4000 gallons becomes $.4\pi R^2$ area or

$.8\pi = 2.5133 = \Theta - \sin\Theta$

$\Theta = 2.825$

$d = 7.57$ in.

6000 gallons becomes

$1.2\pi = 3.7699 = \Theta - \sin\Theta$

$\Theta = 3.4583$

$d = 7.57$ in.

Accordingly

$H_{LI} = 60 + 84 + 96 - 40.43 = 199.57$ in.

$H_{LF} = 0 + 84 + 96 - 55.57 = 124.43$ in.

$H_{LA} = 162.0$ in.

$V_{T1} = 2200$ gal

$V_{L1I} = 2000$ gal

$V_{T2} = 10,000$ gal

$V_{L2I} = 4,000$ gal

$P_A = 407$ in. H_2O

$M_2 = 44.58$ lbm/lbmol

$T_G = 540°R$

$A_{21} = 1.1$ in.^{2} for 2 in. Hose; 2.475 in.^{2} for 3 in. Hose

$Q_L = 420$gpm

$M_A = 28.97$

$A_{A2} = f(Q_V)$ in.^{2} (calculated below)

$$C_1 = \left(\frac{2(1.1) - 1}{2} \right) \left(\frac{199.57 - 124.43}{162.00} \right) = 0.278 \qquad (1 - C_1) = 0.722$$

$$C_2 = \left(\frac{2(10\text{-}4) - 2}{2 \times 2} \right) \left(\frac{199.57 - 124.43}{162.0} \right) = 1.160 \qquad (1 + C_2) = 2.16$$

A_{A2} = 100 ft of 2 in. Schedule 40 pipe with 7 Els at a L/D= 30 and K ent + K exit = 1.5 (Reference 3, Appendix A).

The equivalent orifice area can be calculated from the relation

$$\frac{1}{D_p^{\,4}} \left(4f \times \frac{L}{D} (\text{pipe + fittings}) + K\right) = \frac{1}{D_{2A}^{\,4}} \tag{A.31}$$

where 4f is a function of Reynolds Number Re

$$Re = \left(\frac{\rho V D}{\mu} \right) = \left(\frac{4 \rho Q}{\pi \mu D_p} \right) \tag{A.32}$$

and the relationship is (Reference 4, Chapter 6)

$$4f = \frac{64}{Re} \quad (Re \leq 2000) \tag{A.33}$$

$$4f = \frac{.3164}{Re^{.25}} \quad (Re > 2000) \tag{A.34}$$

This latter expression does not hold for all size pipes but does hold over 2 in. Schedule 40 pipe for the range of Re > 2000 to our interest.

To evaluate Equation A.32 the viscosity of the hydrocarbon-vapor air mixture is computed using the method of Maxwell, (Reference 5, Chapter 9) for gas at atmospheric pressure

$$\mu \text{ mix} = \frac{Y_1 \mu_1 \sqrt{M_1} + Y_2 \mu_2 \sqrt{M_2}}{Y_1 \sqrt{M_1} + Y_2 \sqrt{M_2}} \tag{A.35}$$

$$\mu = \frac{.601\,(.0189)\sqrt{28.97} + .399\,(0.0082)\sqrt{66.7}}{.601\sqrt{28.97} + .399\sqrt{66.7}}$$

$$\mu = 0.0136 \text{ cp } * .00336 = 4.57 \times 10^{-5} \frac{\text{lbm}}{\text{in. min}}$$

$$\rho = \frac{PM}{RT} = \frac{14.7 \quad 44.48}{10.7315\,(540) \quad 7.48} = 0.01512 \frac{\text{lbm}}{\text{gal}}$$

$$Re = 421 \frac{Q_V}{D_p} = 210.5\,(Q_V \text{ gpm}) \qquad (A.36)$$

The actual calculations reduce down to the following steps.

1. Given $\%Q_V/Q_L$, Q_V is calculated
2. Reynolds number (Re) is calculated using Equation A.36
3. 4f and D_{2A} are calculated using Equation A.33, A.34 and A.31
4. D_{2A} is expressed as a flow area $A_{2A}(C_{Re} = 1.0)$
5. Equation A.20 is solved for ΔP_2
6. Equation A.19 is solved for ΔP_1
7. Equation A.21 is solved for Q_T
8. Equation A.28 is solved for A_{A1}
9. A_{A1} is expressed as D_{A1} at $C_{Re} = 0.7$

Calculations are shown in Table A.1 and shown in Figures A.2 and A.3.

A.6 NOMENCLATURE

A(sector)	defined Equation A.29
A_{A1}	tank truck equivalent leakage area, $in.^2$
A_{21}	vapor path equivalent flow area, $in.^2$
A_{2A}	S.S. tank vent line equivalent flow area, in^2
C_1	constant defined by Equation A.23, dimensionless
C_2	constant defined by Equation A.24, dimensionless
C_{Re}	orifice flow coefficient, dimensionless
d	defined Equation A.30
D	diameter
D_{A1}	truck leakage equivalent orifice, in. at $C_{Re} = 0.7$
D_{2A}	vent line equivalent diameter, in. at $C_{Re} = 1.0$
D_p	vent line pipe diameter, 2 in.
f	pipe friction factor, dimensionless
H_{LI}	initial liquid head, in.
H_{LF}	final liquid head when Tank 1 drained, in.
H_{LA}	average liquid head, in.
K	flow factor, dimensionless
M_A	mole weight air, 28.97 lbm/lbmol
M_2	mole weight vapor-air mixture, lbm/lbmol
N_{V1}	moles of gas in V_{G1}, lbmol
N_{V2}	moles of gas in V_{G2}, lbmol
N_{VA1}	moles/sec of gas flowing into Tank 1, lbmol/sec
N_{V21}	moles/sec of vapor return, lbmol/sec
N_{V2A}	moles/sec of vapor vented, lbmol/sec
P_A	ambient pressure, in. H_2O absolute
P_1	absolute Tank 1 pressure, in H_2O
P_2	absolute Tank 2 pressure, in H_2O
ΔP_1	Tank 1 vacuum (Equation A.8), in H_2O
ΔP_2	Tank 2 pressure (Equation A.9), in H_2O

Q_L	average liquid drop rate, gpm
Q_V	average vent flow, gpm
Q_T	average truck leakage, gpm
R	universal gas constant, 10.7315 (psia x cf)/(lbmol x R)
Re	Reynolds number, dimensionless
T_G	absolute temperature, °R
t_F	drop time, min
V_{T1}	volume Tank 1, gal
V_{L1}	volume liquid Tank 1, gal
V_{G1}	volume vapor Tank 1, gal
V_{T2}	volume Tank 2 gal
V_{L2}	volume liquid Tank 2, gal
V_{G2}	volume vapor Tank 2, gal
Y_i	mole fraction vapor, dimensionless
ρ	density, lbm/cf.
π	Pi, 3.14156
μ	absolute viscosity, lbm/in. min

