~~TRANS. AND MARKT.
OF PETR. LIQS.
AP-42 Section 4.4
Reference Number
10~~

TRANS. AND MARKT.
OF PETR. LIQS. 5-2
AP-42 Section ~~4.4~~
Reference Number
11

Pacific Environmental Services, INC.

RECEIVED FEB 23 1978

R. A. Nichols Engineering
519 Iris Avenue, Corona del Mar, Ca. 92625
(714) 644-7735

February 20, 1978

Ms. Katherine Wilson
Pacific Environmental Services, Inc.
1930 14th Street
Santa Monica, CA 90404

Dear Ms. Wilson:

Re: Truck Transit and Transfer Leakage

Our work in Truck emission losses has progressed through several stages:

- First, we roughed out our ideas in "Comments on Proposed CARB Tank Truck Leakage Criteria" dated January 18, 1977. This document is included in the document below.

- Second, we analytically estimated tank truck emissions. This work is summerized in our Harold Uhlig letter of March 23, 1977 and documents: "Vapor Loss During Stage I Fuel Drops" dated February 21, 1977; "Vapor Transfer Model and Quasi-Steady State Solution" dated March 17, 1977; and, "Analytical Calculation of Fuel Transit Breathing Loss", dated March 21, 1977. The above documents were submitted to CARB as a package "Tank Truck Leakage Calculations" dated March 23, 1977.

- Finally, truck tests were conducted and analyzed using previous analytical procedures. These tests showed leakage to be much smaller than estimated. These results are expressed in our June 10, 1977 Harold Uhlig letter; they are qualified slightly in our Dean Simeroth letter of June 17, 1977; and, the data is given and analyzed in "Tank Truck Leakage Measurements" dated June 7, 1977.

We suggest you read the first and last items. Item 2 material is provided for back-up. We would ask that you both acknowledge and reference the above materials if you use them in your work. We would be happy to try and answer any questions.

Very truly yours,

Richard A Nichols

Richard A. Nichols, Ph.D.

RAN:sn
Enc.

R. A. Nichols Engineering

519 Iris Avenue, Corona del Mar, Ca. 92625

(714) 644-7735

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,

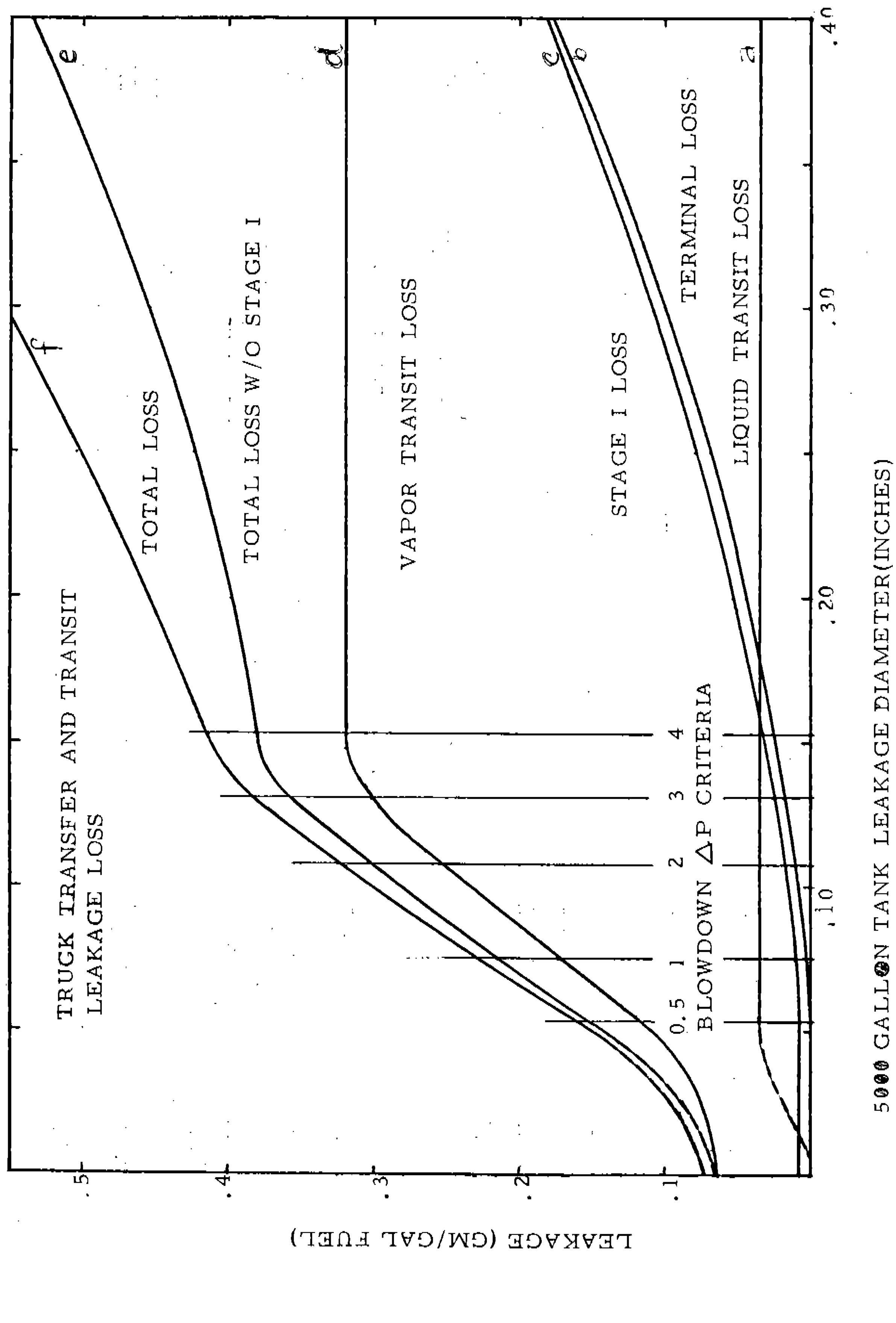
Richard A Nichols

Richard A. Nichols, Ph.D.

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

R. A. Nichols Engineering

f = e + c



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 e

R. A. Nichols Engineering

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

- 1 - 1 1/4" pressure and vacuum over the road relief valves. Max relief pressure 1 psi, vacuum 6 oz. = 10.5" H_2O.
- The 10" dome covers which additionally act as emergency relief valves. Relief pressure 3 psi.
- 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.

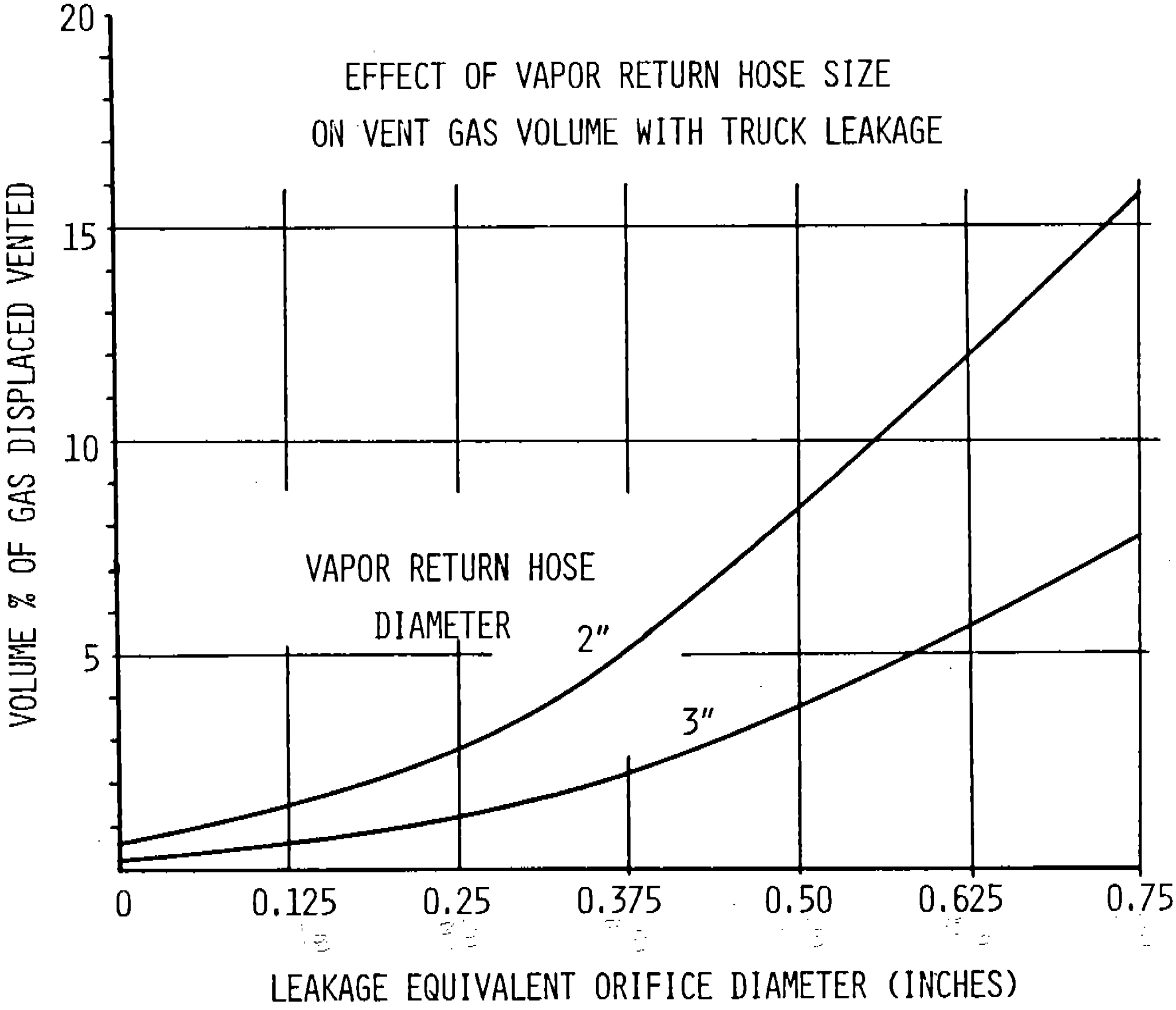

EFFECT OF VAPOR RETURN HOSE SIZE
ON VENT GAS VOLUME WITH TRUCK LEAKAGE
VOLUME % OF GAS DISPLACED VENTED
20
15
10
5
0
VAPOR RETURN HOSE
DIAMETER
2"
3"
0.125
0.25
0.375
0.50
0.625
0.75
LEAKAGE EQUIVALENT ORIFICE DIAMETER (INCHES)

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.

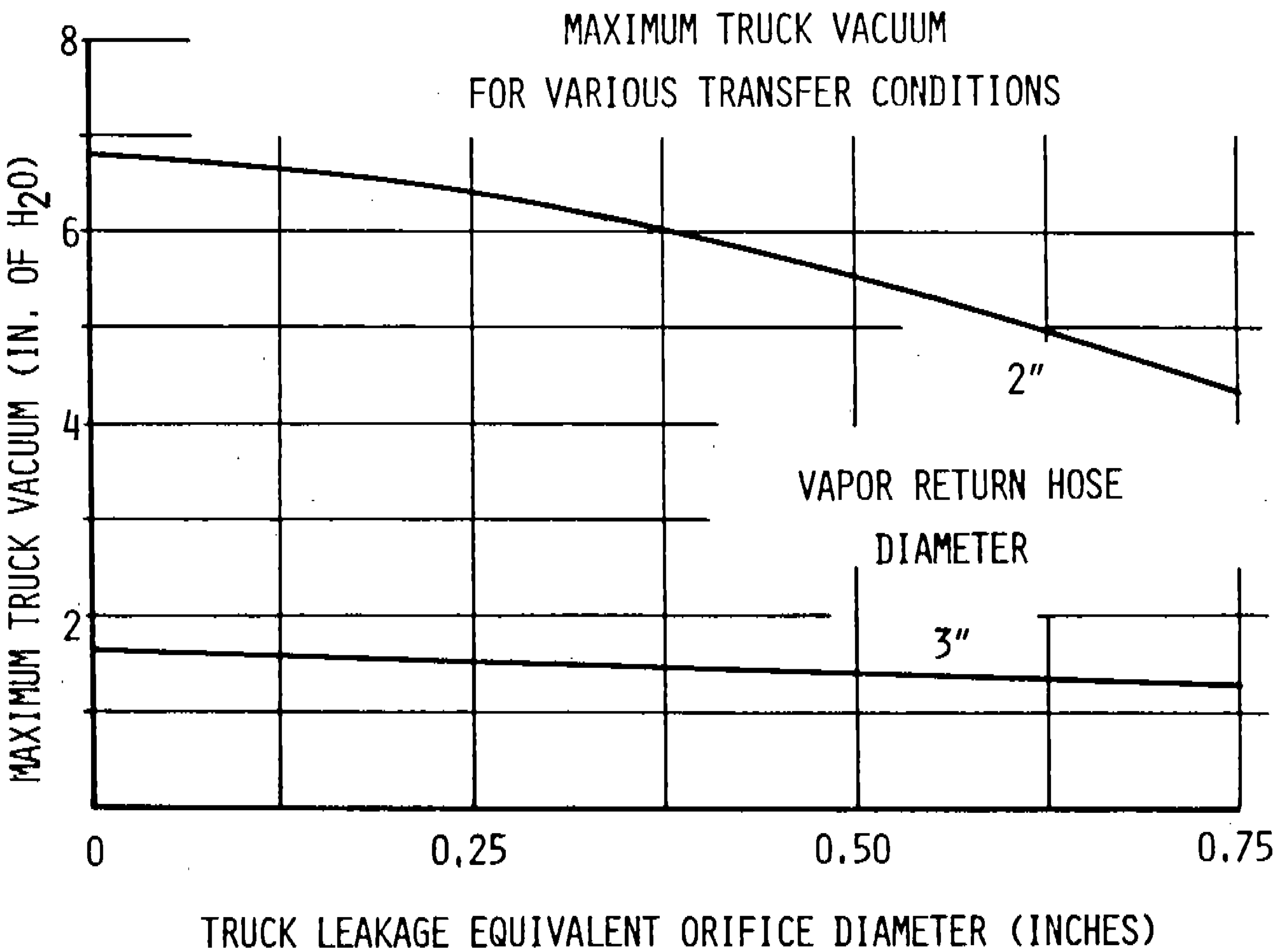

MAXIMUM TRUCK VACUUM
FOR VARIOUS TRANSFER CONDITIONS
MAXIMUM TRUCK VACUUM (IN. OF H_2O)
8
6
4
2
2"
VAPOR RETURN HOSE
DIAMETER
3"
0
0.25
0.50
0.75
TRUCK LEAKAGE EQUIVALENT ORIFICE DIAMETER (INCHES)

Figure 2

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

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

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
P_G = 406 in. H_2O
P_A = 407 in. H_2O
$A = (0.7 \times \pi \times D^2)/4$

V_G = 668.5 cf
T_G = 540°R
M = 28.97 lbm/lbmol

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

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

$$\frac{dW_G}{d_t} = -\dot{W}_v \tag{1}$$

$$W_G = \frac{V_G P_G M}{R T_G} \tag{2}$$

$$\dot{W}_v = \frac{A}{12} \sqrt{\frac{64.4(P_G + P_A)M}{2\,RT_G}\,(P_G - P_A)} \tag{3}$$

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

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

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.

R. A. Nichols
Engineering

Item 2 ... letter ...

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.

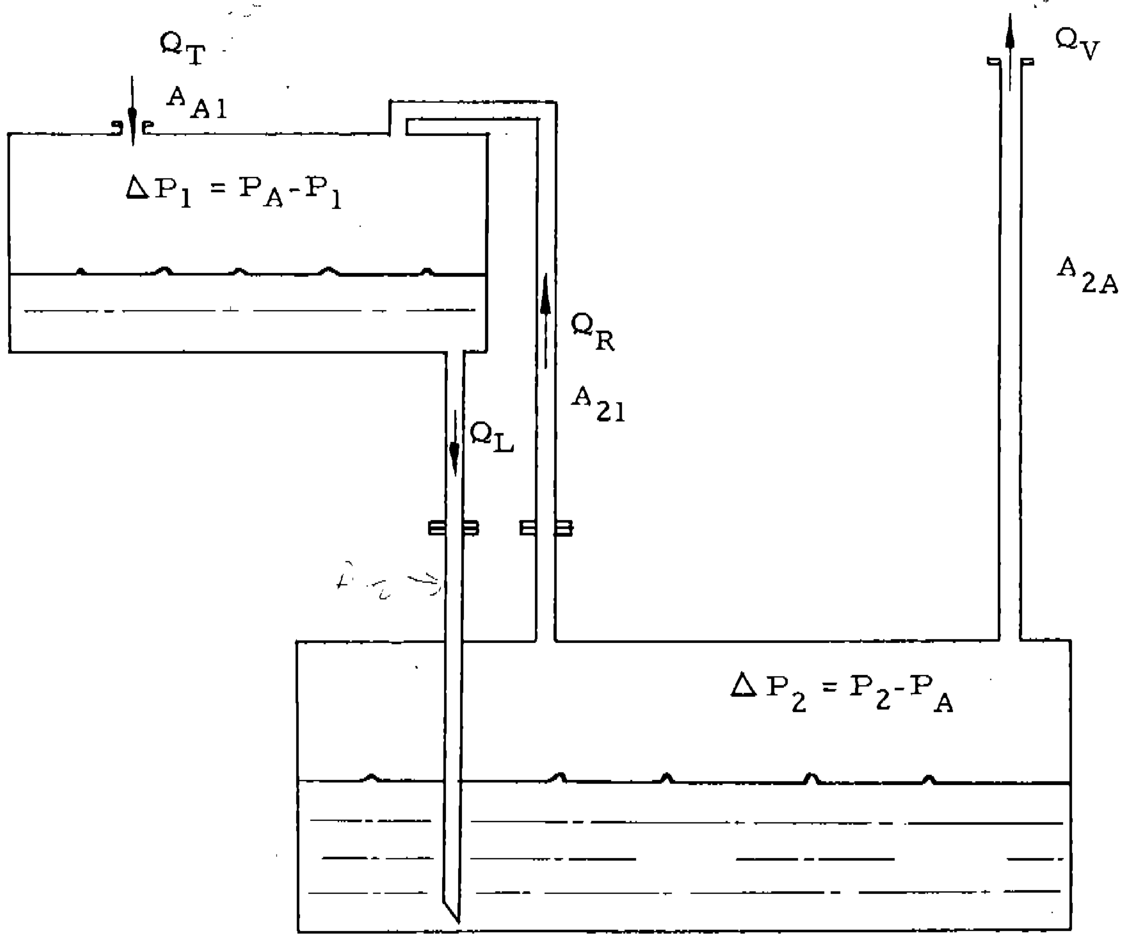
Figure 1 differs from Figure 8 of Reference 1 and Figure 1 of Reference 2. The latter figures were drawn by applying an adjustment factor to computer results which were derived assuming saturated vapor instead of air was drawn in the truck tanks. Unfortunately the factor was misapplied. If the figure "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 injested 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 drops 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. Accordingly 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, ≐ 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

2.6 REFERENCES

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

2. Nichols, R. A. Comments on Proposed CARB Tank Truck Leakage Criteria. R. A. Nichols Engineering, 519 Iris Avenue, Corona del Mar, Ca. 92625. January 18, 1977

3. Nichols, R. A. Draft Report of Chapter 2, A Survey of Emissions from Gasoline Distribution Systems. EPA Contract 68-02-0001. Parker Hannifin Corporation, Irvine Ca 92664

4. Holmes, M. J. Vapour Emissions When Loading Road Tankers With Gasoline in Canada, Part 1-Summary Report. B. P. Trading Ltd., Operations Service Branch. London, England. Report 20599. May, 1971.

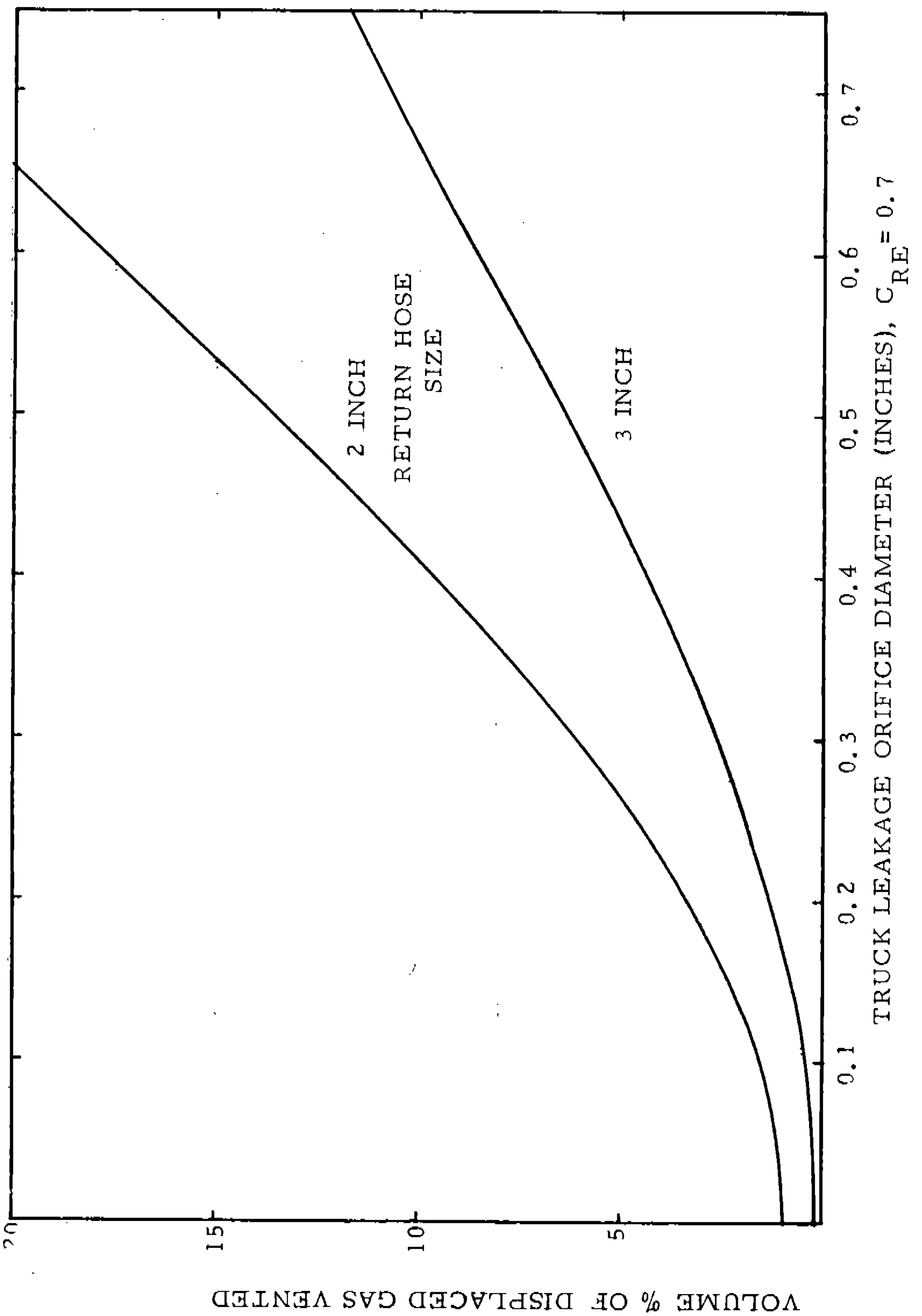

2 INCH
RETURN HOSE
SIZE
3 INCH
0.1
0.2
0.3
0.4
0.5
0.6
0.7
TRUCK LEAKAGE ORIFICE DIAMETER (INCHES), $C_{RE} = 0.7$
5
10
15
20
VOLUME % OF DISPLACED GAS VENTED

Figure 1

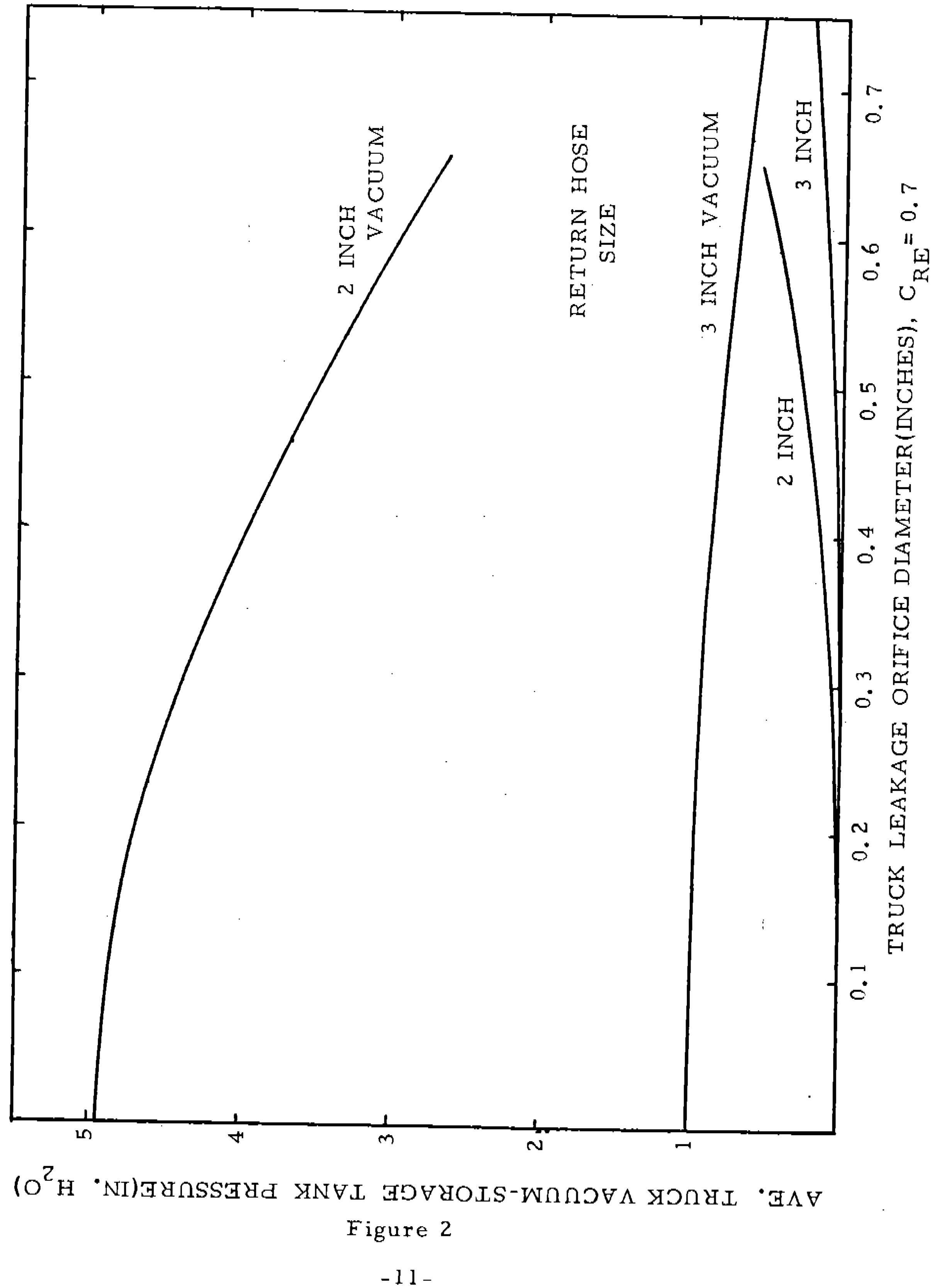

2 INCH VACUUM
RETURN HOSE SIZE
3 INCH VACUUM
2 INCH
3 INCH
0.1
0.2
0.3
0.4
0.5
0.6
0.7
TRUCK LEAKAGE ORIFICE DIAMETER(INCHES), $C_{RE} = 0.7$
1
2
3
4
5
AVE. TRUCK VACUUM-STORAGE TANK PRESSURE(IN. H_2O)

Figure 2

R. A. Nichols
Engineering

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

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

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

Gauge pressures of Tanks 1 and 2 are expressed as

$$\Delta P_1 = P_A - P_1 \tag{A.8}$$

$$\Delta P_2 = P_2 - P_A \tag{A.9}$$

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

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

$$V_{G2} = V_{T2} - V_{L2I} - Q_L t \tag{A.11}$$

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

$$t_F = \frac{V_{L1I}}{Q_L} \tag{A.12}$$

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

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

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

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

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

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

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

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

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

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

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

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

where

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

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}

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

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, $\Delta P_2 = 2.737E{-4}$ in. H_2O

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

$\Delta P_2 = 3.66E{-3}$ 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)

$d(\text{distance to chord of sector}) = R\ \text{COS}\ \frac{\Theta}{2}$ (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)

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

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

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

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

where 4f is a function of Reynolds Number Re

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

and the relationship is (Reference 4, Chapter 6)

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

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

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

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

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

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

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

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

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

A.7 REFERENCES

1. Nichols, R. A. and L. Lee. Vapor Transfer Considerations During Fuel Drops at Service Stations. EPA Contract No. 68-02-1311. Parker Hannifin Corporation, Irvine Ca., dated October 29, 1973.
2. Burington, R. S. Handbook of Mathematical Tables and Formulas. Handbook Publishers, Inc. Sandusky, Ohio. 3rd Edition. 1957.
3. ______Flow of Fluids Through Valves Fittings, and Pipe. Crane Co. of Chicago, Ill. Technical Paper 410. 1957.
4. Bird, R. B., W. E. Stewart and E. N. Lightfoot. Transport Phenomena. John Wiley and Sons. N.Y. 1960.
5. Maxwell, J. B. Data Book on Hydrocarbons-Application to Process Engineering. D. Van Nostrand Co., Inc. 2nd printing, 1951.

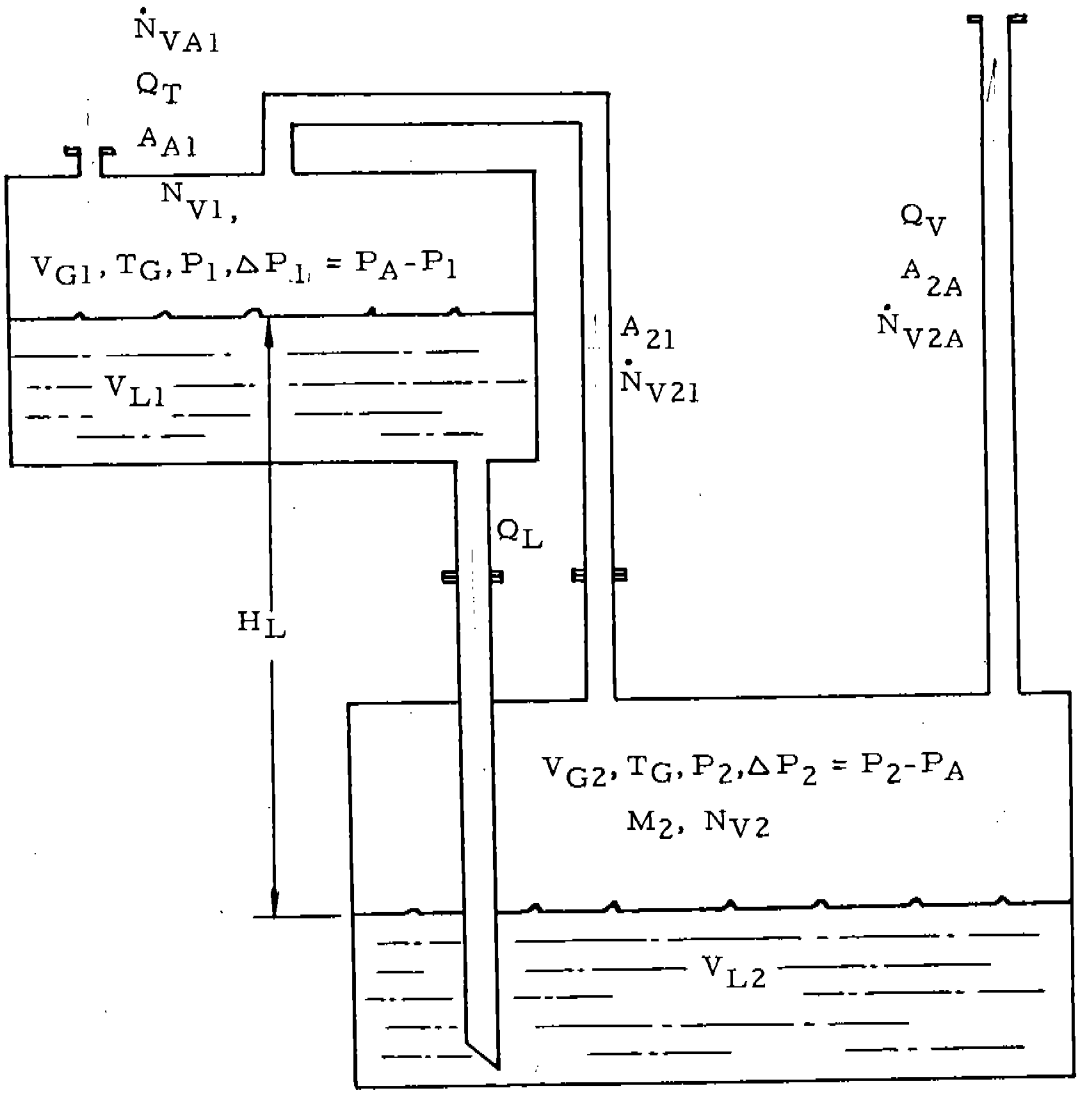


Figure A.1 MODEL SCHEMATIC

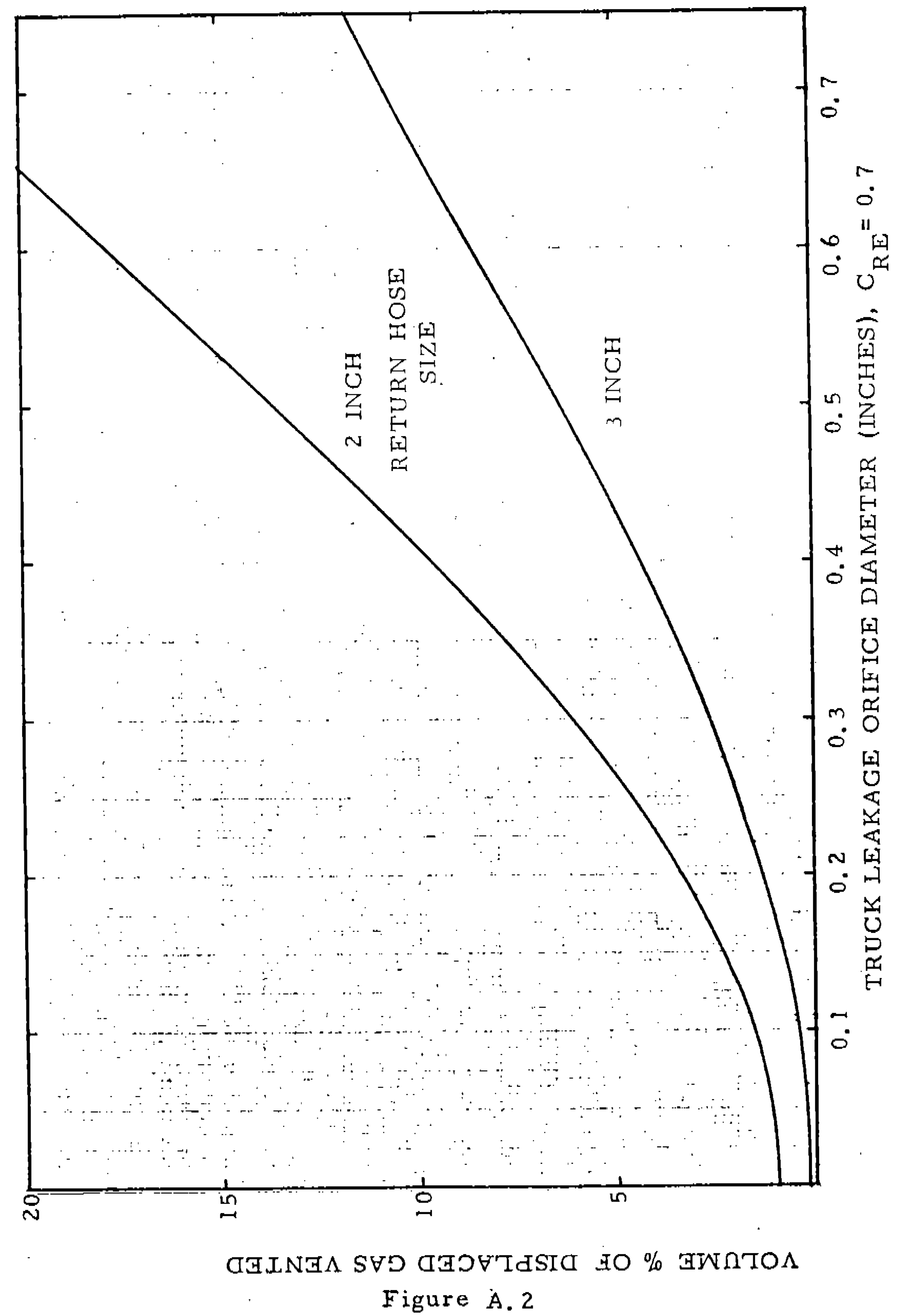

2 INCH
RETURN HOSE
SIZE
3 INCH
TRUCK LEAKAGE ORIFICE DIAMETER (INCHES), $C_{RE} = 0.7$
0.1
0.2
0.3
0.4
0.5
0.6
0.7
VOLUME % OF DISPLACED GAS VENTED
20
15
10
5

Figure A.2

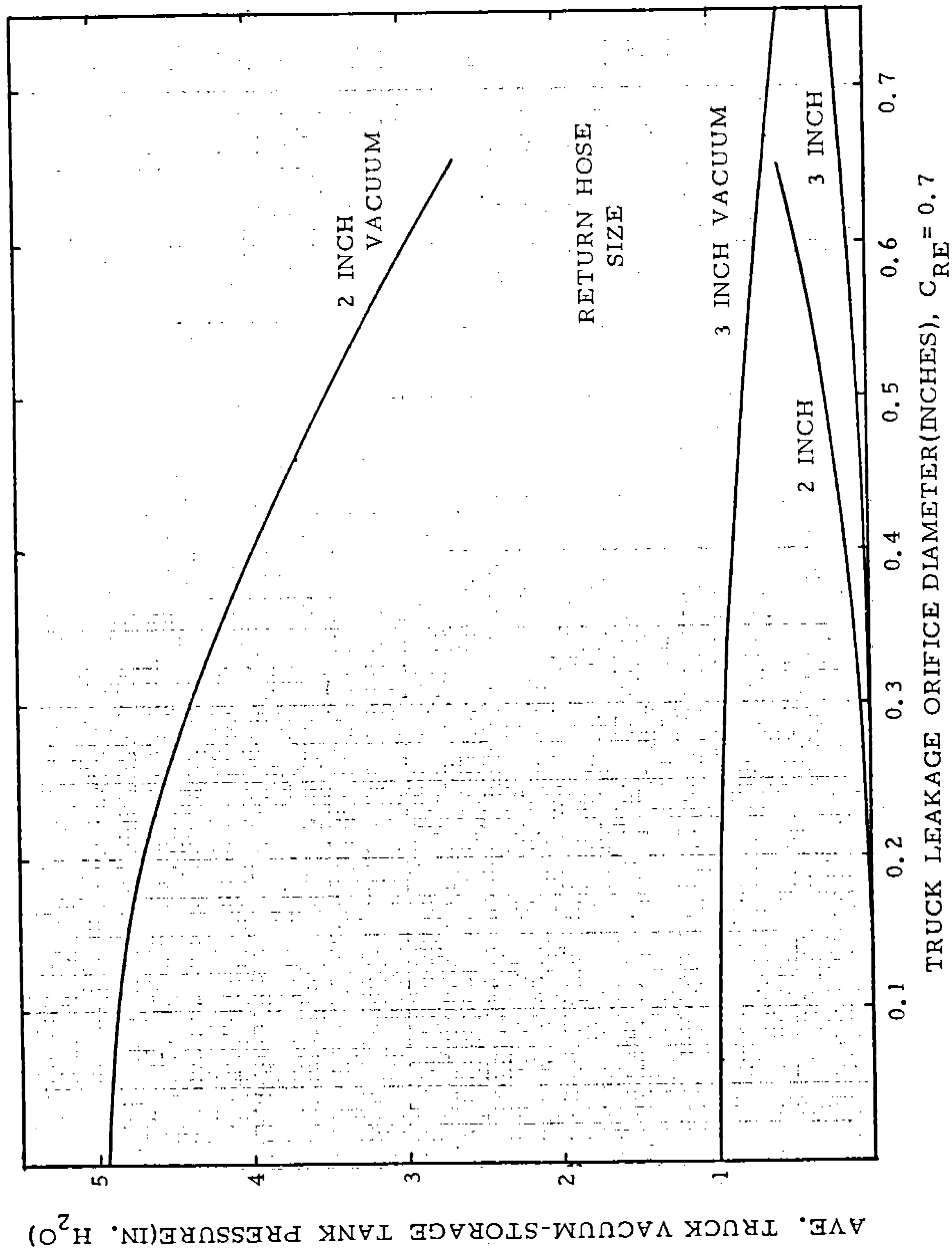

2 INCH
VACUUM
RETURN HOSE
SIZE
3 INCH VACUUM
3 INCH
2 INCH
0.1
0.2
0.3
0.4
0.5
0.6
0.7
TRUCK LEAKAGE ORIFICE DIAMETER(INCHES), C_RE = 0.7
1
2
3
4
5
AVE. TRUCK VACUUM-STORAGE TANK PRESSURE(IN. H2O)

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		
3" HOSE	P_1	.8144	.7738	.7086	.6384	.5373	.3705		
3" HOSE	Q_T	24.44	28.62	34.89	41.16	49.50	61.99		
3" HOSE	A_{A1}	.1287	.1546	.1970	.2448	.3209	.4840		
3" HOSE	$C_{Re=.7}$ D_{A1}	.4838	.5303	.5985	.6672	.7639	.9381		
2" HOSE	P_2	.07052	.0926	.1303	.1736	.2395	.3551	.4662	.5904
2" HOSE	P_1	4.410	4.294	4.117	3.937	3.693	3.318	2.998	2.671
2" HOSE	Q_T	21.76	26.00	32.35	38.70	47.14	59.79	70.31	80.82
2" HOSE	A_{A1}	.0492	.0596	.07578	.0927	.1166	.1560	.1930	.2350
2" HOSE	$C_{Re=.7}$ D_{A1}	.2992	.3293	.3712	.4105	.4604	.5326	.5924	.6537

REF 10

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

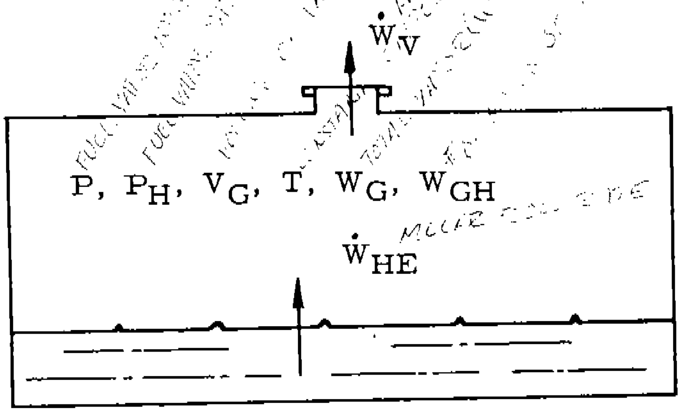
be completely dissipated. By assuming no evaporation during blowdown, blowdown loss was calculated. The single case where the P/V valve showed a residual pressure was calculated separately.