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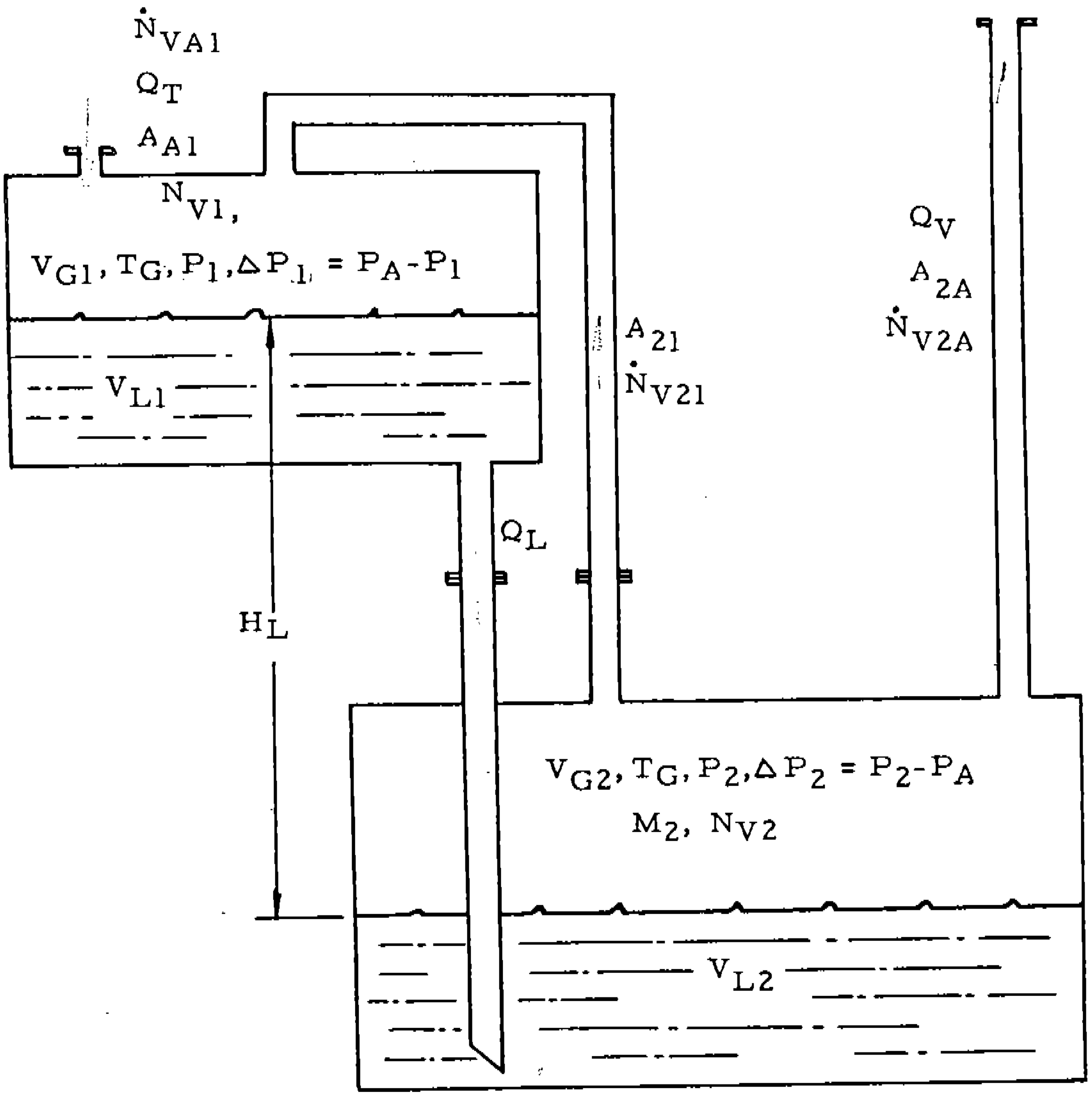

Figure A.1 MODEL SCHEMATIC

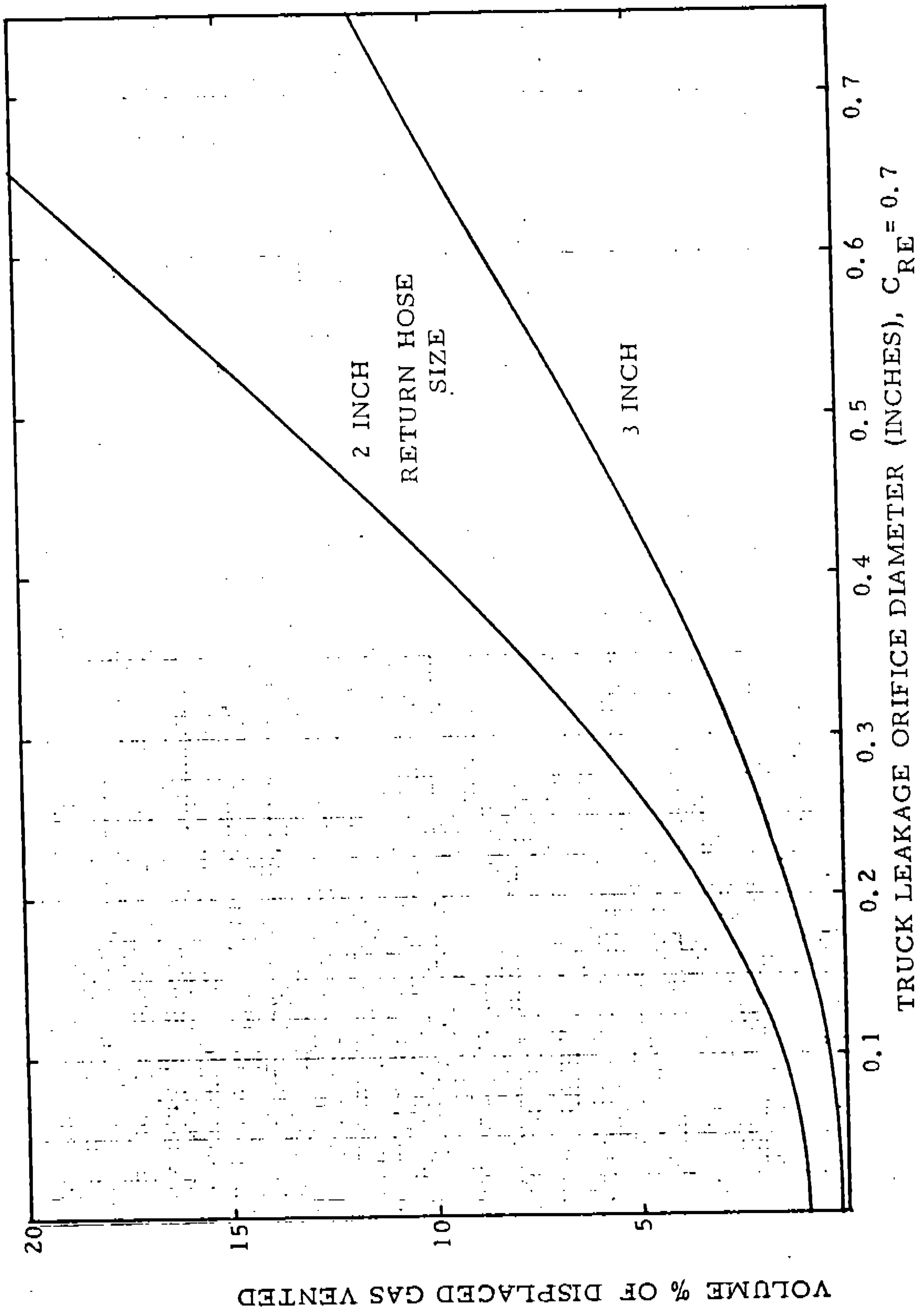
2 INCH
RETURN HOSE SIZE
3 INCH
0.1
0.2
0.3
0.4
0.5
0.6
0.7
TRUCK LEAKAGE ORIFICE DIAMETER (INCHES), $C_{RE} = 0.7$
5
10
15
20
VOLUME % OF DISPLACED GAS VENTED