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.

$$\dot{W}_{HE} = \dot{W}_V \qquad (B.1)$$

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

$$W_{GH} = \frac{P_H V_G}{RT} \qquad (B.2)$$

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

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

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

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

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

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

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

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

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

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

or

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

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

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

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

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

where

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

If $S_1^* > 1$ then

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

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

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

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

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

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

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

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

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

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

1. Shelton, E. M. Motor Gasolines, Summer 1973. Bartlesville Energy Research Center, Bureau of Mines, U.S. Department of the Interior, Bartlesville, Oklahoma. Petroleum Products Survey No. 83. January, 1974
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.

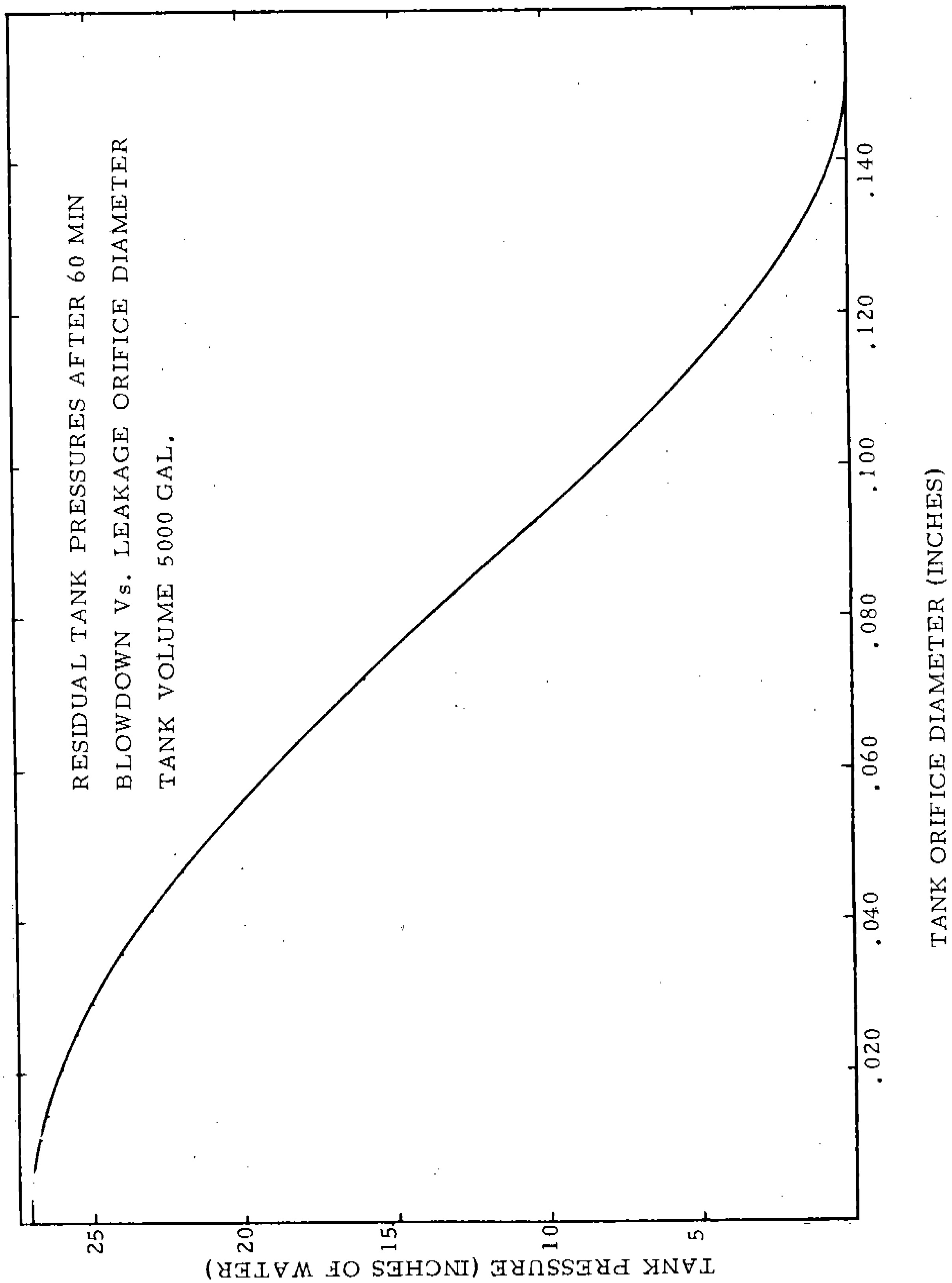

RESIDUAL TANK PRESSURES AFTER 60 MIN
BLOWDOWN Vs. LEAKAGE ORIFICE DIAMETER
TANK VOLUME 5000 GAL.
TANK ORIFICE DIAMETER (INCHES)
.020
.040
.060
.080
.100
.120
.140
TANK PRESSURE (INCHES OF WATER)
25
20
15
10
5

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

R. A. Nichols Engineering
519 Iris Avenue, Corona del Mar, Ca. 92625
(714) 644-7735

June 17, 1977

Dean Simeroth
California Air Resources Board
1709 11th Street
Sacramento, CA 95814

Dear Dean:

Re: Truck Transit and Transfer Leakage

We have refigured our truck transit and transfer loss estimations based upon test data taken at Chevron's Sacramento terminal. The enclosed letter to H. B. Uhlig and test report outlines our results. The results should hold for all similar pipeline terminals with reasonable throughput having floating roof tanks and a similar bottom loading configuration.

The reason the results are not totally general is that truck loading pressures vary with the number of refueling hoses per vapor transfer hose. With two refueling hoses and a single return hose, tank truck pressures will be nearly four times Chevrons measured pressure level. Refueling leakage areas will then approach those measured during CARB leakage tests and losses will approach those previously estimated analytically.

A second reason the results are not entirely general, is that gasoline stored in some marketing terminals may be in air equilibrium. Under such conditions liquid transit vapor loss would increase. Note however, that this maximum is still very small (0.035 gm/gal).

Finally, we would note that for high ΔP drops in the CARB test (more than 6 inches of water from 18 inch start and 10 inches of water from 22 inch start), leakage area below a 6 inch pressure level will be greater than 5% of the CARB measured area. Leakage would then approach maximum values somewhere between present and previously estimated times.

Our major finding is that vapor transit loss is at a maximum from .08 to 0.17 gm/gal; this is between 25 and 50% of what we previously estimated. This was the major loss term previously; and, our reduction is valid whenever compartments are completely unloaded at a single location.

Noting that vapor transit losses are limited to between 0.11 and 0.20 gm/gal maximum, we are led to our original conclusion: "Truck tightness restrictions should be designed to insure efficient vapor transfer conditions take place at the service station drops and during refueling at terminals. Such restrictions will be tight enough to inhibit breathing losses caused by windage."

A tank truck requirement similar to the above might require that tank truck pressures during refueling are at a maximum 80% of relief valve crack pressures and that Stage I delivery efficiency be at least 90%. Such a ruling would insure sufficient valve seating pressures in the terminal to minimize vapor transfer losses and the valves would be tight enough over the road to prevent windage. If the above requirement does not do the job a 5% maximum leakage requirement could be additionally imposed. Leakage would be calculated based upon a blowdown test starting 1 inch of water above maximum refueling pressure and ending 2 inches of water below normal refueling pressure. An orifice calculated from the blowdown test would be used to calculate leakage.

If we can be of help regarding the above, or appended material, please contact us.

Very truly yours,

Richard A Nichols

Richard A. Nichols, Ph.D.

RAN:sn
Enc.

cc: John Snyder, Chevron

R. A. Nichols Engineering

519 Iris Avenue, Corona del Mar, Ca. 92625

(714) 644-7735

June 10, 1977

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

Dear Mr. Uhlig:

Our previous analytical calculations considerably overestimated truck transit and terminal refueling leakage. Updated analysis of a 5000 gallon compartment, using the data and methods developed during the Chevron "Tank Truck Leakage Measurements", indicates leakage will be less than 0.3 gm/gallon of fuel. Terminal and transit leakage, originally addressed by CARB, is less than 0.1 gm/gal. These results are with leakage pressure drops of 16 inches of water in 5 minutes.

Leakage in all transit modes as well as refueling is smaller because leakage area is found to vary with truck pressure and vacuum. CARB leakage tests determine leakage at high pressure and vacuum levels (14-22 inches of water pressure and 4-6 inches of water vacuum). Leakage at lower pressure and vacuum levels (6 inches of water pressure and 3 inches of water vacuum) appears to be much lower or non-existant. It seems conservative to assume pressure leakage below 7 inches of water to be 5% of leakage determined during CARB tests. Vacuum leakage at 3 inches of water may conservatively be assumed to be 50% of that determined during CARB tests starting at 6 inches of water vacuum.

Since Chevron bottom loading truck refueling pressures are less than the 7 inches of water, truck leakage may be assumed to be over-estimated by a factor of twenty.

Transit leakage following truck refueling was overestimated. Our calculations failed to take into account the rich layer at the fuel surface after refueling. This layer greatly reduces the unsaturated vapor space available for saturation. Secondly our calculations assumed free venting above the D.O.T. valve crack pressure of 27 inches of water. In refueling tests of air filled compartments where pressures above this level can occur, venting was restricted. Third-ly, air absorption into the fuel usually occurs. This effect happens because fuel when refined and stored is prevented from coming into equilibrium with air. Since fuel can hold about 20% by volume air, absorption occurs and vacuums are measured during most of transit. With vapor balancing during fuel deliveries, little pressure rise occurs due to vapor saturation (less than 6 inches of pressure). Positive pressures usually become vacuum after less than 5 minutes because of air absorption. Under such conditions vapor loss is negligible.

Transit leakage following fuel delivery at the service station was overestimated. The full vapor concentration of trucks returning to the terminal after a fuel drop without vapor recovery was assumed to be the result of residual fuel and wetted wall evaporation. Tests, to confirm this assumption to the contrary showed little evaporation. Inspection of our original data base as well as test data shows that approximately 50% of the compartment vapor concentration is due to the initially present saturated vapor space above the fuel (10% vapor space x 100% saturation = 100% vapor space x 10% saturated). Evaporation during fuel delivery at the service station can be shown to cause evaporation of up to 2% of the vapor space volume using a diffusion model. With turbulence this could be more, we assume between 0-5%. Subtracting this prior evaporation from that measured, we feel residual fuel evaporation will more nearly account for a maximum of between 5 and 10% vapor space saturation. U.S. practice of dropping a whole fuel compartment at once versus the European practice of splitting loads and metering fuel delivery also should lead to less residual fuel in U.S. tanker compartments. Finally vapor balancing during fuel delivery leads to much richer returning vapor concentrations. Evaporation into richer vapor concentrations will be less in total volume and slower. With vapor leakage at the pressures measured in the U.S.(6 inches of water), a maximum of 20 times less than measured in CARB pressure leakage tests, both maximum and transit vapor loss will be much less than previously thought.

Analytical calculations underestimate truck unloading losses at the service station. Tests showed transfers exceeded required air pollution 90% requirements but fell short of the analytically predicted 99+% efficiency. Our analytical program did not take into account fuel evaporation during truck refueling or possible air injestion at the truck transfer fitting. Fuel evaporation is rather difficult to predict but could lead to from 0 to 5% vapor growth. Air injestion at the fuel hose fitting is known to occur and steps are being taken to improve the connection.

To quantitatively estimate the losses outlined above in the various leakage modes, we have revised our earlier leakage calculations.

Liquid transit vapor leakage has been assumed to be equivalent to 5 minutes of leakage at an average pressure of 3 inches of water. Since pressures in the tank with vapor return are less than 6 inches of water, leakage area is taken as 5% of that measured during the CARB leak test.

Terminal loss is shown at 6 inches of water and 5% of the CARB leak test area.

Vapor transit loss is shown at 6 inches of water and 5% of the CARB leak test area. Maximum leakage has been assumed by calculating the limit either 5 or 10% increased vapor saturation.

Saturation Increase	x	Vapor Pressure Atmosphere	x	Vapor Density Gm/Gal	=	Max Loss Gm/Gal
0.05	x	0.40	x	4.142	=	0.0828
0.10	x	0.40	x	4.142	=	0.1657

Service station delivery loss is assumed made up of two losses: First, a 2% volume loss of saturated vapor is assumed to account for evaporation during defueling. Secondly, the leakage loss is assumed to be at 50% the CARB leak test area. No provision has been made to estimate air injestion presently occurring at vapor transfer fittings.

Leakage calculations are shown in Table 1 and leakage orifice diameter is shown for various leakage pressure drops in a 5 minute leak test from 22 and 18 inches of water. The data of Tables I and II is graphically shown in Figure 1.

As can be readily ascertained the imposition of stringent CARB type leakage requirements causes little or no reduction in truck transit emissions or for that matter terminal and service station fuel transfer emissions. Attached is a test report "Tank Truck Leakage Messurement s" which describes the tests and analysis leading to the above conclusions.

Very truly yours,

Richard A Nichols

Richard A. Nichols, Ph.D.

RAN:sn

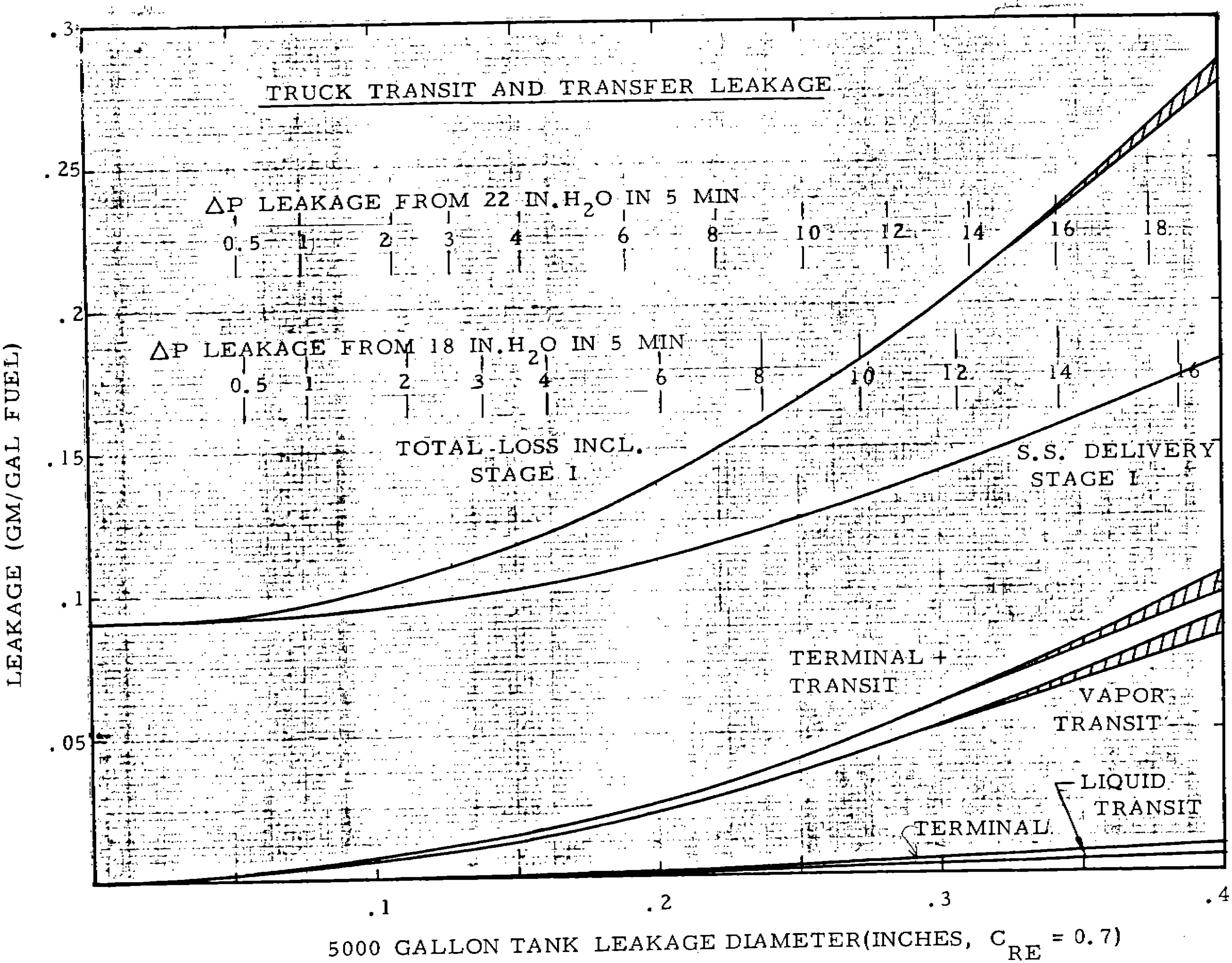


FIGURE 1

R. A. Nichols Engineering

TABLE I

TRUCK TRANSIT AND TRANSFER LEAKAGE LOSS

ΔP Loss In. H_2O	Leak Dia 5000 Gal In. O	Terminal Loss Gm/Gal	Terminal Vapor Vol% Loss	Liquid Trans. Loss Gm/Gal	Vapor Trans. Loss 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	0	.0911	2.20	0	.0911
0.5	.0528	.0002	.0037	.0001	.0016	.0915	2.21	.0019	.0934
1	.0749	.0003	.0076	.0002	.0032	.0924	2.23	.0037	.0961
2	.107	.0006	.0155	.0004	.0065	.0961	2.32	.0075	.1036
3	.131	.0010	.0232	.0006	.0097	.0994	2.40	.0113	.1107
4	.153	.0013	.0316	.0008	.0132	.1019	2.46	.0153	.1172
	.200	.0022	.0537	.0013	.0226	.1110	2.68	.0261	.1371
	.250	.0035	.0840	.0021	.0354	.1267	3.06	.0410	.1677
	.300	.0050	.1210	.0030	.0509	.1400	3.38	.0589	.1989
	.400	.0089	.2150	.0053	(.0828 .0905)	.1802	4.35	(.0970 .1047)	(.2772 .2849)
	.500	.0139	.3358	.0083	(.0828 .1415)	.2278	5.50	(.1051 .1637)	(.3328 .3915)
		$\Delta P = 6''$ Q_L =600gpm D = .05CARB		$\Delta P=3''H_2O$ t=5min Max=.0351 D=.05CARB	$\Delta P=6''H_2O$ t=60 min Max=.0828 .1657 D=.05CARB D=.50CARB				

R. A. Nichols Engineering

LEAKAGE ORIFICE DIA. (IN. C_{RE}=0.7)

P	INIT. PRES	$IN.H_2O$
$IN.H_2O$	22 IN	18
0.5	.053	.056
1.0	.075	.079
2.0	.107	.113
3.0	.131	.139
4.0	.153	.162
6.0	.190	.202
8.0	.222	.238
10.0	.253	.272
12.0	.282	.306
14.0	.312	.343
16.0	.342	.385
18.0	.375	.472

5000 GAL TANK, T = 80°F, M_V = 44.58

TABLE 2

R. A. Nichols
Engineering

TANK TRUCK LEAKAGE MEASUREMENTS

Analysis by

Richard A. Nichols, Ph.D.

Testing by

John Synder

C. R. Lupcho

Chevron U.S.A. Inc.

June 7, 1977

REF 11

ABSTRACT

The attached report describes tests run by Chevron U.S.A. Inc. to verify analytical truck loss calculations made by R. A. Nichols Engineering. The tests show that the analytical calculations considerably overestimate leakage occurring during truck transit and refueling at the terminal. Leakage is shown to be nearly non-existant during Chevron transit and terminal refueling tests and to be nearly negligible analytically in all but the transit mode following fuel delivery. Maximum analytical loss in transit following fuel delivery is shown to be between .083 and 0.17 gm/gal with leakage rates so slow that these maximums will probably not be achieved. Stage I fuel delivery loss at the service station was analytically underestimated but still well within the 90% efficiency required by air pollution agencies. Two factors leading to this underestimation were that the analytical program did not account for air injestion at fuel transfer fittings or fuel evaporation during defueling.

ACKNOWLEDGEMENT

The author would like to acknowledge the work of John Snyder, Chevron U.S.A. Inc. and Alexandra G. Nichols.

1.0 PURPOSE AND SCOPE

Considerable data on truck compartment pressure has been taken but in very few cases has the data been complete enough to fit the results to a scientific model. On the other hand analytical models approximating vapor transfer loss during transit from the terminal and from the service station have been developed. It is the purpose of this program to take sufficient data that the mathematical models can be tested.

These tests were designed to obtain data on trucks bottom loaded from a typical pipeline terminal. A truck and trailer ~~was~~ each vacuum tested after carrying a load of diesel. The two largest compartments of the truck and trailer were instrumented for taking continuous pressure measurements. A smaller compartment of the truck and the trailer was used for taking vapor space measurements by opening the dome cover a small amount and inserting a thermometer.

Chevron Supreme was loaded in the truck and Regular was loaded in the trailer. Compartment pressures were monitored during refueling. The truck and trailer compartment pressures were measured versus time during the trip to the station.

The products were dropped at the station. One pressure instrumented compartment of each the truck and trailer was dropped without vapor balancing. A second pressure instrumented compartment of each the truck and trailer was dropped with vapor balancing. Service station tank and truck compartment pressure versus drop time data were taken and the station vent was bagged to measure expelled vapor during the vapor return tests.

Truck and trailer tank pressures were monitored during the trip back to the terminal.

At the terminal the truck and trailer were once again refueled with Supreme in the truck and Regular in the trailer. Compartment pressures were monitored during refueling.

Finally, truck compartment pressures were monitored on the trip to the next truck drop.

Temperature measurements in the third compartment vapor spaces were taken at the service station and terminal.

Initial calculations indicated that tank truck compartment leakage tests from 18 or 22 inches of water for 5 or 10 minutes might not establish correct compartment leakage at lower pressures. There was also some question on whether there would be appreciable vaporization in a totally sealed compartment returning from a service station. For these reasons several additional tests were conducted: First, pressure and vacuum compartment leakage tests were conducted over a wider pressure range for extended periods of time; and, secondly compartment over the road pressure vent was removed and a pipe plug inserted. Transit pressures in the compartment following a fuel delivery with vapor recovery were monitored.

2.0 RESULTS AND CONCLUSIONS

Tests show that our previous analytical calculations considerably overestimate leakage occurring during truck transit and during refueling at the terminal. Leakage is shown to be nearly non-existant during Chevron transit and terminal refueling tests and to be negligible analytically in all but the transit mode following a fuel delivery. Maximum analytical loss in transit following fuel delivery is shown to be between 0.083 and 0.17 gm/gal with an approach time indicating this to be improbable. Stage I fuel delivery vapor loss at a service station is shown to be underestimated but still within the prescribed 90% efficiency. Two factors leading to this were our not accounting for air injestion at transfer fittings and evaporation effects during defueling which may lead to a net vapor growth.

Section 5.1 shows that tank truck pressure and vacuum leakage becomes less as compartment pressure approaches ambient. The CARB test procedure is incapable of determining leakage rates except at the pressure level being measured. More complete pressure leakage tests showed that two out of three compartments tested were leak tight before the 6.0 inch of water pressure level was reached. The remaining compartment showed only 3.6% the equivalent flow area of the compartment leakage from 18-14.5 inches of water. Three out of four vacuum compartments tested were leak tight before the 3.0 inches of water vacuum was reached. The remaining compartment at 3.0 inches of water had 44% of the equivalent leakage area found at 6-4.5 inches of water.

Section 5.2 verifies the truck loss analytical calculation method. Our previous calculations, however, overestimated the loss by at least 20 times since our tests show the equivalent leakage at loading pressures is more than that much smaller than the area used.

Section 5.3 shows that high pressures following refueling in tank truck compartments were shown only on the refueling of initially air filled tanks or on refueling tanks with large vapor spaces following fuel deliveries at a service station without vapor transfer. Even in these cases the loss is minor since air absorption and partially opening tank valves will reduce leakage. With vapor balancing during fuel delivery at the service station, only small pressure rises occur(probably less than 6 inches of water) which will be trapped by the pressure vacuum valve (remember leakage at 6.0 inches of water is at least 20 times less than previously thought) and in all probability retained by fuel air absorption. Our analytical models did not take into account: 1) The rich vapor layer at the fuel surface remaining in the tank following refueling. 2) The fact that compartment vent valves do not fully open at DOT crack pressures; or 3) The effect of air absorption which during most of transit will create vacuums in the truck vent spaces.

Section 5.4 shows that measured truck unloading loss although well within the 90% efficiency required by air pollution agencies is higher than that predicted by our analytical model. Two possible reasons are examined for the difference. Vapor leakage at the transfer hose fittings primarily at the truck and evaporation during refueling. Air injestion at the fuel hose fitting connection to the truck has been known to occur and steps are being taken to improve this connection. Evaporation loss using a diffusion model could be as high as 1.6%. More data will be needed however to determine these factors.

Section 5.5 analyzes the data taken and finds little residual fuel evaporation during transit following a fuel delivery returning to the terminal. On reanalyzing the analytical assumption which showed considerable loss could occur, we forgot to subtract from measured returning vapor concentrations the vapor concentration caused by dilution of the saturated vapor space in the tanker prior to fuel delivery or the percentage saturation due to fuel vaporization during defueling. Taking into account differences between European metered and partial compartment delivery, and normal full compartment delivery without metering, we believe a better maximum loss to be between one-half to one-fourth our analytical calculation. These maximum losses correspond to tank pressure levels of between 8 to 16 inches of water. Since leakage rates decrease rapidly at tank pressures below these levels, in all probability a sizeable portion of any evaporation occurring will remain as a residual tank pressure following transit.

3.0 TEST PROCEDURE

1. Deliver a load of diesel to purge the truck of gasoline vapor.
2. Run a pressure/vacuum test on each compartment at 22" H_2O pressure and 6" H_2O vacuum. Allow adequate time for a pressure drop approximately 4 inches of H_2O but run the test for 10 minutes maximum. (Do this test on only the four largest compartments).
3. Load unit with one product in the truck, another in the trailer. Record the pressure in each compartment as it is being loaded. Obtain a sample of each product. Record the temperature of the product and vapor space.
4. Drive the unit to the service station, monitoring and recording the pressure in the four largest compartments. (Driving time should be one hour).
5. Record the temperature of the vapor space in the two smallest compartments.
6. Deliver the middle sized truck compartment without connecting vapor recovery; Record:
   a) cargo tank vacuum versus time
   b) underground tank pressure versus time
   c) depth and volume of liquid in underground tank at start and finish
   d) amount of product delivered
   e) time from start of flow to obvious sudden change in pressure or truck vacuum
   f) vapor escaping at station vent
7. Deliver the largest sized truck compartment <u>with</u> vapor recovery connected. Record 6a thru 6f.
8. Repeat step 6 with the trailer.
9. Repeat step 7 with the trailer.

10. Record the temperature of the vapor space in the two small compartments.
11. Drive to the terminal; record the pressure in the four largest compartments.
12. Record the temperature in the two small compartments.
13. Record the ambient temperature.
14. Load the unit with gasoline, the middle sized compartments first. Record the loading pressure in the four largest compartments.
15. Record the temperature of the liquid and vapor in the two smallest compartments.
16. Drive to any station (approximately one hour driving time as before) Record the pressure in the four largest compartments during transit.
17. Record the temperature of the vapor space in the two smallest compartments.

4.0 TEST RESULTS

Test Results are shown on Data Sheets 1 thru 13. Specific data sheet titles are listed below:

Title	Data Sheet No.
Compartment No. 1 Leak Test	1
Compartment No. 2 Leak Test	2
Compartment No. 4 Leak Test	3
Compartment No. 6 Leak Test	4
Truck Loading Data	5
Transport Data from Terminal	6
Compartment 2 Unloading Data	7
Compartment 1 Unloading Data	8
Compartment 4 Unloading Data	9
Compartment 6 Unloading Data	10
Transport Data from the Service Station	11
Truck Loading Data	12
Transport Data from the Terminal	13
Compartment No. 2 and 4 Leak Tests	15
Compartment No. 1 and 6 Leak Tests	16
Product RVP and Distillation Data	14
Vapor Transit following fuel drop-Plugged Pressure Vent	17

5.1 Compartment Leak Rate Analysis

Compartment pressure versus blowdown time is shown for Compartments 1 and 2 in Figure 1 and Compartments 4 and 6 in Figure 2. Compartment vacuum versus leakage time is shown for Compartments 1 and 2 in Figure 3 and Compartments 3 and 4 in Figure 4.

An effort was made to correlate the isothermal turbulent and laminar leakage equations shown below:

Isothermal pressure blow down - turbulent flow

$$\ln \left(\frac{P_G + \sqrt{P_G^2 - P_A^2}}{P_{GI} + \sqrt{P_{GI}^2 - P_A^2}} \right) = -\frac{A}{12} \frac{t}{V_G} \sqrt{\frac{32.2\ RT_G}{M}} \qquad (1)$$

Isothermal pressure blowdown - laminar flow

$$\tan^{-1} \left(\frac{P_{GI}}{P_A} \right) - \tan^{-1} \left(\frac{P_G}{P_A} \right) = \frac{D^4\ P_A t}{256\ \ L\ V_G} \qquad (2)$$

Isothermal vacuum leakage - turbulent flow

$$\sin^{-1} \left(\frac{P_G}{P_A} \right) - \sin^{-1} \left(\frac{P_{GI}}{P_A} \right) = \frac{At}{12 \cdot V_G} \sqrt{\frac{32.2\ R\ T_G}{M}} \qquad (3)$$

Isothermal vacuum leakage - laminar flow

$$\ln \left(\frac{P_A + P_G}{P_A - P_G} \right) - \ln \left(\frac{P_A + P_{GI}}{P_A - P_{GI}} \right) = \frac{D^4\ 2P_A\ t}{256\ \ L\ V_G} \qquad (4)$$

Shown in Figures 1 - 4 and Tables 1 and 2 are our end point correlations. Needless to say neither the laminar or turbulent end point correlations fit the data. Further, the laminar and turbulent correlations are quite close together and plot as nearly straight lines. The shape of the actual data points implies that leakage area varies with pressure level and that leakage area decreases with pressure level.

Both small refief valves and dome vent emergency relief valves are pressure loaded against compliant seats. As compartment pressure and vacuum increases this pressure load decreases until the valve opens. At low compartment pressures and vacuums, valve sealing forces are greater and leakage across the compliant seat is lowest.

To test this theory a complete compartment pressure blowdown and vacuum leakage test must be performed. A more complete test was performed on Compartments 2 and 4, May 11, 1977; the data is shown on Data Sheets 15 and 16 and on Figure 5 and 6. Figure 5 shows the pressure blowdown curves. Compartment 4 pressure and vacuum tests showed no leakage when the pressure reached 14.5 inches and the vacuum reached 3 inches of water. Compartment 2 pressure and vacuum curves showed continued but decreased leakage as the level decreased. The Compartment 2 pressure test was discontinued at the 6.25 inch of water level because of time limitations. By using the fact that both turbulent and laminar flow curves appear relatively straight on the pressure versus time plot over limited regions, equivalent turbulent leakage orifices were calculated for various portions of the pressure leakage curve. By comparing equivalent leakage orifices we can see that leakage areas vary enormously.

Compartment 2 Pressure Leakage Comparison

time (min.)	0 - 5	20 - 120	120 - 155
pressure level (in. H_2O)	18-14.5	13.5-6.75	6.75-6.25
diameter (inches)	0.075	0.026	0.014
area ratio	100	11.9	3.6

The same procedure was used for the vacuum leakage data and two curves were derived using the turbulent flow correlation. Again, even for the only curve which had leakage, the area ratio over the lower vacuum part of the curve varies considerably from the high vacuum portion.

Compartment 2 Vacuum Leakage Comparison

time (min.)	0 - 5	15 - 55
vacuum level (in. H_2O)	6 - 4.5	3.5-0.5
diameter (inches)	0.066	0.044
area ratio	100	44.3

Our conclusion is that using the CARB pressure leakage criteria of no more than between 1 and 4 inch pressure degradation from 18 inches of water (or even more so their previous 22 inches of water level) means that compartment leakage at a 6 inch pressure level is at most a small fraction of the expected amount and probably more nearly zero. Vacuum leakage seems to be similar in nature but the error in using orifices calculated from CARB leakage tests will probably be smaller.

Since our conclusion is so important to our later findings, we had Chevron repeat their latest blowdown test using Compartments 1 and 6. We asked that compartment blowdown pressure versus time be first run at 18 inches of water start pressure and then reduce the compartment pressure to 7 inches of water and repeat the test. As Data Sheet 16 shows Compartment 1 showed a small leak at the 18 inch level which became a zero leak at 16.25 inches of water. When the compartment pressure was reduced to 7 inches of water the pressure increased during blowdown. The technician then bled the tank down to 7 inches of water and during the next 20 minutes pressure increased. We feel these pressure increases are due to thermal effects.

The vacuum tests on Compartments 1 and 6 again stabilized in pressure showing zero leakage.

5.2 Truck Loading Losses

Compartment loading pressures are shown on Data Sheets 5 and 12. They are much as we predicted in Reference 1 for single hose loading. Two product loading with the Chevron manifold system on the trucks implies one hose loading to the truck and one hose loading to the trailer. Since separate vapor return hoses are connected to the truck and trailer, the pressure increase noted on Data Sheet 5 shows only the increase in back pressure of the underground piping system. As underground piping is sized for simultaneous loadings, the pressure rise is as expected small. High truck pressures are found when several products are loaded into the same truck with only a single common vapor return hose. As the vapor return hose is usually the major pressure restriction, tank pressure increases. Since during these times of increased pressure, loading rate is also increased; % loss of vapor per gallon of fuel loaded remains approximately the same if the leakage orifice is constant.

We would note that loading pressures on Data Sheet 5 are somewhat lower than shown on Data Sheet 12. This is explainable since only air is being expelled by the tanks bottom loaded on Data Sheet 5 whereas saturated or partially saturated vapor is being expelled during data taken on Data Sheet 12. Mathematically

$$Q = C A \sqrt{\frac{\Delta P}{M}}$$

so ΔP should incrase proportionally as molecular weight (M) increases for the same flow and flow configuration. From RVP and 10% distillation data fuel molecular weights are about 65 and vapor concentrations about 39%. Consequently saturated vapor refuelings should show pressures about 1.48 times as large.

$$P_2 = \frac{43}{29} \quad \Delta P_1 = 1.48 \Delta P_1$$

Loading pressures expelling air of between 2 and 2.5 inches correspond to loading pressures expelling saturated vapor of between 3 and 3.7 inches. These were approximately what was measured. We would note Compartment 2 refueling on Data Sheet 12 has pressure somewhat between the saturated vapor and air refuelings. On checking refueling modes of the other islands, we can surmise that multiple compartment refueling is the cause of the higher than expected pressure in Compartment 4 of Data Sheet 12.

In conclusion, measured refueling pressures were slightly less than anticipated reflecting more than adequate size plumbing. By combining these low pressures with our leakage expectations at these pressure levels versus those measured during the higher pressure CARB tests (Section 5.1), we expect our analytical leakage calculations probably overestimate losses by a factor of 20.

5.3 Truck Transit Losses Following Refueling

Truck over the road compartment pressures following the refueling of air filled compartments are shown on Data Sheet 6. Truck over the road compartment pressures following the refueling of truck compartments, which returned from service station gasoline deliveries with and without vapor transfer, are shown on Data Sheet 13.

All results appear reasonable although the specific results were influenced by several effects not taken into account in our analytical program.

1. Analytical calculations assumed the vapor layer above the fuel surface was at the average concentration of vapor returning from the service station.
2. Analytical calculations assumed the pressure vacuum valves would open fully at 27 inches of water and vent freely.
3. Analytical calculations did not take into account air absorption which may occur.

In the following discussion, we hope to at least quantitatively show how analytical losses overestimate actual loss by not accounting for the above.

Logic as well as analytical calculations (Chapter 2, Reference 2) indicate that the vapor space at the fuel surface will be saturated with vapor concentrations decreasing to the initially present vapor concentration as we move farther from the fuel surface. The amount of evaporation during refueling varies with the turbulence and type of refueling (Reference 2, Chapter 3). With bottom loading evaporation is minimized because agitation and fuel surface area is minimized, nevertheless, a rich vapor layer exists above the fuel surface. Since tanks have some vapor space remaining following refueling, this rich layer tends to reduce the amount of unsaturated vapor; consequently, a smaller amount of fuel will be vaporized by fuel sloshing during transit. As might be expected the refueling evaporative effect is larger with smaller vapor spaces.

This effect is shown in Data Sheet 6 for transport following refueling of air filled tanks and in Data Sheet 13 for transport following refueling of tanks with mixed vapor. A summary is shown below.

Maximum Tank Pressure Vs Refueling Conditions

Compartment No.	1	2	4	6
% Vapor Space above fuel	18.4	4.9	17.0	15.0
		Data Sheet 6		
Initial Vapor Space Condition	Air	Air	Air	Air
Max Truck Transit Pres(In. H_2O)	50+	24.	43	44
Average % Vapor Saturation	71	86	75	75
		Data Sheet 13		
Initial Vapor Space Condition	VR	No VR	No VR	VR
Max Truck Transit Pres(In. H_2O)	3	7	35	0
Average % Vapor Saturation	98	96	80	100

Note:

Average % vapor saturation is calculated assuming vapor losses are small in the time period that these maximum pressures are generated so that maximum pressure is related to saturated pressure of a closed initally partially saturated tank. Tank initial pressure (P) is

$$P = P_A + S_1 P_H^\circ$$

where S_1 is initial saturation; P_H° is fuel vapor pressure; and, P_A is the air partial pressure. By assuming little air absorption during saturation, the final tank pressure (P_F) can be expressed as

$$P_F = P_A + P_H^\circ$$

Eliminating P_A between equations and solving for S_1 we have

$$S_1 = 1 - \left(\frac{P_T - P}{P_H^\circ} \right)$$

The assumption that leakage and air absorption are negligible during the time saturation takes place is justified by noting maximum pressure is achieved in 30 seconds whereas leakage + air absorption causes pressure drops of less than 7 inches in this time. In addition our calculations are conservative since leakage increases average % saturation.

The table shows high vapor percentage saturation in vent spaces after refueling of even initially air filled tanks; and, that the concentration is significantly higher for smaller vapor space percentages. With vapor return from the service station,the tank vapor space after refueling is virtually saturated. Any vapor growth occurring will be initially contained by the pressure/vacuum valves and in most cases saved because of air absorption taking place at the fuel surface.

Factors 2 and 3, that is the fact that the truck valves do not fully open at 27 inches of water and the fact that significant air absorption takes place, further reduces possible truck transit losses following refueling.

Air absorption takes place because fuel is refined in the absence of air. If the fuel is stored and blended over a short period of time in floating roof tanks and shipped via pipeline, the fuel does not come into equilibrium with air. Since fuel in equilibrium with air can hold about 20% by volume air,considerable air can be and at times is absorbed.

However air absorption is slow compared to evaporation of fuel components. This is the reason that evaporation dominates on leaving the terminal until equilibrium is attained. The slower air absorption process however continues and is the eventual cause of the vacuum experienced in the tank trucks (see Data Sheets 6 and 13).

Note:

The reason air absorption takes place slower than fuel absorption is there is less air in the fuel than the various fuel components so air is governed by liquid diffusion and fuel mixing. Evaporation or fuel vapor equilibrium is usually governed by vapor diffusion, nearly a 100 times faster than liquid diffusion. The main difference is, the number of fuel molecules evaporating is small compared to the number present.

The amount of a particular fuel component available for evaporation is given by the fuel mole fraction. This is related to the partial pressure of that component in the vapor space by Raoults Law

$$P_{Hi} = P^{\circ}_{Hi} X_{Hi} \qquad (i = 1, 2, 3 \ldots n) \qquad (5)$$

The amount of air disolved per volume fuel is given by the Ostwald Coef. $\beta = V_{AF}/V_F$. Putting this in the form of Raolts Law we have

$$(P - P^{\circ}_H) = P^{\circ}_A X_A \qquad (6)$$

where X_A is the moles of air per mole of fuel

$$X_A = \frac{\dfrac{V_F (P - P^{\circ}_H)}{R T}}{(V_F \rho_F / M_F)} \qquad (7)$$

Substituting this expression for X_A into Equation 6 and solving for P°_A we have the pseudo vapor pressure of air in fuel as

$$P^{\circ}_A = \frac{\rho_F R T}{\beta M_F} \qquad (8)$$

Using typical values P_H° = 5.865 psia, ρ_F = 47 lbm/ft^3, T = 520°R, β = 0.2, M_F = 95 lbm/lbmol Liq.

$$P_A^\circ = \frac{47(10.7315)(520)}{0.2(95.0)} = 13,800 \text{ psi}$$

$$X_A = \frac{(14.7 - 5.865)}{13,800} = 6.4 \times 10^{-4}$$

In contrast mole fractions of fuel components are several percent. For example normal butane may represent 40% of the fuel vapor vapor pressure. At 60°, normal butane has a vapor pressure of about 25.4 psia, so its mole fraction in the fuel is

$$\frac{.4(5.865)}{25.4} = X_nC_4 = .092$$

~~Another~~ In other words $_nC_4$ fuel concentration is about 144 times that of air.

In conclusion, with vapor return from the service station and bottom loading, very little vapor growth will occur due to fuel saturation on leaving the terminal. Any small pressure increase will be trapped at least temporarily by the pressure vacuum valve and in all probability saved by the fuel air absorption effect which will cause a vacuum to be drawn on the vapor space. The small amount of vapor lost by leakage in the interim is nearly negligible.

5.4 Truck Unloading Losses

Truck unloading losses were not considered as part of the transit losses by CARB however our analytical work indicated that truck leakage versus vapor return path pressure drop is the major determinate of transfer leakage. For this reason we have included calculations in this area in our previous discussions.

Truck vacuum leakage diameters were found to be quite small. (see Table 2). Correspondingly our calculations in Section 2 and correlation Section 2 Figure 1 indicate vapor loss should be 0.2% (Compartment 1) and 0.4% (Compartment 6). Actual volumes accumulated in 42 inch circumference bags were 74.7 gal. in Compartment 1 and 153.1 gal. in Compartment 6. Dividing by the amount of liquid dropped we find 74.7/2075 = 3.6% loss for Compartment 1 and 153.1/2050 = 7.5% loss for Compartment 6.

According to the above either leakage is occuring at other than the truck or the analytical correlation does not account for all terms contributing to leakage. We suspect that some leakage may be occuring near the truck liquid connection however this leakage should be noted on truck test since the hoses are similarly connected. We are also planning on investigating the second possibility although as shown in Appendix A our truck loss approximate and computer solution seems to correspond quite closely. Enough data was derived to make the correlation.

One factor which is not taken into account in our analytical model is evaporation from the fuel surface during defueling. As is shown in the next section using a diffusion model, between 0 and 1.6% vapor growth could occur for this reason. If tank turbulence is sufficient even this amount may be low. 1.6 + .2 = 1.8% which is fairly close to the Compartment 1 measured value of 3.6%. However a major portion of the 7.5% loss on Compartment 6 still appears to be caused by air injestion at the truck transfer fitting. Air injestion has been known to occur at this fitting and steps are being taken to solve the problem.

5.5 Transit Vapor Loss Following Fuel Drop

Truck compartment pressures during transit after a fuel delivery are shown on Data Sheet 11. Tests were run on compartments following fuel drops with and without vapor transfer.