Figure A.2

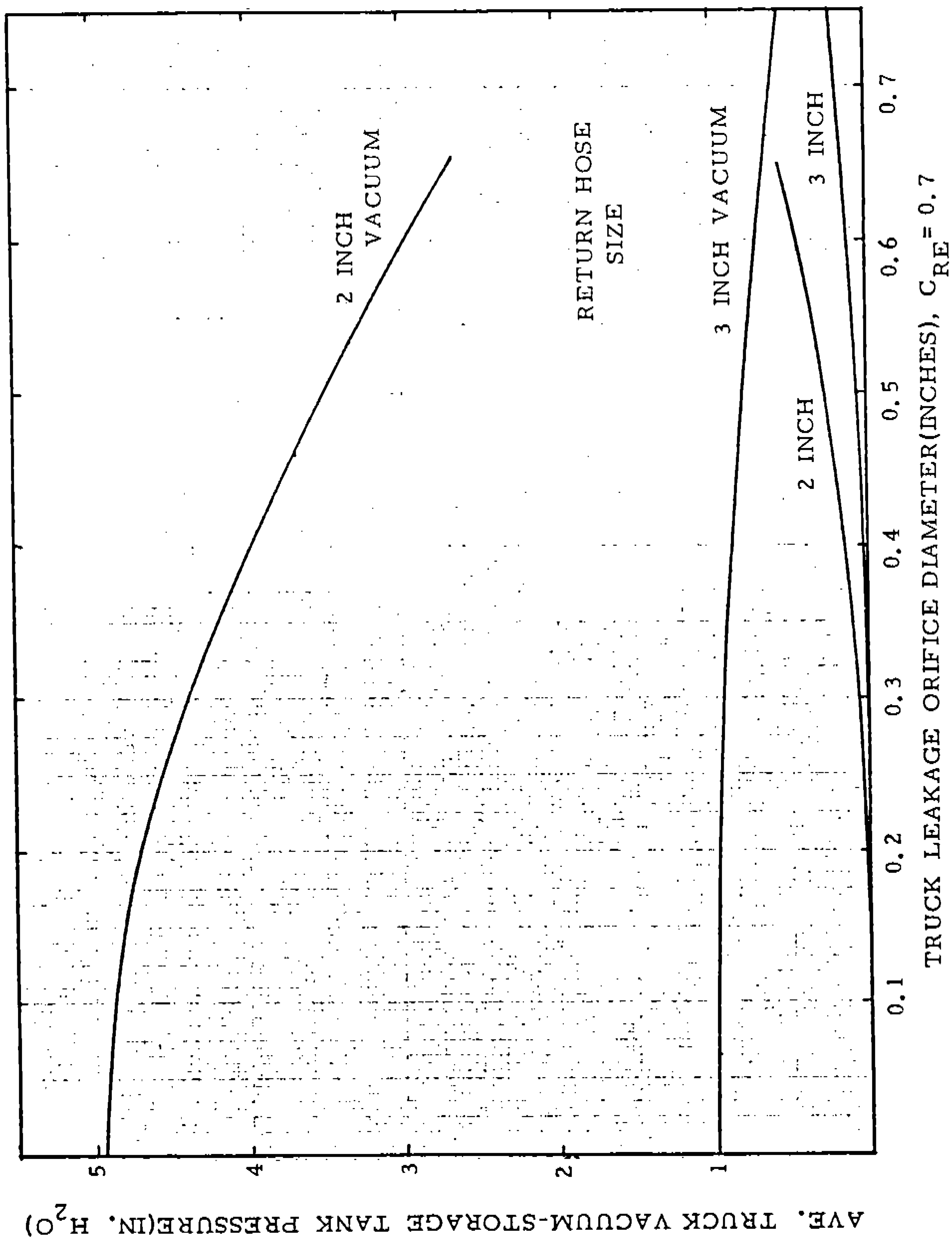
2 INCH VACUUM
RETURN HOSE SIZE
3 INCH VACUUM
2 INCH
3 INCH
TRUCK LEAKAGE ORIFICE DIAMETER(INCHES), C_{RE} = 0.7
0.1
0.2
0.3
0.4
0.5
0.6
0.7
AVE. TRUCK VACUUM-STORAGE TANK PRESSURE(IN. H_2O)
1
2
3
4
5

Figure A.3

TABLE A.1 VENT FLOW Vs TRUCK LEAKAGE CALCULATIONS

	Q_V/Q_L	0.25	0.5	1.0	1.5	2.0	3.0	4.0	5.0
	Q_V	1.05	2.1	4.2	6.3	8.4	12.6	16.8	21.0
	Re	221.0	442.1	884.1	1326	1768	2652	3536	4421
	$C_{Re=1.0}$ D_{2A}	.5102	.6058	.7182	.7924	.8488	.8098	.8238	.8349
	A_{2A}	.2045	.2883	.4051	.4931	.5659	.5150	.5331	.5475
3" HOSE	P_2	9.16-4	.00184	.00374	.00567	.00766	.0208	.0345	.0511
3" HOSE	P_1	.9950	.9891	.9773	.9655	.9537	.9211	.8882	.8526
3" HOSE	Q_T	.3066	1.359	3.464	5.568	7.673	11.87	16.06	20.25
3" HOSE	A_{A1}	.00146	.00649	.01665	.0269	.0373	.0588	.0810	.1042
3" HOSE	$C_{Re=.7}$ D_{A1}	.05155	.1087	.1740	.2213	.2606	.3269	.3838	.4354
2" HOSE	P_2			.00374	.00567	.00766	.02081	.03452	.05114
2" HOSE	P_1			4.963	4.911	4.859	4.748	4.637	4.524
2" HOSE	Q_T			.4942	2.629	4.763	9.017	13.27	17.52
2" HOSE	A_{A1}			.00105	.00564	.01027	.01967	.0293	.0391
2" HOSE	$C_{Re=7}$ D_{A1}			.04378	.1012	.1366	.1891	.2308	.2668

TABLE A.1 (Cont.) VENT FLOW Vs TRUCK LEAKAGE CALCULATIONS

	Q_V/Q_L	6.0	7.0	8.5	10.0	12.0	15.0	17.5	20.0
	Q_V	25.2	29.4	35.7	42.0	50.4	63.0	73.5	84.0
	Re	5305	6189	7515	8841	10610	13260	15470	17680
	$C_{Re=1.0}$ D_{2A}	.8440	.8518	.8617	.8700	.8794	.8910	.8991	.9062
	A_{2A}	.5595	.5698	.5831	.5944	.6074	.6236	.6350	.6450
3" HOSE	P_2	.0705	.0926	.1303	.1736	.2395	.3551		
	P_1	.8144	.7738	.7086	.6384	.5373	.3705		
	Q_T	24.44	28.62	34.89	41.16	49.50	61.99		
	A_{A1}	.1287	.1546	.1970	.2448	.3209	.4840		
	$C_{Re=.7}$ D_{A1}	.4838	.5303	.5985	.6672	.7639	.9381		
2" HOSE	P_2	.07052	.0926	.1303	.1736	.2395	.3551	.4662	.5904
	P_1	4.410	4.294	4.117	3.937	3.693	3.318	2.998	2.671
	Q_T	21.76	26.00	32.35	38.70	47.14	59.79	70.31	80.82
	A_{A1}	.0492	.0596	.07578	.0927	.1166	.1560	.1930	.2350
	$C_{Re=.7}$ D_{A1}	.2992	.3293	.3712	.4105	.4604	.5326	.5924	.6537

R. A. Nichols
Engineering

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APPENDIX 3B

ANALYTICAL CALCULATION OF FUEL TRANSIT BREATHING LOSS

by

Richard A. Nichols, Ph.D.

March 21, 1977

B.1 SUMMARY

A stirred tank model is used to approximate tank truck transit breathing loss following truck refueling and following a fuel drop at the service station. The results are rather startling.

The solution to the equations describing the open venting of an ambient pressure tank truck are calculated. The solution is also derived for tank venting with an ideal P/V valve; that is, no venting occurs until tank pressure reaches vent valve opening pressure. At vent valve opening pressure free venting is assumed to occur.

For truck transit with a full fuel load from the terminal, venting is assumed to occur until the fuel vapor space is saturated to fuel vapor pressure.

For truck transit with an empty truck returning from the service station, the observation that truck vapor spaces are about 20% saturated without vapor return is used to approximate the amount of residual fuel available for evaporation. This same amount of fuel is assumed to evaporate into partially saturated vapor spaces unless such vaporization would cause vapor space vapor concentrations to exceed fuel vapor pressure.

Since in practice there is leakage with tank truck vent valves, this situation was approximated by applying the isothermal blowdown equation to determine the length of time before truck vent space pressure is again ambient or the residual vent space pressure after a 60 minute blowdown.

For truck truck transit with a full load of fuel the vent space is so small that even quite small leaks will leak off pressure in the vent space. With the smallest leakage criteria proposed (i.e. 0.5 inch drop from 22 inches in 5 minutes) and with a vent space equal to 15% of the compartment capacity, vent space pressure had a slight residual (0.9 inches of water). In all other cases the pressure would

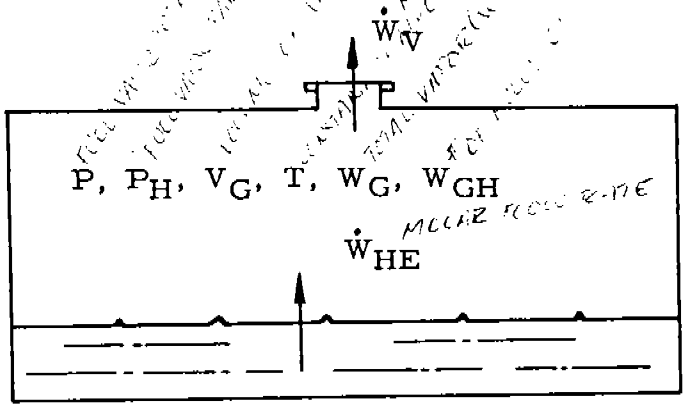
be completely dissipated. By assuming no evaporation during blowdown, blowdown loss was calculated. The single case where the P/V valve showed a residual pressure was calculated separately.

For truck transit following a fuel drop leakage was again calculated. With only a limited amount of fuel available for evaporation, calculations vary with the degree of fuel saturation present. Further since the vapor volume is much larger, residual pressures are present in the case of more restrictive leakage criteria. By using the fact that no further evaporation can occur, leakage losses were again calculated.

Finally vapor savings during transit, because of the P/V valve, were calculated both following refueling and following a fuel drop. Savings are shown to be minimal. After refueling savings can actually be negative where small initial tank vapor saturations are present. These situations occur when vapor return from the service station is not required. Vapor savings following fuel drops increase with tank tightness and vapor return with highly saturated vapors. With all but the most restrictive tank tightness requirements vapor savings can be negative. The reason is higher concentration vapors will be vented with a pressure vacuum valve during transit leakage. The remaining tank vapor on arriving at the terminal can actually then have less fuel vapor with a vent valve than without.

B.2 MODEL DESCRIPTION

An isothermal stirred tank model has been used for venting calculations. A schematic is shown below



Evaporation from fuel is represented by molar flow rate $\dot{W}_{HE}$, into the stirred tank vapor space V_G. The number of moles of fuel vapor W_{GH} and total vapor W_G in V_G are proportional to the fuel vapor partial pressure P_H and total pressure P respectively. $\dot{W}_V$ moles of gas are vented at pressure P (open venting) or pressure P_V (ideal vent valve pressure, see Section B.4). Temperature (T) is assumed constant.

B.3 OPEN VENT DERIVATION

Assume constant vapor volume (V_G, cf)and temperature (T, °R). Since the number of moles of vapor (W_G) is then constant, the number of moles evaporating from the surface ($\dot{W}_{HE}$) is equal to the number of moles of gas vented ($\dot{W}_V$), assuming the ideal gas law is valid. i.e.

$$\dot{W}_{HE} = \dot{W}_V \tag{B.1}$$

The moles of fuel vapor W_{GH} in W_G is

$$W_{GH} = \frac{P_H V_G}{RT} \tag{B.2}$$

The rate of change in the amount of fuel vapor in V_G is

$$\frac{dW_{GH}}{dt} = \dot{W}_{HE} - \dot{W}_V \frac{P_H}{P} \tag{B.3}$$

By substituting Equation B.1 and B.2 and remembering our constant temperature assumption the number of moles of gas evaporated and in turn vented are

$$\int \dot{W}_V dt = \int \dot{W}_{HE} dt = \frac{PV_G}{RT} \ln \left(\frac{P-P_{HI}}{P-P_{HF}} \right) \tag{B.4}$$

The number of moles of fuel vapor vented is then found by combining Equations B.2, B.3 and B.4

$$\int \dot{W}_V \frac{P_H}{P} dt = \frac{PV}{RT} \left[\ln\left(\frac{P-P_{HI}}{P-P_{HF}} \right) + \left(\frac{P_{HI}}{P} - \frac{P_{HF}}{P} \right) \right] \tag{B.5}$$

The volume of vapor-air mixture vented (V_V) to vent space V_G is (moles vapor vented) x (volume/mole)

$$\frac{V_V}{V_L} = \frac{RT}{PV_L} \int \dot{W}_V dt = \frac{V_G}{V_L} \ln \left(\frac{P-P_{HI}}{P-P_{HF}} \right) \tag{B.6}$$

It is sometimes more convenient to equate the initially present fuel vapor pressure (P_{HI}) in terms of a vapor saturation factor (S_1) and the vapor pressure of the fuel present (P°_H). Similarly it is convenient to express the final fuel vapor pressure (P_{HF}) in terms of a final vapor saturation factor (S_2) and the fuel vapor pressure (P°_H). In terms of these variables Equations B.6 and B.5 become

$$V_V/V_L = \frac{V_G}{V_L} \ln \left(\frac{P - S_1 P^\circ_H}{P - S_2 P^\circ_H} \right) \tag{B.7}$$

$$M \int W_V \frac{P_H}{P} dt = M \frac{PV}{RT} \left[\ln\left(\frac{P - S_1 P^\circ_H}{P - S_2 P^\circ_H} \right) + \frac{P^\circ_H}{P} (S_1 - S_2) \right] \tag{B.8}$$

For transit from the terminal to the station S_2 is normally considered saturated (i.e. $S_2 = 1.0$).