Data taken seems to indicate that pressures were at their highest or nearly so on leaving the service station and that there was little pressure change during transit.

Truck leakage data indicates, that at the truck compartment pressures measured (less than 6 inches of water), leakage will be a maximum of 5% of the leakage measured at the CARB leak test level (18 or 22 inches of water). Most truck compartment pressures measured showed zero leakage at the 6 inch of water pressure level although they showed 1 to 4 inches of water pressure drop in 5 minutes at a 22 inch starting pressure level.

Since absolute temperature is about 540°R and ambient pressure about 407 inches of water and since the ideal gas laws shown absolute pressure varies inversely with absolute temperature for the same mass and volume of gas, we can deduce that a 1.3°F temperature change will cause a 1 inch of water pressure change. Temperature changes of 5 or even 10 degrees can and do occur during our tests and could easily cause the pressure changes noted.

In an effort to determine whether appreciable transit leakage is occurring the 1 inch pressure vent of Compartment 1 was removed and a pipe cap inserted. Vacuum tests on the compartment (Data Sheet 16) indicate 0 vacuum leakage at the 4.5 inch pressure level and we can surmize at below this vacuum level. Pressure measurements on the return trip are shown on Data Sheet 17. We might conclude pressure leakage except for the fact that the pressure went to vacuum. We are led to the unmistakeable conclusion that temperature effects cause most of the pressure phenomena seen and that leakage is near zero.

It follows that evaporation due to fuel remaining within the compartment is near zero which is quite different from the assumption made in our analytical calculation. On reviewing the data we find that our analytical assumption is incorrect. It is true that vapor space saturation on return to terminal following loads dropped at a single station gives vapor space saturation of about 20%. However, since tank vapor spaces for these loads averaged between 5 and 10% and since in travelling over the road these spaces become saturated, this vapor will be present in the tank on defueling and must be subtracted from the 20% initial saturation. One more effect must be taken into account. As the fuel drop occurs air is sucked into the truck tank and evaporation occurs from the receding fuel surface. Since this evaporation occurs during defueling and not from evaporation of residual fuel during transit this fractional saturation must also be subtracted from the 20% initial saturation. This implies the % saturation due to evaporation is probably 10% or less.

To refine this further a group of British Petroleum refuelings in Germany (Reference 3) having low initial fractional saturations and believed to be compartments unloaded at a single location are analyzed.

Test No.	S_1(%)	%Ullage	$S_E + S_D$(%)
20	12.0	1.0	11.0
45	14.0	3.3	10.7
51	12.0	8.6	3.4
54	22.0	19.0	3.0
69	25.0	15.0	10.0
73	15.0	4.3	10.7
74	14.0	0.0	14.0
77	21.0	17.4	3.6
78	14.0	9.1	4.9

95	16.0	9.6	6.4
100	17.0	17.2	-0.2
101	18.0	13.3	4.7
106	17.0	7.9	9.1
108	15.0	3.5	11.5
110	12.0	14.0	-2.0
111	17.0	8.3	8.7
113	11.0	4.2	6.8
114	16.0	5.3	10.7
115	17.0	9.3	7.7
Number	19	19	19
Ave	16.05	8.96	7.09
Std. Dev.	3.63	5.71	4.26
Std. Er.	0.83	1.31	0.98

S_V is the % saturation from the initially present vapor space; and, $S_E + S_D$ is used to denote the residual fuel and defueling evaporative saturation contributions.

Work done by Nichols (Reference 2) allows us to approximate the evaporative emission during defueling assuming that diffusion controls. Nichols shows that the number of moles evaporating is given by

$$W_V = 2 \frac{PS}{RT} \varphi \sqrt{D_{HA} t} \qquad (9)$$

where W_V is in lbmoles; P is the pressure in psi; S is the evaporation surface area in ft^2; R is the universal gas constant 10.7315 (psi X cf)/(lbmol X °R); T is the temperature in °R; D_{HA} is the diffusion coefficient for hydrocarbon in air (88.26×10^{-6} ft^2/sec); and, t is the time in seconds.

$$\varphi = f\left(\frac{Y_{HO} - Y_{HI}}{1 - Y_{HO}}\right) \qquad (10)$$

where $Y_{HO} = P^{\circ}_{H}/P$ and $Y_{HI} = P_{HI}/P$. Here, P°_{H} is the fuel vapor pressure in psi; P is the ambient pressure in psia; and, P_{HI} is the initial partial pressure of the vapor at the fuel interface. The functional relationship of Equation 10 is given in graphical form in Figure 7.

For an example we will choose a tank and calculate the volume of gas evaporated per gallon of tank capacity.

tank 6' x 10' x 5' high = 2244 gal.
P = 14.7psi
T = 80°F = 540°R
t = 5 min = 300 sec

$$\frac{V_E}{V_T} = \frac{W_V RT}{P} \; \frac{7.48}{2244} = \frac{2 \times 7.48}{2244} \; S\varphi\sqrt{D_{HA}t} \qquad (11)$$

$$\frac{V_E}{V_T} = 6.509 \times 10^{-2}\,\varphi \qquad (12)$$

where V_E/V_T is the gallons of fuel vapor evaporated per gallon of tank volume.

Three assumptions are possible for $P_{HI} = S_I P^{\circ}_{H}$.

1. Since the vapor space of the fuel compartment is saturated prior to fuel removal, and since the fuel vapors are heavier than air, we can assume the vapors remain saturated at the fuel surface. In this case $P_{HI} = P^{\circ}_{H}$; $Y_{HO} - Y_{HI} = 0$; $\varphi = 0$ from Figure 7, and, the volume of evaporated vapor is zero (i.e. $V_E/V_T = 0$).

2. The other extreme is to assume the concentration at the fuel surface is equal to the final equilibrium concentration if there was no evaporation. This would assume considerable mixing of fuel surface and the entering vapor air mixture ($P_{HI} = 0.1\ P_H^\circ$). This implies $(Y_{HO} - Y_{HI})/(1 - Y_{HO}) = 0.6$. Figure 7 is used to approximate φ ($\varphi = 0.248$). In this case $V_E/V_T = 0.01614$.

3. The alternate is to assume some average value, for example $P_{HI} = 0.55\ P_H^\circ$. $(Y_{HO} - Y_{HI})/(1 - Y_{HO}) = 0.367$. From Figure 7 $\varphi = 0.167$ and $V_E/V_T = 0.01087$.

Since by the ideal gas law PV = const at constant mass and temperature we can write

$$S_D P_H^\circ (V_T + V_E) = PV_E$$

$$S_D = V_E/V_T/(P_H^\circ/P(1 + V_E/V_T))$$

For an assumed initial interface condition $P_{HI} = S_V P_H^\circ$, we have

S_I	0.1	0.55	1.0
V_E/V_T	0.01614	0.01087	0.0
S_D	0.03971	0.02688	0.0
$S_D + S_V$	0.13971	0.12688	0.1
S_E	0.06029	0.07312	0.1

where S_I is the assumed initial interface concentration; S_V is the vapor space fraction; S_D is the defueling vapor fraction saturated on defueling; and, S_E is the fractional saturation assumed on the return trip.

The amount of gasoline which must be evaporated to increase the vapor space saturation by a given fraction S_E is

$$V_E = S_E \frac{P_H^\circ\ M_H\ \ V_T}{RT\ \ D\ \ 7.48} \qquad (13)$$

where, P°_H is the vapor pressure in psia, M_H is the vapor molecular weight; V_T is the compartment volume; R is the universal gas constant (10.7315); T is the temperature in °R; and, D is the condensed vapor density in lbm/gal

$$D = 6.95 - \frac{120}{M_H} \tag{14}$$

By assuming

$P^\circ_H = 0.4(14.7) = 5.88$ psi

$M_H = 75$

$V_T \doteq 2244$ gal

$D = 5.35$ lbm/gal (Eqn. 14)

Equation 13 becomes

$$V_E = S_E \frac{5.88(75)2244}{10.7315(540)(5.35)7.48} = 4.267\ S_E$$

S_E	0.0	0.025	0.050	0.075	0.100	0.150
V_E	0.0	0.107	0.213	0.320	0.427	0.640

Calculations assume about 50% of the gasoline vaporizes. M. H. Holmes (Reference 3) assumes compartments are empty if they contain less than 2 liters of fuel. Since this corresponds to approximately 10% saturation, this value seems a probable average saturation. $S_E P^\circ_H$ would then be the approximate compartment pressure rise (P_V) which would take place.

$$P_V = 27.7\ P^\circ_H\ S_E = 162.9\ S_E$$

This would say a 10% vapor saturation would lead to a 16.3 inch pressure rise; and, 5% saturation would lead to an 8.2 inch pressure rise.

Chevron data seems to indicate pressure rises of 8 inches of water or less indicating less liquid is trapped than the B.P. data. This is quite possible since the German truck delivery data indicated a high percentage of split compartment drops (i.e. the fuel in one compartment is dropped at more than one location). Since such compartments have higher vapor saturations, if there is an accounting mistake the drop load average becomes considerably higher. Since most trucks in Reference 3 had split loads and some split loads had lower vapor concentrations, we assume some mistakes occurred.

Two other factors might cause Chevron trucks to have smaller evaporative emissions on the return trip than the German trucks:

1. The B.P. trucks in Germany probably meter off their load. Under such conditions fuel retains are more likely to occur since the customer may not want the full amount of fuel in the truck.

2. Vapor return in this country leads to higher initial vapor space saturations and less driving force for evaporation to occur.

Finally we would like to quote M. H. Holmes (Reference 3) observations: "The vapour phase component analysis show that the loading and preloading vapours are similar this suggests that most of the vapour is evolved from the liquid surface of the bulk gasoline during unloading rather than from the drainings or by drying of the wetted tank walls. Therefore, the true vapour pressure should have a direct effect on the vapour content. The presence of more heavy components would have indicated evaporation of a substantial portion of the liquid, in which case true vapour pressure would not be such a good parameter."

Our conclusion is that little vaporization occurs during transit following a fuel drop. The amount occurring will be at a maximum 25 to 50% of the amount assumed in our original calculations. This smaller amount will be trapped by a P/V valve at from 8 to 16 inches of pressure. Leakage of any volume of vapor so formed will be considerably less than that indicated by an orifice calculated from a CARB leakage test.

5.6 Test Temperature Observations

Below are summarized 2/15/77 Test Temperature Data

	Loading Temp	Vapor Space Arrival S. S.	Vapor Space Start SS	Vapor Space Arrival Term
Truck	T_{LS} = 61.5			
Trailer	T_{LR} = 58.5	T_{VS} = 78°F	T_{VS} = 85°	T_{VS} = 75°
	Data Sheet 5	T_{VR} ≐ 77°F	T_{VR} = 78°	T_{VR} = 76°
		T_A = 75°F	T_A = 76°F	
		Data Sheet 6	Data Sheet 11	

	Loading Temp	Vapor Space Lv Terminal	Vapor Space Arrival St.
Truck	T_{LS} = 62.5°F	T_{VS} = 72°F	T_{VS} = 62°F
Trailer	T_{LR} ≐ 59°F	T_{VR} ≐ 71°F	T_{VR} ≐ 65.5°F
	Data Sheet 12	T_A = 76°F	T_A = 64°F
		Data Sheet 13	Data Sheet 13

These observations seem to indicate that vapor space temperatures during transit lie close to ambient. This may be explained by the fact that air movement over the truck (convection heat transfer) dominates either radiant heat transfer or cooling from bulk liquid temperature. This latter observation may be justified by the warm fuel layer effect seen in storage tanks. Here the surface fuel is warmed and remains at the surface due to its lighter specific gravity.

It should be observed that tank truck vapor space temperatures can vary appreciably from ambient in non-moving tankage. Under these circumstances the radiant heating effect of the sun can be appreciable.

6.0 REFERENCES

1. Nichols, R. A. Comments On Proposed CARB Tank Truck Leakage Criteria. R. A. Nichols Engineering, 519 Iris Avenue, Corona del Mar, CA. Jan 18, 1977.

2. Nichols, R. A. Draft Report of A Survey of Emissions From Gasoline Distribution Systems, Chapter 2. EPA Contract No. 68-02-001. Parker Hannifin Corporation, Irvine, CA. 92664 (1975)

3. Holmes, M. J. Emission of Gasoline Vapour when Loading Transport Media in Germany. Part 2. Operations Service Branch. B. P. Trading Ltd., London, England. August 1973.

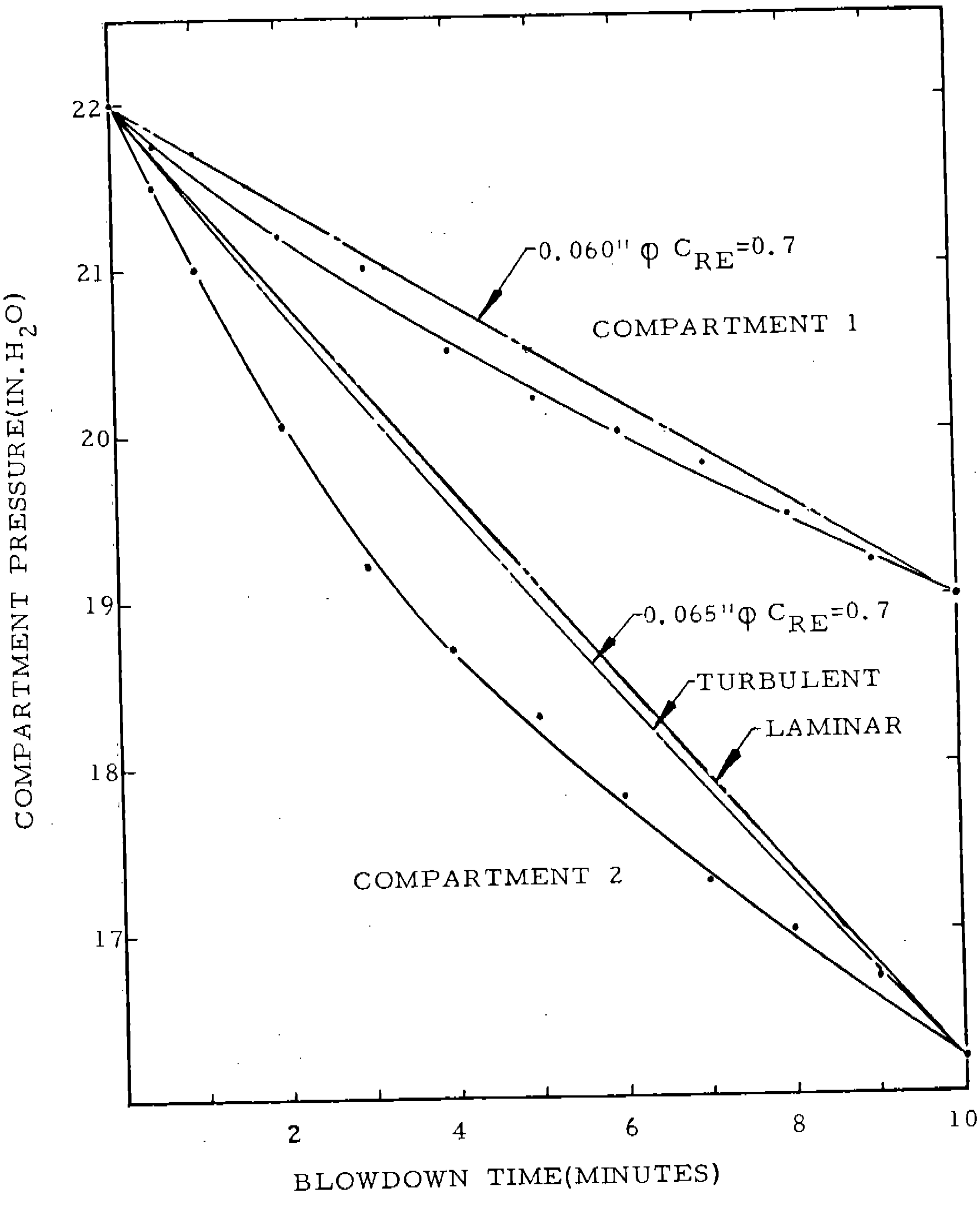

22
21
20
19
18
17
COMPARTMENT PRESSURE(IN.H2O)
0.060" φ C RE=0.7
COMPARTMENT 1
0.065"φ C RE=0.7
TURBULENT
LAMINAR
COMPARTMENT 2
2
4
6
8
10
BLOWDOWN TIME(MINUTES)

Figure 1

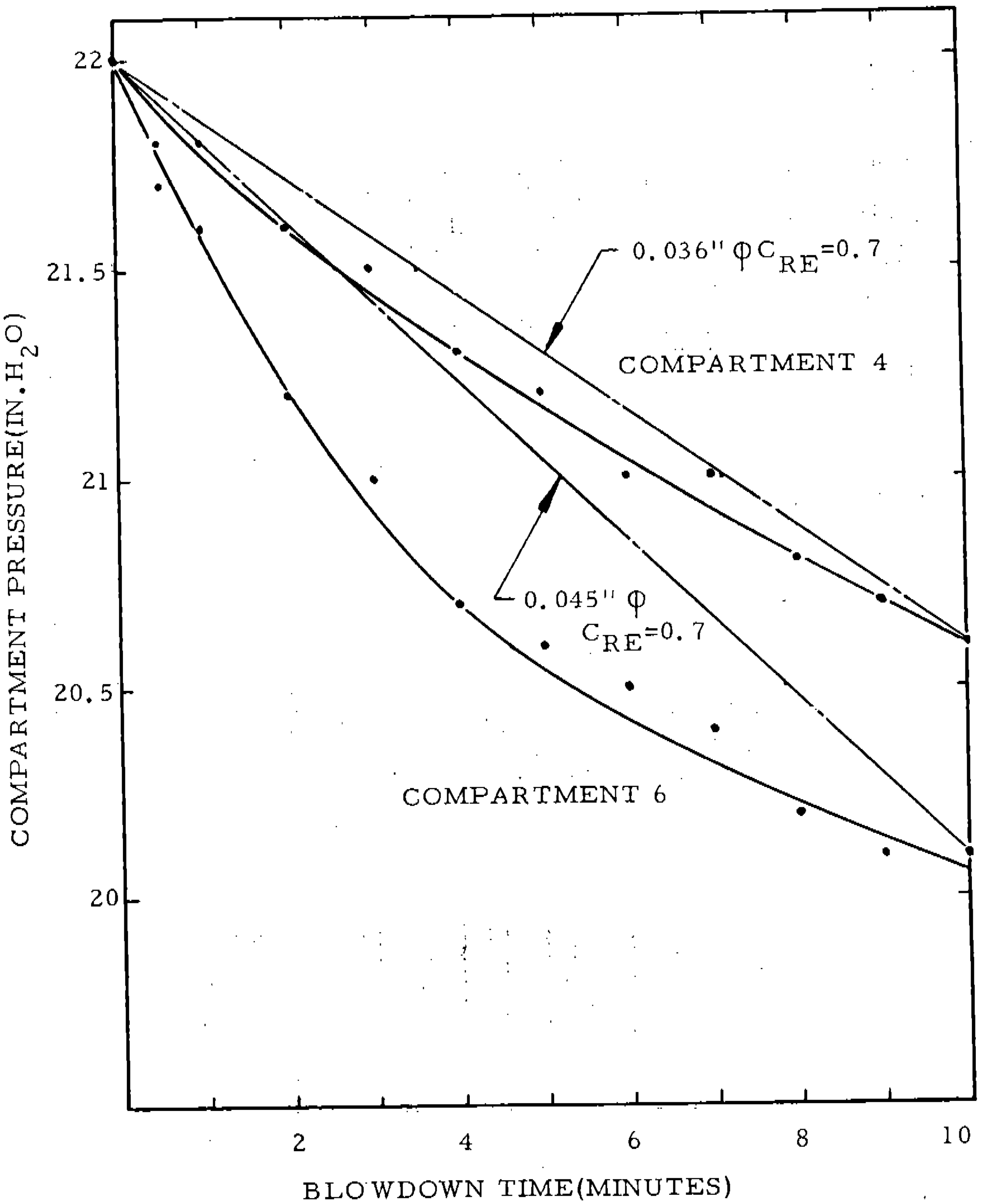

22
21.5
21
20.5
20
COMPARTMENT PRESSURE(IN. H2O)
2
4
6
8
10
BLOWDOWN TIME(MINUTES)
0.036" φ CRE=0.7
COMPARTMENT 4
0.045" φ
CRE=0.7
COMPARTMENT 6

Figure 2

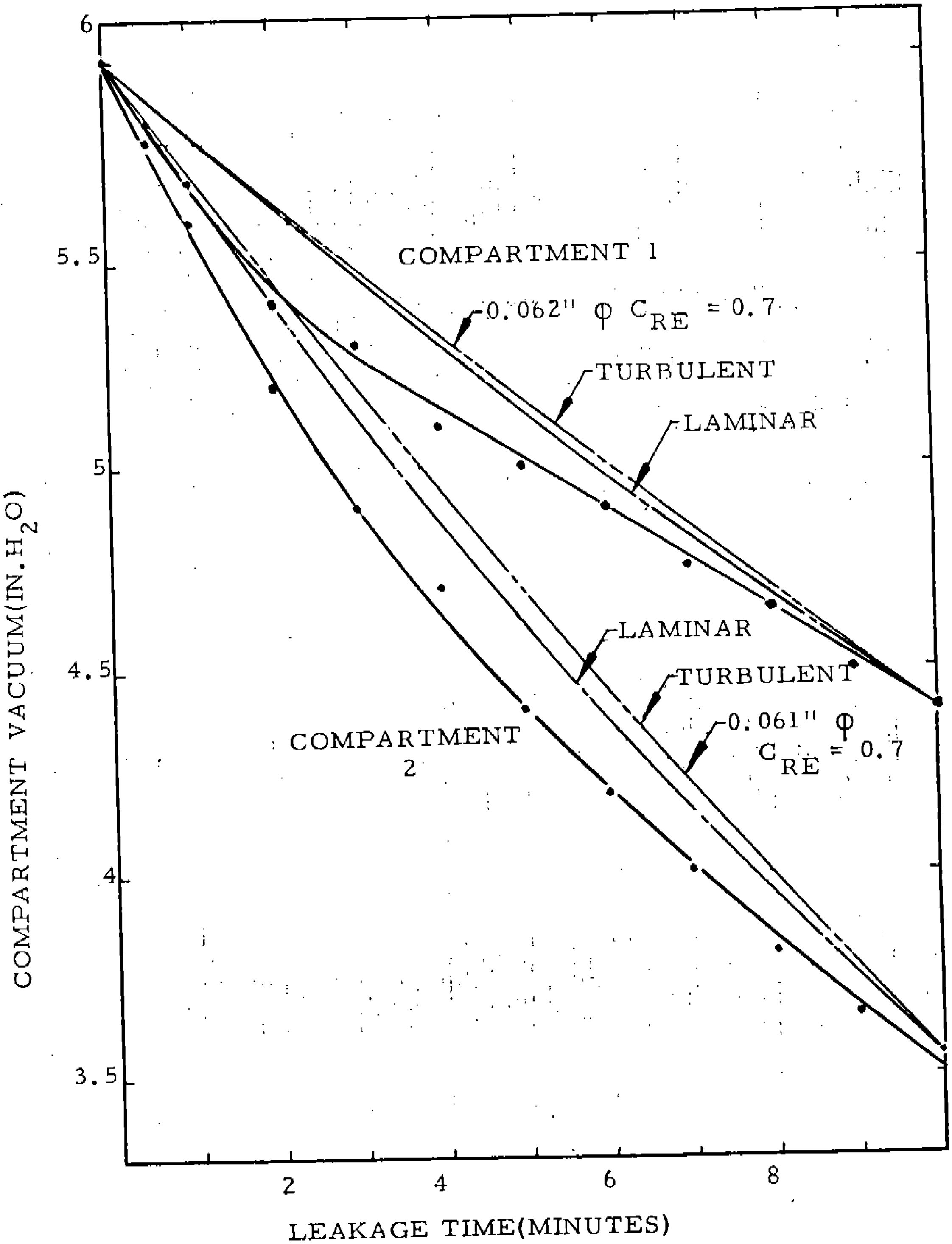

6
5.5
5
4.5
4
3.5
2
4
6
8
COMPARTMENT VACUUM(IN. H_2O)
LEAKAGE TIME(MINUTES)
COMPARTMENT 1
0.062" φ C_{RE} = 0.7
TURBULENT
LAMINAR
LAMINAR
TURBULENT
0.061" φ
C_{RE} = 0.7
COMPARTMENT
2

Figure 3

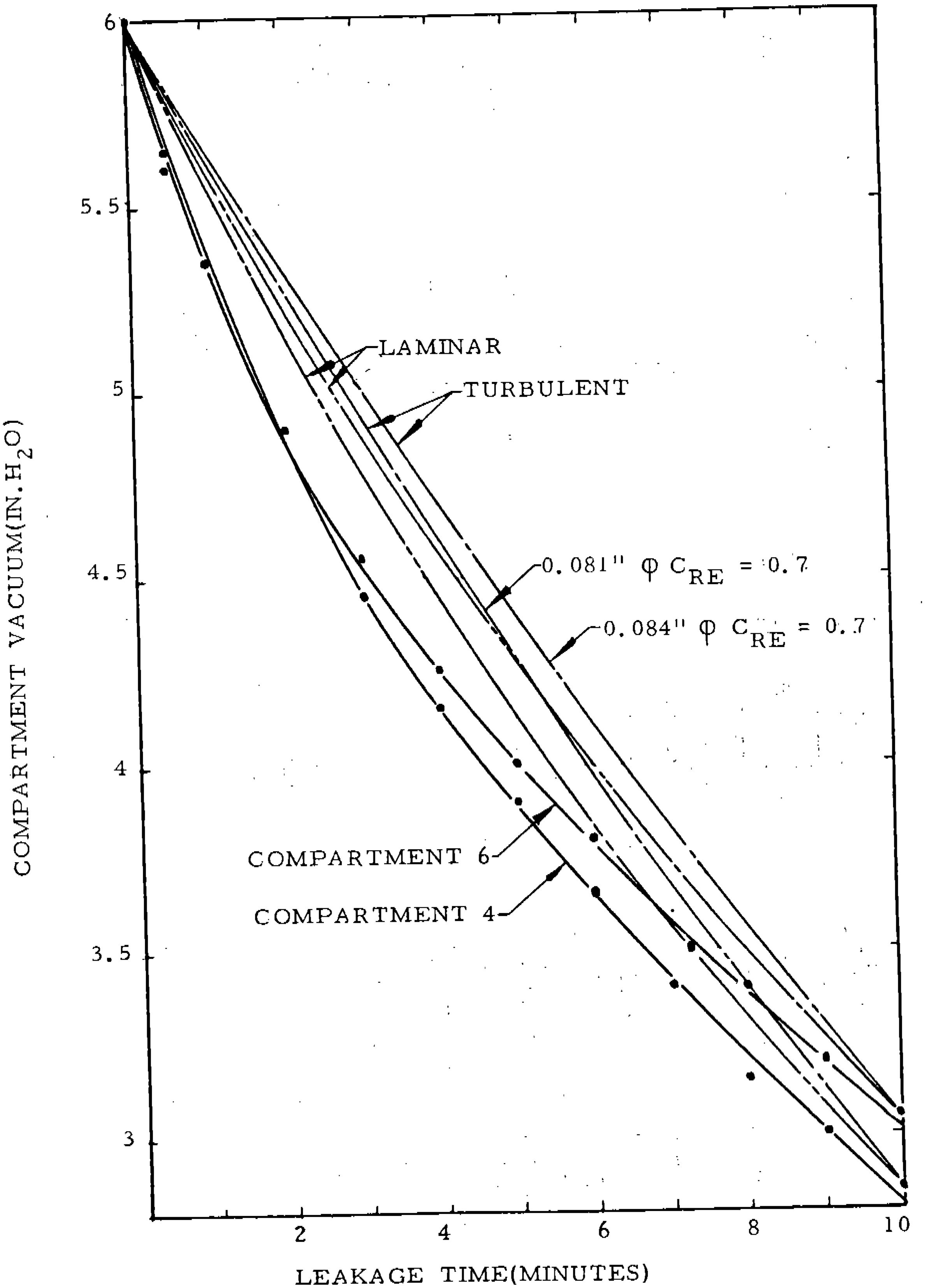

6
5.5
5
4.5
4
3.5
3
2
4
6
8
10
COMPARTMENT VACUUM(IN. H_2O)
LEAKAGE TIME(MINUTES)
LAMINAR
TURBULENT
0.081" φ C_{RE} = 0.7
0.084" φ C_{RE} = 0.7
COMPARTMENT 6
COMPARTMENT 4

Figure 4

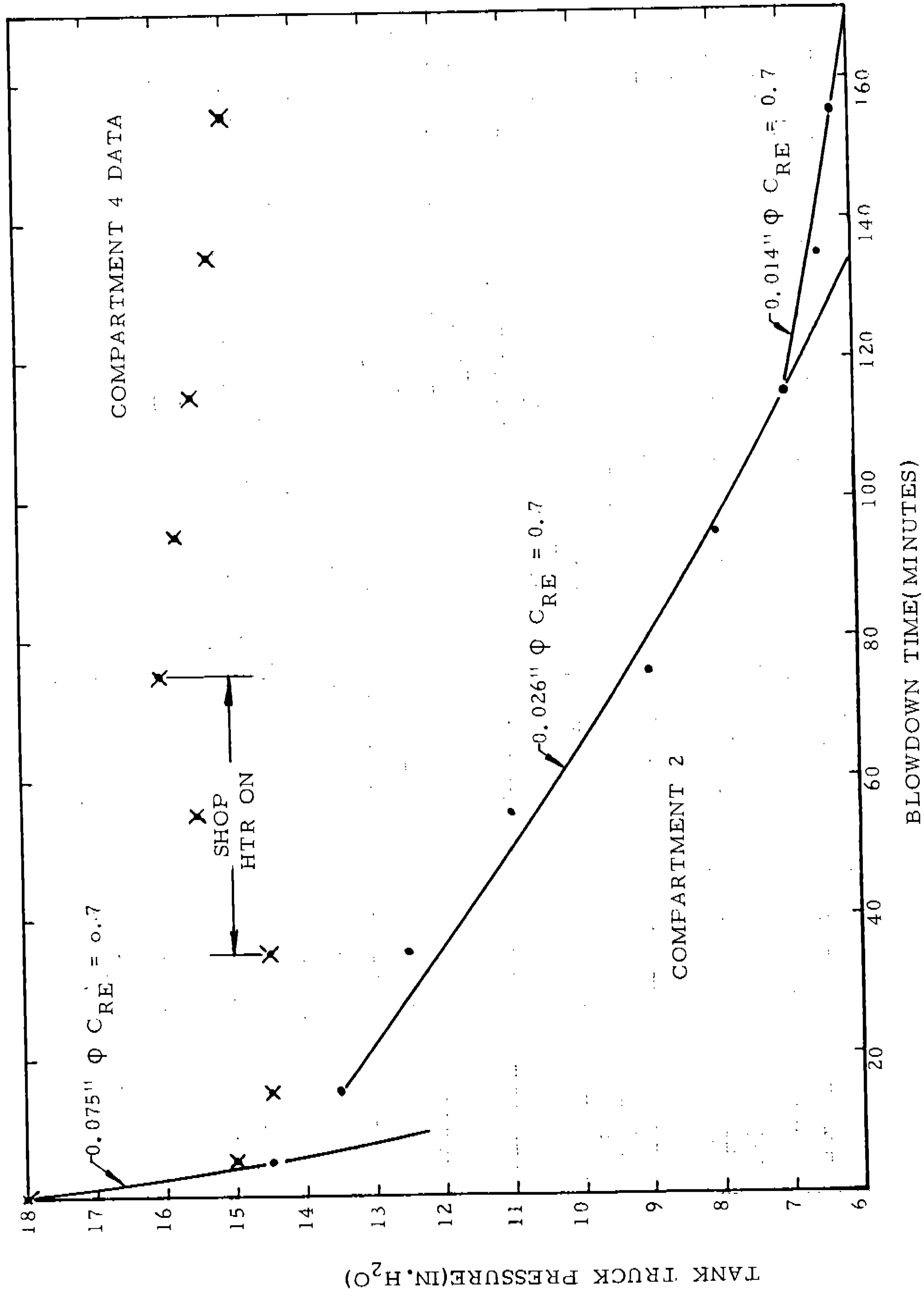

COMPARTMENT 4 DATA
COMPARTMENT 2
SHOP HTR ON
0.075" Φ C RE = o.7
0.026" Φ C RE = 0.7
0.014" Φ C RE = 0.7
BLOWDOWN TIME(MINUTES)
TANK TRUCK PRESSURE(IN. H2O)
20
40
60
80
100
120
140
160
18
17
16
15
14
13
12
11
10
9
8
7
6

Figure 5

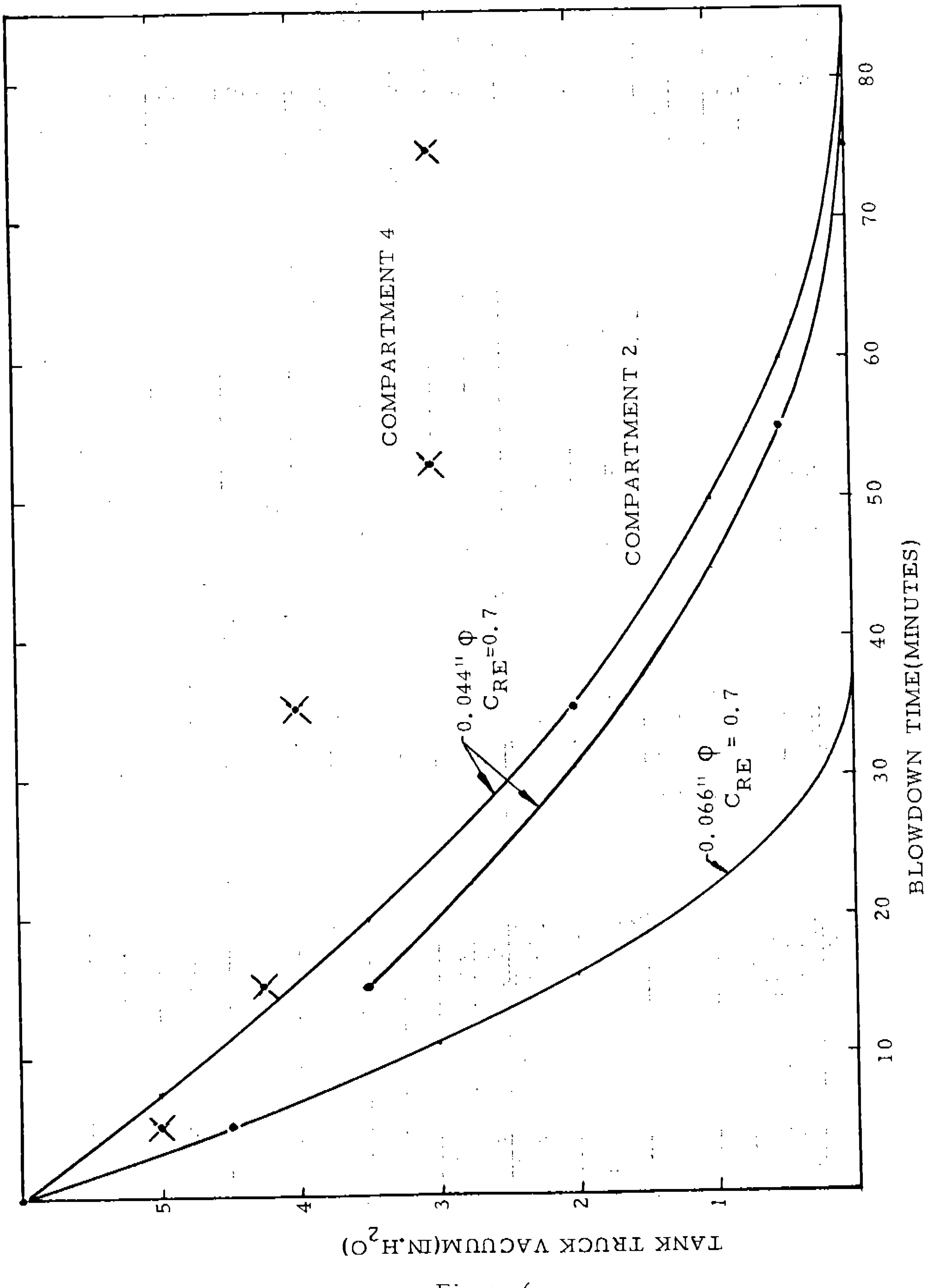

COMPARTMENT 4
COMPARTMENT 2
0.044" Φ
C_RE=0.7
0.066" Φ
C_RE = 0.7
BLOWDOWN TIME(MINUTES)
10
20
30
40
50
60
70
80
TANK TRUCK VACUUM(IN.H2O)
1
2
3
4
5

Figure 6

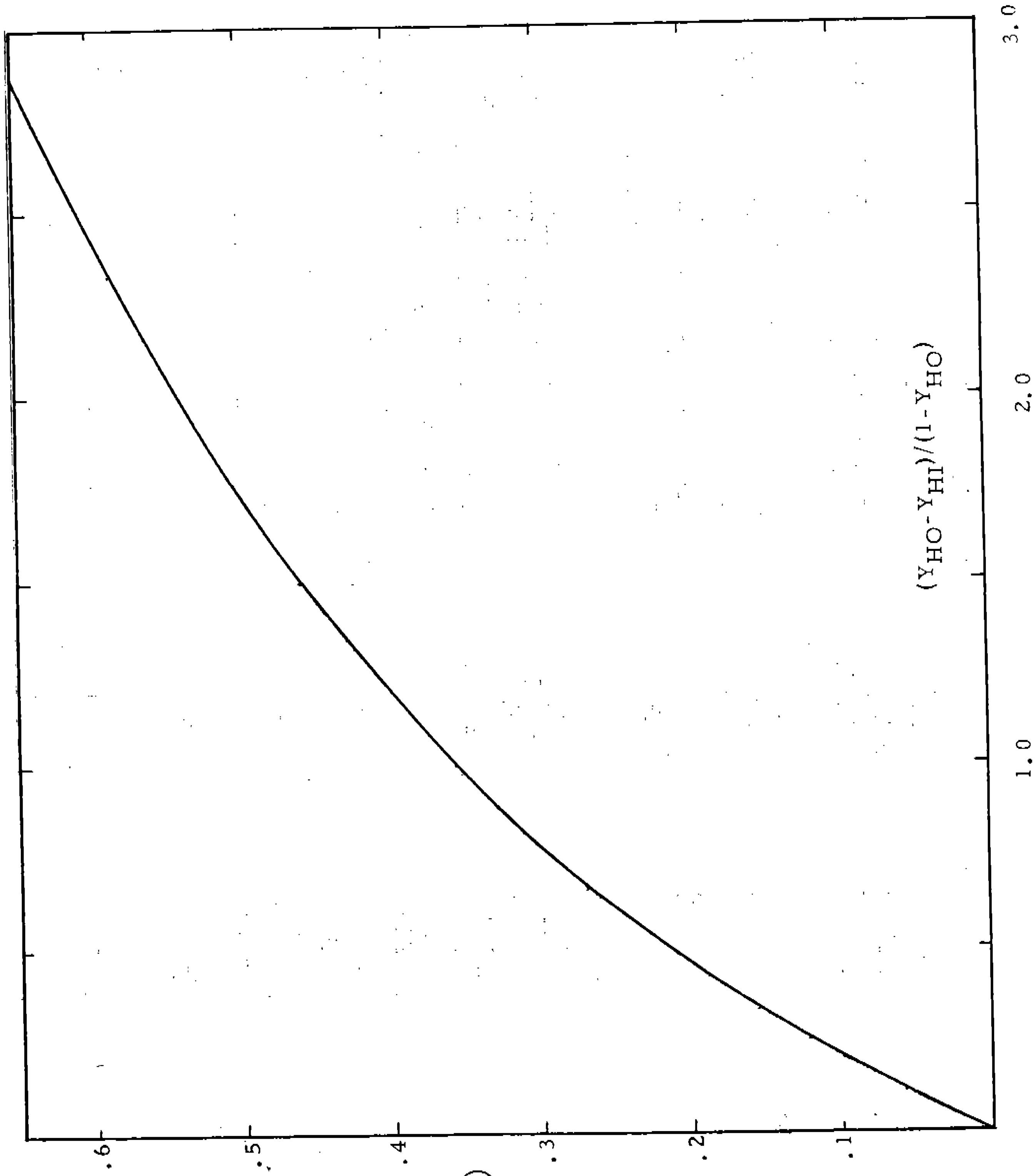


Figure 7

TABLE 1

PRESSURE LEAKAGE END POINT CORRELATION

Comp. No.	Tank Volume Gal.	End Point Pressure In. H_2O	Leakage Dia. (In.) Turbulent C_{RE}=0.7	Laminar .5 InPath
1	2543	19.0	0.060	0.035
2	1525	16.2	0.065	0.036
4	2017	20.6	0.036	0.027
6	2329	20.1	0.045	0.030

Initial Pressure 22.0" H_2O

Blowdown time 10 minutes

TABLE 2

VACUUM LEAKAGE END POINT CORRELATIONS

Comp No.	Tank Volume Gal.	End Point Vacuum In. H_2O	Leakage Dia. (In.) Turbulent C_{RE} =0.7	Leakage Dia. (In.) Laminar .5 InPath
1	2543	4.4	0.062	0.033
2	1525	3.55	0.061	0.033
4	2017	2.85	0.081	0.038
6	2329	3.05	0.084	0.039

Initial Vacuum 6.0 In. H_2O

Blowdown time 10 minutes

DATA SHEET 1

TRUCK LEAK RATE TEST

TIME 10:40 A.M.

DATE 2/15/77

TRUCK # 68-177

COMPT.# 1 COMPT. CAP (SHELL FULL) 2543 Gals.

	PRESS	VAC.
TIME 0	22"H_2O	6"H_2O
30 Sec.	21.75	5.85
1 Min.	21.70	5.7
2	21.2	5.4
3	21.0	5.3
4	20.5	5.1
5	20.2	5.0
6	20.0	4.9
7	19.8	4.75
8	19.5	4.65
9	19.2	4.5
10	19.0	4.4

DATA SHEET 2

TRUCK LEAK RATE TEST

TIME 11:00

DATE 2/15/77

TRUCK # 68-177

COMPT. # 2 COMPT. CAP (SHELL FULL) 1525 Gals.

	PRESS	VAC.
TIME 0	22" H_2O	6" H_2O
30 Sec.	21.5	5.8
1 Min.	21.0	5.6
2	20.1	5.2
3	19.4	4.9
4	18.7	4.7
5	18.3	4.4
6	17.8	4.2
7	17.3	4.0
8	17.0	3.8
9	16.7	3.65 ±
10	16.2	3.55

DATA SHEET 3

TRUCK LEAK RATE TEST

TIME 11:55

DATE 2/15/77

TRUCK # 68-177

COMPT.# 4 COMPT. CAP. (SHELL FULL) 2017 Gals.

	PRESS	VAC.
TIME 0	22" H_2O	6" H_2O
30 Sec.	21.8	5.6
1 Min.	21.8	5.35
2	21.6	4.9
3	21.5	4.45
4	21.3	4.15
5	21.2	3.9
6	21.0	3.65
7	21.0	3.4
8	20.8	3.15
9	20.7	3.0
10	20.6	2.85

DATA SHEET 4

TRUCK LEAK RATE TEST

TIME 12:10

DATE 2/15/77

TRUCK # 68-177

COMPT.# 6 COMPT. CAP. (SHELL FULL) 2329 Gal.