B.4 IDEAL VENT VALVE DERIVATION

In the case of a perfect vent valve no venting occurs until the vent release pressure is reached. At that point, we assume open venting occurs. Accordingly the overall mass balance becomes

$$\frac{dW_G}{dt} = \dot{W}_{HE} \qquad P < P_V \tag{B.9}$$

$$\dot{W}_{HE} = \dot{W}_V \qquad P = P_V \tag{B.10}$$

Since the second case has already been solved for the open vented system with $P = P_V$, we proceed with Case 1. The ideal gas law in terms of moles of gas present is

$$W_G = \frac{PV_G}{RT} \tag{B.11}$$

The molar balance for fuel vapor is

$$\frac{dW_{GH}}{dt} = \dot{W}_{HE} \tag{B.12}$$

And, the ideal gas law for fuel vapor in V_G is Equation B.2. By substituting Equation B.11 into B.9 and Equation B.2 into B.12 and integrating we have

$$\int_1^2 \dot{W}_{HE} dt = \frac{V_G}{RT} (P_F - P_I) = \frac{V_G}{RT} (P_{HF} - P_{HI}) \qquad (B.13)$$

or

$$P_F = P_I + (P_{HF} - P_{HI}) = P_I + P_H^{\circ} (S_2 - S_1) \qquad (B.14)$$

If when P_{HF} is substituted into Equation B.14, P_F is less than P_V, ideally no venting occurs. If on substitution $P_F > P_V$, then P_V, is substituted into Equation B.14 and

$$P_{HI}^{*} = P_{HF} = P_{HI} + (P_V - P_I) \qquad (B.15)$$

where $P_{HI}^{*} \leq P_H^{\circ}$. This new variable becomes the initial condition for the open venting condition at $P = P_F$.

Combining the transient and open venting cases we have

$$\int \dot{W}_{HE} dt = \frac{V_G}{RT} [(P_V - P_I) + P_V \ \ln (\frac{P_V - S_1^{*} P_H^{\circ}}{P_V - S_2^{*} P_H^{\circ}})] \qquad (B.16)$$

where

$$S_1^{*} = 1 + \frac{P_V - P_I}{P_H^{\circ}} \leq 1 \qquad (B.17)$$

If $S_1{*} > 1$ then

$$P_F = P + P_H^{\circ}(1 - S_1) \qquad (B.18)$$

and no venting occurs. The amount of vapor evaporated is then given by Equation B.13.

The volume of vapor vented by analogy to Equation B.6 is

$$\frac{V_V}{V_L} = \frac{RT}{PV_L} \int_2^3 \dot{W}_V dt = \frac{V_G}{V_L} \frac{P_V}{P} \ln (\frac{P_V - S_1^{*} P_H^{\circ}}{P_V - S_2^{*} P_H^{\circ}}) \qquad (B.19)$$

and the number of moles of vapor vented is by analogy to Equation B.5

$$\int_2^3 W_V \frac{P_H}{P_V}\, dt = \frac{P_V V_G}{RT} \left[\ln \left(\frac{P_V - S_1^* P_H^\circ}{P_V - S_2^* P_H^\circ} \right) + \frac{P_H^\circ}{P_V} (S_1^* - S_2^*) \right] \qquad (B.20)$$

B. 5 VENT LOSS FOLLOWING REFUELING

Consider truck to service station loss in Sacramento during the summer. Data on average summer properties is given in Reference 1 and 2.

$P = 14.7$psia $\quad P_H^\circ = 5.87$ psia $\quad T = 74.1°F = 534.1°R$

$M_H = 66.7$ lbm/lbmol $\quad P_V = 27.$ in.H_2O = 15.675 psia

$S_2 = 0,\ 0.2,\ 0.5,\ 0.85,\ 0.95$

Equation B.8 was evaluated to calculate gm/gal liquid when V_G/V_L is given

$$gm/gal = 0.7057 \left(\frac{V_G}{V_L}\right) P \left[\ln \left(\frac{P - S_1 P_H^\circ}{P - S_2 P_H^\circ} \right) + \frac{P_H^\circ}{P} (S_1 - S_2) \right] \qquad (B.21)$$

For venting on the way to the service station, the various S_1 given above were used and $S_2 = 1.0$. The latter value assumes enough fuel is present to completely saturate the residual vapor space.

A vent valve opening at 27 inches of water opening pressure is used for these calculations.

When S_1^* calculated by Equation B.17 is greater than 1.0, there is no venting as tank saturation was reached before the P/V valve setting. In this case tank pressure is determined from Equation B.18.

When S_1^* calculated by Equation B.17 is less than 1.0, the volume of vapor vented is calculated using Equation B.19 and the gm/gal of vapor is calculated using a modification of B.20

$$\frac{gm}{gal} = 0.7057 \frac{V_G}{V_L} P_V \left[\ln \left(\frac{P_V - S_1^* P_H^\circ}{P_V - S_2^* P_H^\circ} \right) + \frac{P_H^\circ}{P_V} (S_1^* - S_2^*) \right] \qquad (B.22)$$

In Equations B.19 and B.22 given above $S_2^* = 1.0$. This assumes there is enough fuel in the compartment to saturate the vapor space.

Venting calculations with and without an ideal P/V valve opening at 27 inches of water are shown in Table B.1.

B.6 VENT LOSS FOLLOWING A FUEL DROP

The transit loss following a fuel drop calculation is based upon the observation that trucks drop loaded at service stations arrive back at the terminal with an average vapor saturation of 20%. We assume this same amount of vapor will be evaporated in cases where the initial vapor in the tank is partially saturated, unless the tank becomes saturated with a smaller amount of vaporization.

The amount of fuel vaporized to give a vapor concentration of 20% is calculated from Equation B.7 by setting $S_1 = 0.0$ and $S_2 = 0.2$. The vapor loss with an ambient vent is given by Equation B.21.

To find the initial saturation corresponding to any given higher final saturation, we solve Equation B.7 for the value of S_1 which gives the same amount of evaporation as in the base case ($S_1 = 0.0$, $S_2 = 0.2$). Having determined S_1, vapor loss is calculated using these new values of S_1 and S_2 in Equation B.16. The reason for determining S_1 from S_2 is the values have been observed and estimated for truck vapor concentrations initially present during refueling.