	PRESS.	VAC.
TIME 0	22" H_2O	6" H_2O
30 Sec.	21.7	5.65
1 Min.	21.6	5.35
2	21.2	4.9
3	21.0	4.55
4	20.7	4.25
5	20.6	4.0
6	20.5	3.8
7	20.4	3.6
8	20.2	3.4
9	20.1	3.2
10	20.1	3.05

DATA SHEET 5

TRUCK LOADING DATA

(TEMPERATURE MEASURED COMPARTMENTS
ARE NO. 3 AND 5)

TIME 1:05
DATE 2/15/77
TRUCK # 68-177

SUBSTANCE IN COMPARTMENT AT START OF LOADING

TRUCK	1	Air	TRUCK	4	Air
	2	Air		5	Air
	3	Air		6	Air

TRUCK LOADING TEMP. 61.5°F PRODUCT LOADED IN TRUCK SUPREME
TRAILER LOADING TEMP. 58.5°F PRODUCT LOADED IN TRLR. REGULAR

LOADING PRESSURES	TRUCK		TRAILER	
TIME	COMPT.#1	COMPT.#2	COMPT.#4	COMPT.#6
0	0	0	0	3.0 (3)
30 Sec.	2" H_2O	2.5	3.5(2)	3.0
1 Min	2 (1)	2.5	2.0	3.5
2	2	2.5	2.0	1.0
3	2.5		0	

NOTES:

(1) Single Hose Loading
(2) Two Product Loading
(3) Multiple Truck Loading

DATA SHEET 6

TRUCK TRANSPORT DATA

TIME STARTED 1:30

TIME FINISHED 2:10

DATE 2/15/77

TRUCK # 68-177

AMBIENT TEMP. 75°F

CARGO TANK CONDITION Loaded

VAPOR SPACE TEMP.(START) IN CONTROL COMPT(#3)

VAPOR SPACE TEMP.(FINISH) IN CONTROL COMPT(#5)

TRANSPORT PRESSURES

	TRUCK		TRAILER	
TIME	COMPT.#1	COMPT.#2	COMPT.#4	COMPT.#6
0	25	24	14.5	17
30 Sec.	50+	24	43	44
1 Min.	43	20	40	39
2	35	15	34	32
3	31	10	30	29
4	29	5	28	26
5	27	1	26	25
6	24	-?(1)	21	23
9	19	0	14	19
10	17	-?	14	17
13	13	-?	10	15
15	11	-?	8	13
18	7	-?	4	10
21	5	-?	2	8
24	3	-?	1	6
27	3	-?	1	5

DATA SHEET 6 (CONT.)

	TRUCK		TRAILER	
TIME	COMPT.#1	COMPT.#2	COMPT.#4	COMPT.#6
30(2)	-?	-?	-?	-?
31	-?	-?	-?	-?
32	-?	-?	-?	-?
33	-?	-?	-?	-?
36	-?	-?	-?	-?
37	-?	-?	-?	-?
38	-?	-?	-?	-?
39	-?	-?	-?	-?
40	-?	-?	-?	-?

end of run (at Station #9148)

(1) Opened Dome to check

(2) Turn around truck at Milk Farm

DATA SHEET 7

TRUCK UNLOADING DATA

TIME 2:45

DATE 2/15/77

COMPT. 2 PRODUCT Sup. VAPOR RECOVERY No TRUCK#68-177

UNDERGROUND TANK

QUANTITY AT START 550 DEPTH BELOW GROUND 9'10"

QUANTITY AT FINISH 2100 DEPTH BELOW GROUND 8'10"

QUANTITY DELIVERED 1450 DELIVERY TIME 3 min. 15sec.

LENGTH OF BAG ON STATION VENT N/A

DELIVERY DATA

TIME	CARGO TANK VACUUM	UNDERGROUND TANK PRESS.
0	0	0
30 Sec.	1.15	6.6
1 Min.	1.20	8.6
2	1.20	7.2
3	1.10	6.0
3:05	1.0	2.0
3:15	0	0

DATA SHEET 8

TRUCK UNLOADING DATA

TIME 2:55

DATE 2/15/77

COMPT.# 1 PRODUCT Sup. VAPOR RECOVERY Yes TRUCK #68-177

UNDERGROUND TANK

QUANTITY AT START 2100 DEPTH BELOW GROUND 8'10"

QUANTITY AT FINISH 4450 DEPTH BELOW GROUND 7'4"

QUANTITY DELIVERED 2075 DELIVERY TIME 4 min. 56 sec

LENGTH OF BAG ON STATION VENT 10'3"(1)

DELIVERY DATA

TIME	CARGO TANK VACUUM	UNDERGROUND TANK PRESS.
0	0	0
30 Sec.	1.75	.05
1 Min.	1.75	.05
2	1.70	.04
2.5	1.70	.03
3.0	1.65	.025
3.5	1.60	.025
4.0	1.55	.025
4.5	1.50	.03
4:56	1.0	0

(1) 42 inch circumference bag

DATA SHEET 9

TRUCK UNLOADING DATA

TIME 3:20

DATA 2/15/77

COMPT.# 4 PRODUCT CLL VAPOR RECOVERY No TRUCK# 68-177

UNDERGROUND TANK

QUANTITY AT START 900 DEPTH BELOW GROUND 9'6"

QUANTITY AT FINISH 2650 DEPTH BELOW GROUND 8'2 1/2"

QUANTITY DELIVERED 1675 DELIVERY TIME 4 min 9 sec.

LENGTH OF BAG ON STATION VENT None

DELIVERY DATA

TIME	CARGO TANK VACUUM	UNDERGROUND TANK PRESS.
0	0	0
30 Sec.	.95	5.8
1 Min.	.95	7.5
1.5 Min.	.95	8.0
2.0	.95	7.4
2.5	.90	7.0
3.0	.80	6.6
3.5	.85	6.15
4.0	.78	6.0
4:09	0	0

DATA SHEET 10

TRUCK UNLOADING DATA

TIME 3:35

DATE 2/15/77

COMPT. 6 PRODUCT CLL VAPOR RECOVERY Yes TRUCK#68-177

UNDERGROUND TANK

QUANTITY AT START 2650 DEPTH BELOW GROUND 8'2 1/2"

QUANTITY AT FINISH 4700 DEPTH BELOW GROUND 6' 11"

QUANTITY DELIVERED 1980 DELIVERY TIME 4 min 23 sec.

LENGTH OF BAG ON STATION VENT 21' 0" (1)

DELIVERY DATA

TIME	CARGO TANK VACUUM	UNDERGROUND TANK PRESS.
0	0	0
30 Sec.	1.55	.15
1 Min.	1.52	.15
2 Min.	1.50	.08
2.5	1.45	.07
3.0	1.40	.06
3.5	1.38	.06
4.0	1.35	.05+
4.23	1.30	.05

(1) 42" circumference bag

DATA SHEET 11

TRUCK TRANSPORT DATA

TIME STARTED 4:04

TIME FINISHED 4:37

DATE 2/15/77

TRUCK # 68-177

AMBIENT TEMP. 76°F

CARGO TANK CONDTION Empty

VAPOR SPACE TEMP. (START) COMPT. (#3) TRK 85°F
(#5) TRLR 78°F

VAPOR SPACE TEMP. (FINISH) COMPT. (#3) TRK 75°F
(#5) TRLR 76°F

TRANSPORT PRESSURES

	TRUCK		TRAILER	
	V.R.	No V.R.	No V.R.	V.R.
TIME	COMPT. #1	COMPT. #2	COMPT. #4	COMPT. #6
0	5	5	3	5
30 Sec.	5	5	3	5
1 Min.	5	5	3	5.5
2 Min.	5	5.5	3	5.5
3	5.5	6	3.5	6.0
4	5.5	6	3	6
5	5.5	6	3	6
6	6	6	3	6
7	5.5	6	3	6
8	5	6	2.5	5.5
9	5.5	6	2.5	6
10(1)	5	5.5	2	5
11	5	6	2	5
12	5.5	6	3	6

DATA SHEET 11 (CONT.)

	TRUCK		TRAILER	
	V.R.	No V.R.	No V.R.	V.R.
TIME	COMPT.#1	COMPT.#2	COMPT#4	COMPT.#6
13	5.5	6.5	2.5	6
14	5.5	6	2.5	6
15	5.5	6	2.5	6
18	5	6	2	6
21	5	6	2	6
24	5	6	2	6
27	5	6	1.5	6
30	4.5	5.5	1.5	5.5
33	3.5	4.5	0.5	4.5

(1) turn around head for Sacramento

DATA SHEET 12

TRUCK LOADING DATA

(TEMP CONTROL COMPTS. ARE #3 and 5)

TIME 4:45
DATE 2/15/77
TRUCK#68-177

SUBSTANCE IN COMPT. AT START OF LOADING

TRUCK	1	Vapor	TRLR. 4	Air
	2	Air	5	Vapor
	3	Vapor	6	Vapor

TRUCK LOADING TEMP. 62.5°F PRODUCT LOADED IN TRUCK Sup

TRAILER LOADING TEMP.59°F PRODUCT LOADED IN TRLR. CLL

LOADING PRESSURES	TRUCK		TRAILER	
TIME	COMPT#1	COMPT#2	COMPT#4	COMPT#6
0	1	1	1	1
30 Sec.	3.5	3	4	3.5
1 Min.	3.5	3	4	4
2	4	3.5	4	4
3	4			

DATA SHEET 13

TRUCK TRANSPORT DATA

TIME STARTED 5:18

TIME FINISHED 5:59

DATE 2/15/77

TRUCK #68-177

AMBIENT TEMP. 76

CARGO TANK CONDITION Full

VAPOR SPACE TEMP.(START) COMPT. (#3) TRUCK 72°
(#5) TRAILER 71°

VAPOR SPACE TEMP.(FINISH) COMPT. (#3) TRUCK 62.0°
(#5) TRAILER 65.5°

TRANSPORT PRESSURES

	TRUCK		TRAILER	
TIME	COMPT. #1	COMPT. #2	COMPT. #4	COMPT. #6
0	0	5	3	0
30 Sec	2.5	7	35	-2
1 Min.	3	4	34	-6
2 Min.	1	-5	31	-8
3	-1	-7	29	-9
4	-1.5	->10	28	-10
5	-2	-8.5	27	-9.5
6	-2	-8.5	26	-9.5
7	-3	-9	21	-9.5
8	-4	-7	20	-9
9	-4.5	-6	19	-9
10	-5.5	-7	18	-9
11	-5.5	-7.5	17	-9
12	-5.5	-7.5	17	-9

DATA SHEET 13 (CONT.)

	TRUCK		TRAILER	
TIME	COMPT. #1	COMPT. #2	COMPT. #4	COMPT. #6
13	-6	-7.5	16	-9
14	-7	-9	13	-9
15	-7	-8	12	-9
18	-8.5	-6.5	9	-9
21	-8	-5.5	8	-9
24	-8	-6	7	-9
27	-10	-10	3	-10
30	-8	-6.5	1	-9
33	-8	-5	1	-8
36	-8	-6	-1	-8

DATA SHEET 14

RVP AND FUEL D-216 DISTILLATION DATA

FOR DATA SHEETS 1 THRU 13

FUEL	REGULAR		SUPREME	
SAMPLE	1	2	1	2
RVP	11.0	11.3	11.3	11.1
RVP REPEAT	11.0	11.2	11.3	11.2
% CONDENSED	DISTILLATION TEMPERATURES, °F			
START	83	78	79	78
5%	101	100	99	99
10%	114	113	109	110
15%	124	124	118	120
20%	135	134	128	131
25%	146	144	137	140
30%	154	153	147	149

DATA SHEET 15

COMPARTMENT 2 and 4 LEAK TESTS

DATE 5/11/77

TRUCK #68-177

TRUCK COMPARTMENT 2 -1525 GAL.

PRESSURE TEST

Hr : Min	In. H_2O
0:00	18.0
0:05	14.5
0:15	13.5
0:35	12.5
0:55	11.0
1:15	9.0
1:35	8.0
1:55	7.0
2:15	7.0
2:15	6.5
2:35	6.25

VACUUM TEST

Hr : Min	In. H_2O
0:00	6.0
0:05	4.5
0:15	3.5
0:35	2.0
0:55	0.5
1:15	0.0

TRAILER COMPARTMENT 4 - 2017 GAL.

PRESSURE TEST

Hr : Min	In. H_2O	
0:00	18.0	
0:05	15.0	
0:15	14.5	
0:35	14.5	
0:55	15.5	(2)
1:15	16.0	
1:35	15.75	
1:55	15.5	
2:15	15:25	
2:35	15.0	

VACUUM TEST

Hr : Min	In. H_2O
0:00	6.0
0:05	5.0
0:15	4.5
0:35	4.0
0:55	3.0
1:15	3.0
1:35	3.0

Notes: (1) Vacuum Test run morning, #4 Pres over lunch, #2 pressure last
(2) Shop heater came on and was shut off when ΔP rise found.

DATA SHEET 16

COMPARTMENT 1 and 6 LEAK TESTS

DATE 5/25/77

TRUCK #68-177

TRUCK COMPARTMENT 1 - 2543 GAL

PRESSURE TEST

Min	In. H_2O
0.	18.0
5	17.0
10	16.75
15	16.5
20	16.25
25	16.25
0	7.0 (1)
20	9.0
0	7.0 (1)
20	7.375

VACUUM TEST

Min	In. H_2O
0	6
5	5
10	4.5
15	4.5

TRAILER COMPARTMENT 6 - 2329 GAL

VACUUM TEST

Min	In. H_2O
0	6
5	5
10	4.5
15	4.5

PRESSURE TEST

Min	In. H_2O
0	18.0
3	15.0

Notes:

(1) Tank pressure bled down to 7.0 inches water, leakage test started.

(2) Pressure tests run 1st, 1" Pressure vent plugged with pipe plug and the vacuum tests run.

DATA SHEET 17

VAPOR TRANSIT PRESSURE AFTER FUEL DROP

DATE 5/25/77

TRUCK #68-177

TRUCK COMPARTMENT 1 - 2017 GAL.

AMBIENT TEMP. 70°F
FUEL LOAD TEMP. 72°F
HAZY SUN

Min	In. H_2O
0	0.6
1	0.8
2	1.2
3	1.0
4	0.7
5	0.7
6	0.4
7	0.1
8	0.0
9	-0.2(1)
10	-0.4
11	-0.4
12	-0.1(2)
13	-0.5
14	-0.7(3)
15	-0.8
16	-1.3(4)

Notes:

(1) Minus sign means vacuum

(2) Came off freeway

(3) Stop and Go traffic

(4) Arrive terminal

AP-42
5th edition
Section 5.2
#11

R. A. Nichols Engineering

519 Iris Avenue, Corona del Mar, Ca. 9262

(714) 644-7735

June 10, 1977

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

Dear Mr. Uhlig:

Our previous analytical calculations considerably overestimated truck transit and terminal refueling leakage. Updated analysis of a 5000 gallon compartment, using the data and methods developed during the Chevron "Tank Truck Leakage Measurements", indicates leakage will be less than 0.3 gm/gallon of fuel. Terminal and transit leakage, originally addressed by CARB, is less than 0.1 gm/gal. These results are with leakage pressure drops of 16 inches of water in 5 minutes.

Leakage in all transit modes as well as refueling is smaller because leakage area is found to vary with truck pressure and vacuum. CARB leakage tests determine leakage at high pressure and vacuum levels (14-22 inches of water pressure and 4-6 inches of water vacuum). Leakage at lower pressure and vacuum levels (6 inches of water pressure and 3 inches of water vacuum) appears to be much lower or nonexistant. It seems conservative to assume pressure leakage below 7 inches of water to be 5% of leakage determined during CARB tests. Vacuum leakage at 3 inches of water may conservatively be assumed to be 50% of that determined during CARB tests starting at 6 inches of water vacuum.

Since Chevron bottom loading truck refueling pressures are less than the 7 inches of water, truck leakage may be assumed to be overestimated by a factor of twenty.

Transit leakage following truck refueling was overestimated. Our calculations failed to take into account the rich layer at the fuel surface after refueling. This layer greatly reduces the unsaturated vapor space available for saturation. Secondly our calculations assumed free venting above the D.O.T. valve crack pressure of 27 inches of water. In refueling tests of air filled compartments where pressures above this level can occur, venting was restricted. Third-ly, air absorption into the fuel usually occurs. This effect happens because fuel when refined and stored is prevented from coming into equilibrium with air. Since fuel can hold about 20% by volume air, absorption occurs and vacuums are measured during most of transit. With vapor balancing during fuel deliveries, little pressure rise occurs due to vapor saturation (less than 6 inches of pressure). Positive pressures usually become vacuum after less than 5 minutes because of air absorption. Under such conditions vapor loss is negligible.

Transit leakage following fuel delivery at the service station was overestimated. The full vapor concentration of trucks returning to the terminal after a fuel drop without vapor recovery was assumed to be the result of residual fuel and wetted wall evaporation. Tests, to confirm this assumption to the contrary showed little evaporation. Inspection of our original data base as well as test data shows that approximately 50% of the compartment vapor concentration is due to the initially present saturated vapor space above the fuel (10% vapor space x 100% saturation = 100% vapor space x 10% saturated). Evaporation during fuel delivery at the service station can be shown to cause evaporation of up to 2% of the vapor space volume using a diffusion model. With turbulence this could be more, we assume between 0-5%. Subtracting this prior evaporation from that measured, we feel residual fuel evaporation will more nearly account for a maximum of between 5 and 10% vapor space saturation. U.S. practice of dropping a whole fuel compartment at once versus the European practice of splitting loads and metering fuel delivery also should lead to less residual fuel in U.S. tanker compartments. Finally vapor balancing during fuel delivery leads to much richer returning vapor concentrations. Evaporation into richer vapor concentrations will be less in total volume and slower. With vapor leakage at the pressures measured in the U.S. (6 inches of water), a maximum of 20 times less than measured in CARB pressure leakage tests, both maximum and transit vapor loss will be much less than previously thought.

Analytical calculations underestimate truck unloading losses at the service station. Tests showed transfers exceeded required air pollution 90% requirements but fell short of the analytically predicted 99+% efficiency. Our analytical program did not take into account fuel evaporation during truck refueling or possible air injestion at the truck transfer fitting. Fuel evaporation is rather difficult to predict but could lead to from 0 to 5% vapor growth. Air injestion at the fuel hose fitting is known to occur and steps are being taken to improve the connection.

To quantitatively estimate the losses outlined above in the various leakage modes, we have revised our earlier leakage calculations.

Liquid transit vapor leakage has been assumed to be equivalent to 5 minutes of leakage at an average pressure of 3 inches of water. Since pressures in the tank with vapor return are less than 6 inches of water, leakage area is taken as 5% of that measured during the CARB leak test.

Terminal loss is shown at 6 inches of water and 5% of the CARB leak test area.

Vapor transit loss is shown at 6 inches of water and 5% of the CARB leak test area. Maximum leakage has been assumed by calculating the limit either 5 or 10% increased vapor saturation.

Saturation Increase	x	Vapor Pressure Atmosphere	x	Vapor Density Gm/Gal	=	Max Loss Gm/Gal
0.05	x	0.40	x	4.142	=	0.0828
0.10	x	0.40	x	4.142	=	0.1657

Service station delivery loss is assumed made up of two losses: First, a 2% volume loss of saturated vapor is assumed to account for evaporation during defueling. Secondly, the leakage loss is assumed to be at 50% the CARB leak test area. No provision has been made to estimate air injestion presently occurring at vapor transfer fittings.

Leakage calculations are shown in Table 1 and leakage orifice diameter is shown for various leakage pressure drops in a 5 minute leak test from 22 and 18 inches of water. The data of Tables I and II is graphically shown in Figure 1.

As can be readily ascertained the imposition of stringent CARB type leakage requirements causes little or no reduction in truck transit emissions or for that matter terminal and service station fuel transfer emissions. Attached is a test report "Tank Truck Leakage Messurements" which describes the tests and analysis leading to the above conclusions.

Very truly yours,

Richard A Nichols

Richard A. Nichols, Ph.D.