When an ideal vent value is present the initial condition S_1 has been assumed as calculated above. The value of S_2 is determined by calculating the amount of hydrocarbons vaporized with an ideal vent value (Equation B.16) with the amount of fuel vaporized in the Base case (Equation B.4; S_1=0, S_2=0.2). Values of S_2 greater than 1.0 correspond to saturation being reached before all the available fuel is vaporized. Since saturation stops the vaporization the calculation is stopped there.

Venting calculations with and without an ideal P/V valve opening at 27 inches of water are shown in Table B.2

B.7 TRANSIT LEAKAGE FOLLOWING REFUELING

When a truck is refueled the vapor space above the fuel is composed of a combination of initial and refueling generated vapors. The proportion of each depends upon the turbulence generated during refueling, the initial fuel space vapor concentration, and the fraction of total tank volume which remains as vapor space.

When the tank truck departs from the terminal for the trip to the service station the load is subject to agitation, which tends to cause fuel vapor space mixing and consequent fuel evaporation. This happens rather quickly; and, depending on initial vapor space saturation and loading method, considerable vapor can be generated. If enough vapor is generated the tank pressure will rise to the relief valve opening pressure and a vapor-air mixture will be vented. For these calculations, we assume venting will occur at the DOT pressure limit of 27 inches of water. Since DOT requires relief valves to open by this pressure but gives no minimum opening pressure, the assumption of 27 inches of water as venting pressure is the most conservative allowable meeting the law.

It is possible that the fuel loaded into the tank truck is not in equilibrium with air at the fuel vapor pressure. This can happen since fuels are manufactured in an air deficient atmosphere and stored in floating roof tanks which restrict the fuel surface area available for air absorption. If this is the case air absorption can occur in the tank truck vapor space and a vacuum can be pulled on the vapor space. Since the ability of fuel to dissolve air is much more limited than its ability to dissolve volatile fuel components, evaporation effects are much faster than air absorption effects. The latter are more diffusion dependent. The point is that air absorption effects will not usually restrict initial tank venting caused by

evaporation but air absorption will reduce tank blowdown leakage from vent valve pressure.

Tank blowdown time, leakage, and blowdown relationships were given in Reference 3, Equation 4. By using this relationship the equivalent orifice diameter, at an inlet orifice coefficient of $C_{Re} = 0.7$, was calculated for 5 minute blowdowns from 22 inches of water pressure for different allowable pressure drop (ΔP) versus time transients. Results are shown in Table B.3.

By using these orifices (shown previously in Reference 3), blowdown times were calculated for a 5000 gallon tank with 5, 10 and 15% vent spaces. The results are again shown in Table B.3. All tank vent space pressure is dissipated within 60 minutes except for the 0.5 inch blowdown criteria from 27 inches of water with a 15% vent space. Residual pressure in this single case was 0.9 inches of water.

The blowdown loss after refueling assuming no evaporation takes place during blowdown is

$$\text{Blowdown Loss} = \frac{(P_F - P)}{P_F} \quad \frac{P_H^\circ M_H}{R\ T} \quad \frac{V_G}{V_L}$$

$$= \left(\frac{P_F - P}{P_F} \right) \frac{V_G}{V_L} \ 4.142 \text{ gm/gal}$$

Calculations are shown in Table B.4.

B.8 P/V SAVINGS FOLLOWING REFUELING

P/V valve savings following refueling can be expressed as

OPEN VENT LOSS	(TABLE B.1)
- 27 IN. VENT LOSS	(TABLE B.1)
- BLOWDOWN LOSS	(TABLE B.4)
P/V VALVE SAVINGS	(TABLE B.5)

Table B.5 shows that losses can occur with a P/V valve. The reason is a more concentrated vapor is being vented during blowdown. If we had assumed that vapor space saturation continued to take place, loss during blowdown would have been higher reflecting the evaporation which takes place.

The reason for the added line in Table B.5 is that complete blowdown is not achieved in 60 minutes with an orifice corresponding to the 0.5 inch blowdown criteria. Consequently there is some added savings with a P/V valve in this case for low initial vapor space saturation refueling conditions.

B.9 TRANSIT LEAKAGE FOLLOWING FUEL DROP

When a truck leaves the service station after a drop, the tank has a small amount of residual fuel in it and a load of injested air and/or service station tank vapor. The fraction service station tank vapor depends upon having vapor transfer at the station and the leak tightness of the vapor space piping and tank truck.

The amount of residual fuel which will be evaporated depends upon the vapor concentration of the truck vent space following the drop. The maximum loss that could occur would be if the residual fuel immediately vaporized causing vapor venting from the tank at the highest initial tank pressure. These losses would be greatest since the ΔP for leakage would always be the greatest.

By assuming a 5000 gallon compartment and the blowdown equation used previously and presented in Reference 3 as Equation 4, pressure versus orifice diameters relationships were derived for 1 hour blowdown from 27 inches of water. Results of the calculations are shown in Table B.6 and Figure B.1.

Orifice diameters in Figure B.1 are related to saturated molecular weight M = 44.036. To adjust the diameter to other molecular weights we use the relationship

$$D^2 = D_{B.1}^{\;2} \sqrt{\frac{M}{44.036}}$$

where

$$M = (1-S_2^* \, .399)\, 28.97 + S_2^*(.399) 66.7$$

and S_2^* is the saturation fraction from Table B.2. Having determined the new equivalent diameter, the new residual pressure can be determined from Figure B.1.

The amount of vapor lost during blowdown, assuming the vapor concentration remains constant (i.e. No liquid remains to evaporate) is

$$\text{Blowdown Loss} = S_2^* \frac{(27-\ P_R)}{434} \frac{V_G}{V_L} \frac{5.87(66.7)}{10.7315(534.1)} \frac{(453.59)}{(7.48)}$$

$$= S_2^* (27-\ P_R) \frac{V_G}{V_L} \frac{4.142}{434} \frac{gm}{gal}$$

Calculations of blowdown loss are shown in Table B.7.

B.10 P/V SAVINGS FOLLOWING FUEL DROP

P/V valve savings following fuel drop can be expressed as

OPEN VENT LOSS	(TABLE B.2)
-27 IN. VENT LOSS	(TABLE B.2)
-BLOWDOWN LOSS	(TABLE B.7)
P/V VALVE SAVINGS	(TABLE B.8)

The interesting aspect is that the P/V valve can actually cause vapor losses over a more freely vented system. The reason is the P/V valve dilutes the vapor concentration remaining in the tank. If there is no more fuel to vaporize and a P/V valve tight enough to cause venting at P/V valve pressure, the remaining vapor concentration will be slightly less than without the P/V valve. If leakage brings the tank pressure back to ambient pressure before arriving at the terminal the residual vapor concentration will be slightly less than in the open venting situation. In this case which is representative of a relatively tight tank (3 to 4 inch pressure fall off in 5 minutes) the P/V valve causes greater vapor loss.

B.11 NOMENCLATURE

M	Vapor-air mixture mole weight, lbm/lbmol
M_H	Fuel vapor mole weight, lbm/lbmol
P	Atmospheric pressure, psia
P_F	Final pressure, psia
P_H°	Fuel vapor pressure, psia
P_{HF}	Final fuel vapor pressure, psia
P_{HI}	Initial fuel vapor pressure, psia
P_V	Vent pressure, psia
R	Universal gas constant, 10.7315 (psia x cf)/(lbmol x °R)
S_1	Initial % vapor saturation
S_1^*	Vent valve pressure, initial % vapor saturation
S_2	Final % vapor saturation
S_2^*	Vent valve pressure, final % vapor saturation
T	Ambient temperature, °R
V_G	Vapor space volume, cf
V_L	Liquid fuel volume, cf

B. 12 REFERENCES

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2. Evaporation Loss in the Petroleum Industry - Causes and Control. American Petroleum Institute. Washington, D.C. API Bulletin 2513. February, 1959.

3. Nichols, R. A. Comments on Proposed CARB Tank Truck Leakage Criteria. R. A. Nichols Engineering. Corona Del Mar, California. January 18, 1977.

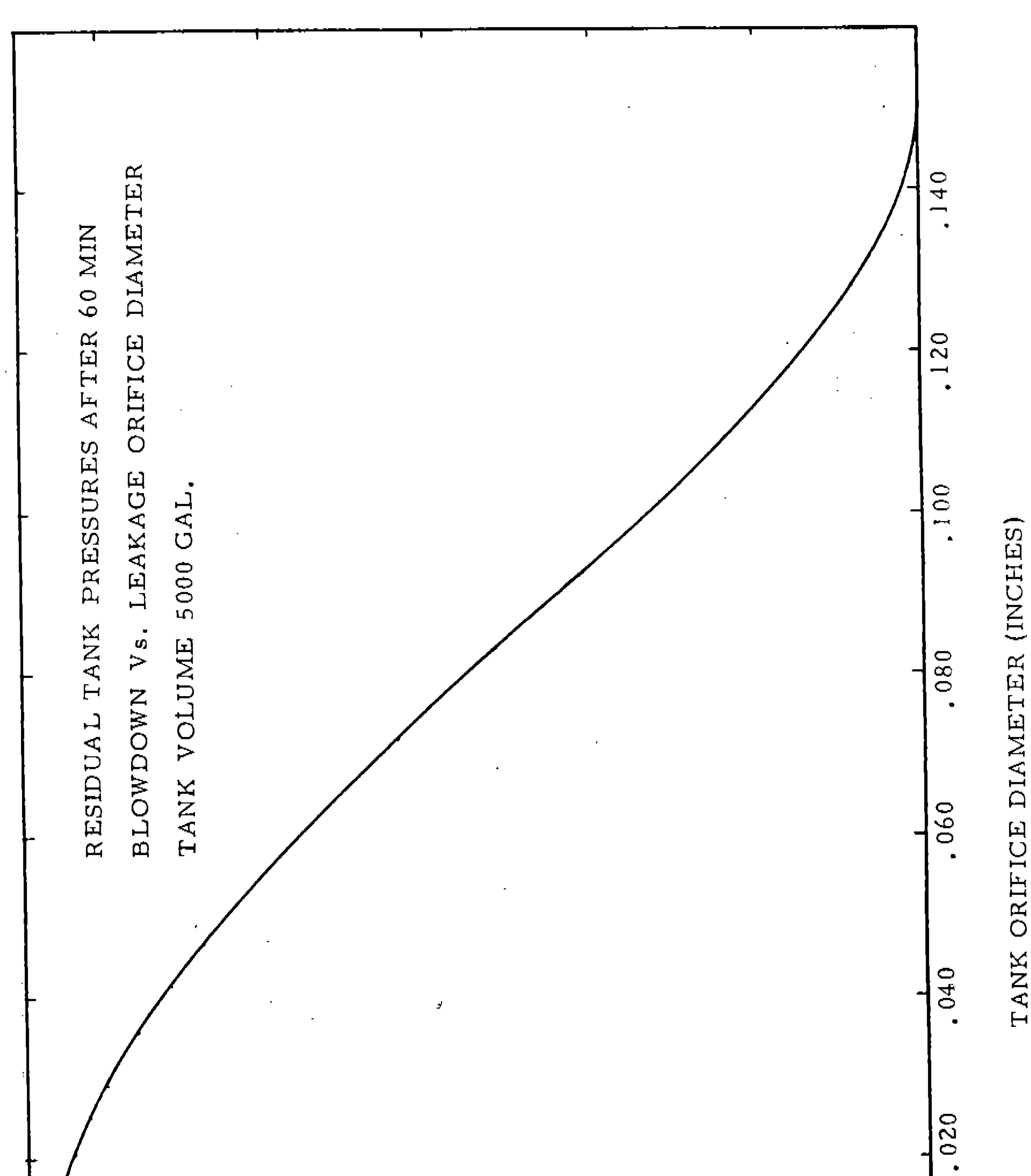
RESIDUAL TANK PRESSURES AFTER 60 MIN
BLOWDOWN Vs. LEAKAGE ORIFICE DIAMETER
TANK VOLUME 5000 GAL.
TANK ORIFICE DIAMETER (INCHES)
.020
.040
.060
.080
.100
.120
.140
TANK PRESSURE (INCHES OF WATER)
25
20
15
10
5

Figure B.1

TABLE B.1 VENT LOSS AFTER REFUELING

OPEN VENT CALCULATION						
P = 14.7	S_1 =	0.	.2	.5	.85	.95
	V_V/V_G	.5097	.4265	.2870	.0951	.0327
GM/GAL VENTED	V_G/V_L = 0.05	.0572	.0555	.0453	.0182	.0066
	V_G/V_L = 0.10	.1145	.1110	.0906	.0365	.0132
	V_G/V_L = 0.15	.1717	.1665	.1359	.0547	.0198
IDEAL 27 IN. H_2O VENT CALCULATION						
P = 15.675	S_1^* =	.1661	.3661	.6661	1.000	1.000
	V_V/V_G	.4050	.3217	.1822	0.000	0.000
GM/GAL VENTED	V_G/V_L = 0.05	.0513	.0466	.0316	0.881[1]	0.294[1]
	V_G/V_L = 0.10	.1025	.0933	.0633	24.4[2]	8.1[2]
	V_G/V_L = 0.15	.1538	.1399	.0949		

Notes:

1. Max Tank Pressure, PSIG
2. Max Tank Pressure, IN. H_2O

TABLE B.2 VENT LOSS AFTER FUEL DROP

OPEN VENT LOSS					
P = 14.7	S_1 =	.0	.3261	.7065	.8152
	S_2 =	.2	.5000	.8500	.9500
	V_V/V_G =	.0832	.0832	.0832	.0832
GM/GAL VENTED	V_G/V_L = 1.05	.0367	.1499	.2820	.3197
	V_G/V_L = 1.10	.0385	.1571	.2954	.3350
	V_G/V_L = 1.15	.0402	.1642	.3088	.3502
IDEAL 27 IN. H_2O VENT LOSS					
	S_1 =	.0000	.3261	.7065	.8152
	S_1^* =	.1661	.4922	.8726	.9813
	S_2^* =	.2055	.5265	.9009	1.000
	V_V/V_G =	.0159	.0159	.0159	.0112
GM/GAL VENTED	V_G/V_L = 1.05	.0128	.0351	.0612	.0481
	V_G/V_L = 1.10	.0134	.0368	.0641	.0504
	V_G/V_L = 1.15	.0140	.0385	.0670	.0527

TABLE B.3 BLOWDOWN TIME (MIN) FOR A GIVEN TANK LEAKAGE CRITERIA

INITIAL PRESSURE 27 INCHES WATER

		4	3	2	1	0.5
P(IN. H_2O)		4	3	2	1	0.5
D IN. AT C_{Re} = 0.7		0.153	0.131	0.107	0.075	0.053
VENT SPACE $V_G V_L$	5%	2.9	3.9	6.0	12.1	24.4
	10%	5.8	7.9	12.0	24.3	48.8
	15%	8.8	11.8	18.0	36.4	73.3

TANK VOL = 5000 GAL

TABLE B.4 BLOWDOWN LOSS GM/GAL FUEL

NO EVAPORATION

V_G/V_L =		5%	10%	15%	.5 in. 15%
P_I	27	.0129	.0258	.0387	.0374
IN	24.4	.0117	.0234	.0351	.0351
H_2O	8.1	.0040	.0081	.0121	.0121

P_I = INITIAL PRESSURE

TABLE B.5 P/V VALVE SAVINGS FOLLOWING REFUELING

		S_1 = 0	0.2	0.5	0.85	0.95
GM/GAL SAVINGS	V_G/V_L = 0.05	-.0069	-.0041	.0008	.0066	.0026
	V_G/V_L = 0.10	-.0138	-.0081	.0015	.0131	.0051
	V_G/V_L = 0/15	-.207	-.0122	.0023	.0197	.0077
	0.5 IN. PRESSURE BLOWDOWN CRITERIA P_R=0.9 IN.					
	V_G/V_L = 0.15	-.0195	-.0108	.0036	.0197	.0077

TABLE B.6 LEAKAGE DIAMETER FOR 60 MINUTE BLOWDOWN,
P_{GI} = 27 In H_2O, S_2 = 1.0 V = 5000 GAL

P_G (In. H_2O)	D In. C_{Re} = 0.7	P_G (In. H_2O)	D In. C_{Re} = 0.7
0	0.151	21	.052
.25	.143	22	.047
0.5	.140	23	.042
1.0	.135	24	.036
2.0	.128	25	.029
4.0	.118	25.5	.025
6.0	.109	26	.020
8.0	.101	26.5	.014
10	.094	26.7	.011
13	.083	26.9	.006
16	.072		
19	.060		

TABLE B.7 BLOWDOWN LOSS FOR VARIOUS FUEL DROP VENT SPACE AND TANK LEAKAGE SITUATIONS

ΔP Criteria	4	3	2	1	0.5	
		$S_2^* = 1.0$	M = 44.036			
D IN AT C_{Re} = 0.7	0.153	0.131	0.107	0.075	0.053	
P_R IN. H_2O	0.0	1.54	6.69	15.23	20.72	
GM/GAL VENTED V_G/V_L = 1.05	.2706	.2552	.2035	.1180	.0629	
GM/GAL VENTED V_G/V_L = 1.10	.2835	.2673	.2132	.1236	.0659	
GM/GAL VENTED V_G/V_L = 1.15	.2964	.2795	.2229	.1292	.0689	
		$S_2^* = .9009$	M = 42.543			
D IN. AT C_{Re} = 0.7	0.152	0.130	0.106	0.074	.053	
ΔP_R IN. H_2O	0.0	1.8	7.12	15.35	20.75	
GM/GAL VENTED V_G/V_L = 1.05	.2438	.2275	.1795	.1052	.0564	
GM/GAL VENTED V_G/V_L = 1.10	.2554	.2384	.1880	.1102	.0591	
GM/GAL VENTED V_G/V_L = 1.15	.2670	.2492	.1966	.1152	.0618	
		$S_2^* = .5265$	M = 39.902			
D IN. AT C_{Re} = 0.7	0.149	0.128	0.104	0.073	0.052	
ΔP_R IN. H_2O	0.0	2.2	7.2	15.7	21.0	
GM/GAL VENTED V_G/V_L = 1.05	.1425	.1309	.1045	.0596	.0317	
GM/GAL VENTED V_G/V_L = 1.10	.1492	.1371	.1094	.0625	.0332	
GM/GAL VENTED V_G/V_L = 1.15	.1560	.1433	.1144	.0653	.0347	
		$S_2^* = .2055$	M = 32.066			
D IN AT C_{Re} = 0.7	0.141	0.121	0.099	0.069	0.049	
ΔP_R IN H_2O	0.45	3.45	7.46	16.7	21.6	0.0
GM/GAL VENTED V_G/V_L = 1.05	.0547	.0485	.0402	.0212	.0111	.0556
GM/GAL VENTED V_G/V_L = 1.10	.0573	.0508	.0422	.0222	.0117	.0583
GM/GAL VENTED V_G/V_L = 1.15	.0599	.0531	.0441	.0232	.0122	.0609

TABLE B.8 P/V VALVE SAVINGS AFTER FUEL DROP

▲P CRITERIA	4	4	3	2	1	0.5
	S_1 = 0.0	S_2 = 0.2	S_1^* = 0.1661		S_2^* = .2055	
▲P_R IN. H_2O	0.0	0.45	3.45	7.46	16.7	21.6
GM/GAL SAVINGS V_V/V_G = 1.05	-.0317	-.0246	-.0246	-.0163	.0027	.0128
GM/GAL SAVINGS V_V/V_G = 1.10	-.0332	-.0323	-.0258	-.0171	.0028	.0134
GM/GAL SAVINGS V_V/V_G = 1.15	-.0347	-.0337	-.0269	-.0179	.0030	.0140
	S_1 = .3261	S_2 = 0.500	S_1^* = .4972		S_2^* = .5265	
▲P_R IN. H_2O		0.0	2.2	7.2	15.7	21.0
GM/GAL SAVINGS V_V/V_G = 1.05		-.0277	-.0161	.0103	.0552	.0831
GM/GAL SAVINGS V_V/V_G = 1.10		-.0290	-.0169	.0108	.0578	.0871
GM/GAL SAVINGS V_V/V_G = 1.15		-.0303	-.0176	.0113	.0605	.0910
	S_1 = .7065	S_2 = .850	S_1^* = .8726		S_2^* = .9009	
▲P_R IN. H_2O		0.0	1.8	7.12	15.35	20.75
GM/GAL SAVINGS V_V/V_G = 1.05		-.0230	-.0067	.0413	.1156	.1644
GM/GAL SAVINGS V_V/V_G = 1.10		-.0241	-.0070	.0433	.1211	.1722
GM/GAL SAVINGS V_V/V_G = 1.15		-.0252	-.0073	.0452	.1266	.1801
	S_1 = .8152	S_2 = .950	S_1^* = .9813		S_2^* = 1.000	
▲P_R IN H_2O		0.0	1.54	6.69	15.23	20.72
GM/GAL SAVINGS V_V/V_G = 1.05		.0010	.0164	.0681	.1536	.2087
GM/GAL SAVINGS V_V/V_G = 1.10		.0010	.0172	.0713	.1609	.2186
GM/GAL SAVINGS V_V/V_G = 1.15		.0011	.0180	.0746	.1682	.2286