RAN:sn

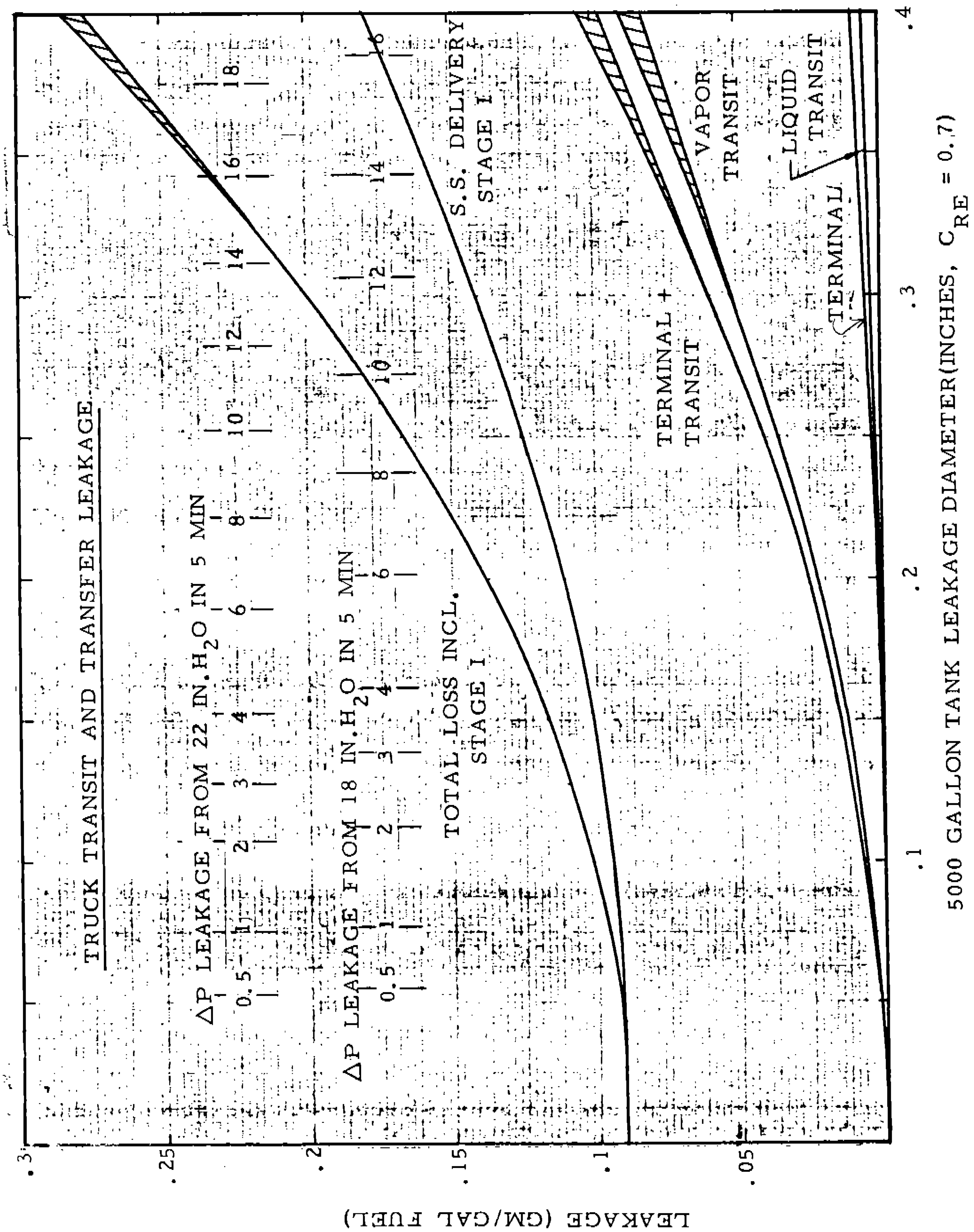

TRUCK TRANSIT AND TRANSFER LEAKAGE
ΔP LEAKAGE FROM 22 IN. H_2O IN 5 MIN
0.5
1
2
3
4
6
8
10
12
14
16
18
ΔP LEAKAGE FROM 18 IN. H_2O IN 5 MIN
0.5
1
2
3
4
6
8
10
12
14
16
TOTAL LOSS INCL. STAGE I
S.S. DELIVERY STAGE I
TERMINAL + TRANSIT
VAPOR TRANSIT
LIQUID TRANSIT
TERMINAL
5000 GALLON TANK LEAKAGE DIAMETER (INCHES, C_{RE} = 0.7)
.1
.2
.3
.4
LEAKAGE (GM/GAL FUEL)
.05
.1
.15
.2
.25
.3

FIGURE 1

TABLE 1

TRUCK TRANSIT AND TRANSFER LEAKAGE LOSS

ΔP Loss In. H_2O	Leak Dia 5000 Gal In. O	Terminal Loss Gm/Gal	Terminal Vapor Vol%Loss	Liquid Trans. Loss Gm/Gal	Vapor Trans. Loss 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	0	.0911	2.20	0	.0911
0.5	.0528	.0002	.0037	.0001	.0016	.0915	2.21	.0019	.0934
1	.0749	.0003	.0076	.0002	.0032	.0924	2.23	.0037	.0961
2	.107	.0006	.0155	.0004	.0065	.0961	2.32	.0075	.1036
3	.131	.0010	.0232	.0006	.0097	.0994	2.40	.0113	.1107
4	.153	.0013	.0316	.0008	.0132	.1019	2.46	.0153	.1172
	.200	.0022	.0537	.0013	.0226	.1110	2.68	.0261	.1371
	.250	.0035	.0840	.0021	.0354	.1267	3.06	.0410	.1677
	.300	.0050	.1210	.0030	.0509	.1400	3.38	.0589	.1989
	.400	.0089	.2150	.0053	(.0828 .0905)	.1802	4.35	(.0970 .1047)	(.2772 .2849)
	.500	.0139	.3358	.0083	(.0828 .1415)	.2278	5.50	(.1051 .1637)	(.3328 .3915)
		ΔP = 6"		ΔP=3"H_2O	ΔP=6"H_2O				
		Q_L =600gpm		t=5min	t=60 min				
				Max=.0351	Max=.0828 .1657				
		D = .05CARB		D=.05CARB	D=.05CARB	D=.50CARB			

R. A. Nichols Engineering

LEAKAGE ORIFICE DIA. (IN. C_{RE}=0.7)

P	INIT. PRES	IN. H_2O
IN. H_2O	22 IN	18
0.5	.053	.056
1.0	.075	.079
2.0	.107	.113
3.0	.131	.139
4.0	.153	.162
6.0	.190	.202
8.0	.222	.238
10.0	.253	.272
12.0	.282	.306
14.0	.312	.343
16.0	.342	.385
18.0	.375	.472

5000 GAL TANK, T = 80°F, M_V = 44.58

TABLE 2

TANK TRUCK LEAKAGE MEASUREMENTS

Analysis by

Richard A. Nichols, Ph.D.

Testing by

John Synder

C. R. Lupcho

Chevron U.S.A. Inc.

June 7, 1977

R. A. Nichols
Engineering

ABSTRACT

The attached report describes tests run by Chevron U.S.A. Inc. to verify analytical truck loss calculations made by R. A. Nichols Engineering. The tests show that the analytical calculations considerably overestimate leakage occurring during truck transit and refueling at the terminal. Leakage is shown to be nearly non-existant during Chevron transit and terminal refueling tests and to be nearly negligible analytically in all but the transit mode following fuel delivery. Maximum analytical loss in transit following fuel delivery is shown to be between .083 and 0.17 gm/gal with leakage rates so slow that these maximums will probably not be achieved. Stage I fuel delivery loss at the service station was analytically underestimated but still well within the 90% efficiency required by air pollution agencies. Two factors leading to this underestimation were that the analytical program did not account for air injestion at fuel transfer fittings or fuel evaporation during defueling.

ACKNOWLEDGEMENT

The author would like to acknowledge the work of John Snyder, Chevron U.S.A. Inc. and Alexandra G. Nichols.

1.0 PURPOSE AND SCOPE

Considerable data on truck compartment pressure has been taken but in very few cases has the data been complete enough to fit the results to a scientific model. On the other hand analytical models approximating vapor transfer loss during transit from the terminal and from the service station have been developed. It is the purpose of this program to take sufficient data that the mathematical models can be tested.

These tests were designed to obtain data on trucks bottom loaded from a typical pipeline terminal. A truck and trailer ~~was~~ each vacuum tested after carrying a load of diesel. The two largest compartments of the truck and trailer were instrumented for taking continuous pressure measurements. A smaller compartment of the truck and the trailer was used for taking vapor space measurements by opening the dome cover a small amount and inserting a thermometer.

Chevron Supreme was loaded in the truck and Regular was loaded in the trailer. Compartment pressures were monitored during refueling. The truck and trailer compartment pressures were measured versus time during the trip to the station.

The products were dropped at the station. One pressure instrumented compartment of each the truck and trailer was dropped without vapor balancing. A second pressure instrumented compartment of each the truck and trailer was dropped with vapor balancing. Service station tank and truck compartment pressure versus drop time data were taken and the station vent was bagged to measure expelled vapor during the vapor return tests.

Truck and trailer tank pressures were monitored during the trip back to the terminal.

At the terminal the truck and trailer were once again refueled with Supreme in the truck and Regular in the trailer. Compartment pressures were monitored during refueling.

Finally, truck compartment pressures were monitored on the trip to the next truck drop.

Temperature measurements in the third compartment vapor spaces were taken at the service station and terminal.

Initial calculations indicated that tank truck compartment leakage tests from 18 or 22 inches of water for 5 or 10 minutes might not establish correct compartment leakage at lower pressures. There was also some question on whether there would be appreciable vaporization in a totally sealed compartment returning from a service station. For these reasons several additional tests were conducted: First, pressure and vacuum compartment leakage tests were conducted over a wider pressure range for extended periods of time; and, secondly compartment over the road pressure vent was removed and a pipe plug inserted. Transit pressures in the compartment following a fuel delivery with vapor recovery were monitored.

2.0 RESULTS AND CONCLUSIONS

Tests show that our previous analytical calculations considerably overestimate leakage occurring during truck transit and during refueling at the terminal. Leakage is shown to be nearly non-existant during Chevron transit and terminal refueling tests and to be negligible analytically in all but the transit mode following a fuel delivery. Maximum analytical loss in transit following fuel delivery is shown to be between 0.083 and 0.17 gm/gal with an approach time indicating this to be improbable. Stage I fuel delivery vapor loss at a service station is shown to be underestimated but still within the prescribed 90% efficiency. Two factors leading to this were our not accounting for air injestion at transfer fittings and evaporation effects during defueling which may lead to a net vapor growth.

Section 5.1 shows that tank truck pressure and vacuum leakage becomes less as compartment pressure approaches ambient. The CARB test procedure is incapable of determining leakage rates except at the pressure level being measured. More complete pressure leakage tests showed that two out of three compartments tested were leak tight before the 6.0 inch of water pressure level was reached. The remaining compartment showed only 3.6% the equivalent flow area of the compartment leakage from 18-14.5 inches of water. Three out of four vacuum compartments tested were leak tight before the 3.0 inches of water vacuum was reached. The remaining compartment at 3.0 inches of water had 44% of the equivalent leakage area found at 6-4.5 inches of water.

Section 5.2 verifies the truck loss analytical calculation method. Our previous calculations, however, overestimated the loss by at least 20 times since our tests show the equivalent leakage at loading pressures is more than that much smaller than the area used.

Section 5.3 shows that high pressures following refueling in tank truck compartments were shown only on the refueling of initially air filled tanks or on refueling tanks with large vapor spaces following fuel deliveries at a service station without vapor transfer. Even in these cases the loss is minor since air absorption and partially opening tank valves will reduce leakage. With vapor balancing during fuel delivery at the service station, only small pressure rises occur(probably less than 6 inches of water) which will be trapped by the pressure vacuum valve (remember leakage at 6.0 inches of water is at least 20 times less than previously thought) and in all probability retained by fuel air absorption. Our analytical models did not take into account: 1) The rich vapor layer at the fuel surface remaining in the tank following refueling. 2) The fact that compartment vent valves do not fully open at DOT crack pressures; or 3) The effect of air absorption which during most of transit will create vacuums in the truck vent spaces.

Section 5.4 shows that measured truck unloading loss although well within the 90% efficiency required by air pollution agencies is higher than that predicted by our analytical model. Two possible reasons are examined for the difference. Vapor leakage at the transfer hose fittings primarily at the truck and evaporation during refueling. Air injestion at the fuel hose fitting connection to the truck has been known to occur and steps are being taken to improve this connection. Evaporation loss using a diffusion model could be as high as 1.6%. More data will be needed however to determine these factors.

Section 5.5 analyzes the data taken and finds little residual fuel evaporation during transit following a fuel delivery returning to the terminal. On reanalyzing the analytical assumption which showed considerable loss could occur, we forgot to subtract from measured returning vapor concentrations the vapor concentration caused by dilution of the saturated vapor space in the tanker prior to fuel delivery or the percentage saturation due to fuel vaporization during defueling. Taking into account differences between European metered and partial compartment delivery, and normal full compartment delivery without metering, we believe a better maximum loss to be between one-half to one-fourth our analytical calculation. These maximum losses correspond to tank pressure levels of between 8 to 16 inches of water. Since leakage rates decrease rapidly at tank pressures below these levels, in all probability a sizeable portion of any evaporation occurring will remain as a residual tank pressure following transit.

3.0 TEST PROCEDURE

1. Deliver a load of diesel to purge the truck of gasoline vapor.
2. Run a pressure/vacuum test on each compartment at 22" H_2O pressure and 6" H_2O vacuum. Allow adequate time for a pressure drop approximately 4 inches of H_2O but run the test for 10 minutes maximum. (Do this test on only the four largest compartments).
3. Load unit with one product in the truck, another in the trailer. Record the pressure in each compartment as it is being loaded. Obtain a sample of each product. Record the temperature of the product and vapor space.
4. Drive the unit to the service station, monitoring and recording the pressure in the four largest compartments. (Driving time should be one hour).
5. Record the temperature of the vapor space in the two smallest compartments.
6. Deliver the middle sized truck compartment without connecting vapor recovery; Record:
   a) cargo tank vacuum versus time
   b) underground tank pressure versus time
   c) depth and volume of liquid in underground tank at start and finish
   d) amount of product delivered
   e) time from start of flow to obvious sudden change in pressure or truck vacuum
   f) vapor escaping at station vent
7. Deliver the largest sized truck compartment <u>with</u> vapor recovery connected. Record 6a thru 6f.
8. Repeat step 6 with the trailer.
9. Repeat step 7 with the trailer.

10. Record the temperature of the vapor space in the two small compartments.
11. Drive to the terminal; record the pressure in the four largest compartments.
12. Record the temperature in the two small compartments.
13. Record the ambient temperature.
14. Load the unit with gasoline, the middle sized compartments first. Record the loading pressure in the four largest compartments.
15. Record the temperature of the liquid and vapor in the two smallest compartments.
16. Drive to any station (approximately one hour driving time as before) Record the pressure in the four largest compartments during transit.
17. Record the temperature of the vapor space in the two smallest compartments.

4.0 TEST RESULTS

Test Results are shown on Data Sheets 1 thru 13. Specific data sheet titles are listed below:

Title	Data Sheet No.
Compartment No. 1 Leak Test	1
Compartment No. 2 Leak Test	2
Compartment No. 4 Leak Test	3
Compartment No. 6 Leak Test	4
Truck Loading Data	5
Transport Data from Terminal	6
Compartment 2 Unloading Data	7
Compartment 1 Unloading Data	8
Compartment 4 Unloading Data	9
Compartment 6 Unloading Data	10
Transport Data from the Service Station	11
Truck Loading Data	12
Transport Data from the Terminal	13
Compartment No. 2 and 4 Leak Tests	15
Compartment No. 1 and 6 Leak Tests	16
Product RVP and Distillation Data	14
Vapor Transit following fuel drop-Plugged Pressure Vent	17

5.1 Compartment Leak Rate Analysis

Compartment pressure versus blowdown time is shown for Compartments 1 and 2 in Figure 1 and Compartments 4 and 6 in Figure 2. Compartment vacuum versus leakage time is shown for Compartments 1 and 2 in Figure 3 and Compartments 3 and 4 in Figure 4.

An effort was made to correlate the isothermal turbulent and laminar leakage equations shown below:

Isothermal pressure blow down - turbulent flow

$$\ln\left(\frac{P_G + \sqrt{P_G^2 - P_A^2}}{P_{GI} + \sqrt{P_{GI}^2 - P_A^2}}\right) = -\frac{A}{12}\,\frac{t}{V_G}\sqrt{\frac{32.2\ RT_G}{M}} \qquad (1)$$

Isothermal pressure blowdown - laminar flow

$$\tan^{-1}\left(\frac{P_{GI}}{P_A}\right) - \tan^{-1}\left(\frac{P_G}{P_A}\right) = \frac{D^4\ P_A t}{256\quad L\ V_G} \qquad (2)$$

Isothermal vacuum leakage - turbulent flow

$$\sin^{-1}\left(\frac{P_G}{P_A}\right) - \sin^{-1}\left(\frac{P_{GI}}{P_A}\right) = \frac{At}{12\cdot V_G}\sqrt{\frac{32.2\ R\ T_G}{M}} \qquad (3)$$

Isothermal vacuum leakage - laminar flow

$$\ln\left(\frac{P_A + P_G}{P_A - P_G}\right) - \ln\left(\frac{P_A + P_{GI}}{P_A - P_{GI}}\right) = \frac{D^4\ 2P_A\ t}{256\quad L\ V_G} \qquad (4)$$

Shown in Figures 1 - 4 and Tables 1 and 2 are our end point correlations. Needless to say neither the laminar or turbulent end point correlations fit the data. Further, the laminar and turbulent correlations are quite close together and plot as nearly straight lines. The shape of the actual data points implies that leakage area varies with pressure level and that leakage area decreases with pressure level.

Both small refief valves and dome vent emergency relief valves are pressure loaded against compliant seats. As compartment pressure and vacuum increases this pressure load decreases until the valve opens. At low compartment pressures and vacuums, valve sealing forces are greater and leakage across the compliant seat is lowest.

To test this theory a complete compartment pressure blowdown and vacuum leakage test must be performed. A more complete test was performed on Compartments 2 and 4, May 11, 1977; the data is shown on Data Sheets 15 and 16 and on Figure 5 and 6. Figure 5 shows the pressure blowdown curves. Compartment 4 pressure and vacuum tests showed no leakage when the pressure reached 14.5 inches and the vacuum reached 3 inches of water. Compartment 2 pressure and vacuum curves showed continued but decreased leakage as the level decreased. The Compartment 2 pressure test was discontinued at the 6.25 inch of water level because of time limitations. By using the fact that both turbulent and laminar flow curves appear relatively straight on the pressure versus time plot over limited regions, equivalent turbulent leakage orifices were calculated for various portions of the pressure leakage curve. By comparing equivalent leakage orifices we can see that leakage areas vary enormously.

Compartment 2 Pressure Leakage Comparison

time (min.)	0 - 5	20 - 120	120 - 155
pressure level (in. H_2O)	18-14.5	13.5-6.75	6.75-6.25
diameter (inches)	0.075	0.026	0.014
area ratio	100	11.9	3.6

The same procedure was used for the vacuum leakage data and two curves were derived using the turbulent flow correlation. Again, even for the only curve which had leakage, the area ratio over the lower vacuum part of the curve varies considerably from the high vacuum portion.

Compartment 2 Vacuum Leakage Comparison

time (min.)	0 - 5	15 - 55
vacuum level (in. H_2O)	6 - 4.5	3.5-0.5
diameter (inches)	0.066	0.044
area ratio	100	44.3

Our conclusion is that using the CARB pressure leakage criteria of no more than between 1 and 4 inch pressure degradation from 18 inches of water (or even more so their previous 22 inches of water level) means that compartment leakage at a 6 inch pressure level is at most a small fraction of the expected amount and probably more nearly zero. Vacuum leakage seems to be similar in nature but the error in using orifices calculated from CARB leakage tests will probably be smaller.

Since our conclusion is so important to our later findings, we had Chevron repeat their latest blowdown test using Compartments 1 and 6. We asked that compartment blowdown pressure versus time be first run at 18 inches of water start pressure and then reduce the compartment pressure to 7 inches of water and repeat the test. As Data Sheet 16 shows Compartment 1 showed a small leak at the 18 inch level which became a zero leak at 16.25 inches of water. When the compartment pressure was reduced to 7 inches of water the pressure increased during blowdown. The technician then bled the tank down to 7 inches of water and during the next 20 minutes pressure increased. We feel these pressure increases are due to thermal effects.

The vacuum tests on Compartments 1 and 6 again stabilized in pressure showing zero leakage.

5.2 Truck Loading Losses

Compartment loading pressures are shown on Data Sheets 5 and 12. They are much as we predicted in Reference 1 for single hose loading. Two product loading with the Chevron manifold system on the trucks implies one hose loading to the truck and one hose loading to the trailer. Since separate vapor return hoses are connected to the truck and trailer, the pressure increase noted on Data Sheet 5 shows only the increase in back pressure of the underground piping system. As underground piping is sized for simultaneous loadings, the pressure rise is as expected small. High truck pressures are found when several products are loaded into the same truck with only a single common vapor return hose. As the vapor return hose is usually the major pressure restriction, tank pressure increases. Since during these times of increased pressure, loading rate is also increased; % loss of vapor per gallon of fuel loaded remains approximately the same if the leakage orifice is constant.

We would note that loading pressures on Data Sheet 5 are somewhat lower than shown on Data Sheet 12. This is explainable since only air is being expelled by the tanks bottom loaded on Data Sheet 5 whereas saturated or partially saturated vapor is being expelled during data taken on Data Sheet 12. Mathematically

$$Q = C\,A\,\sqrt{\frac{\Delta P}{M}}$$

so ΔP should incrase proportionally as molecular weight (M) increases for the same flow and flow configuration. From RVP and 10% distillation data fuel molecular weights are about 65 and vapor concentrations about 39%. Consequently saturated vapor refuelings should show pressures about 1.48 times as large.

$$P_2 = \frac{43}{29}\ \Delta P_1 = 1.48\,\Delta P_1$$

Loading pressures expelling air of between 2 and 2.5 inches correspond to loading pressures expelling saturated vapor of between 3 and 3.7 inches. These were approximately what was measured. We would note Compartment 2 refueling on Data Sheet 12 has pressure somewhat between the saturated vapor and air refuelings. On checking refueling modes of the other islands, we can surmise that multiple compartment refueling is the cause of the higher than expected pressure in Compartment 4 of Data Sheet 12.

In conclusion, measured refueling pressures were slightly less than anticipated reflecting more than adequate size plumbing. By combining these low pressures with our leakage expectations at these pressure levels versus those measured during the higher pressure CARB tests (Section 5.1), we expect our analytical leakage calculations probably overestimate losses by a factor of 20.

5.3 Truck Transit Losses Following Refueling

Truck over the road compartment pressures following the refueling of air filled compartments are shown on Data Sheet 6. Truck over the road compartment pressures following the refueling of truck compartments, which returned from service station gasoline deliveries with and without vapor transfer, are shown on Data Sheet 13.

All results appear reasonable although the specific results were influenced by several effects not taken into account in our analytical program.

1. Analytical calculations assumed the vapor layer above the fuel surface was at the average concentration of vapor returning from the service station.
2. Analytical calculations assumed the pressure vacuum valves would open fully at 27 inches of water and vent freely.
3. Analytical calculations did not take into account air absorption which may occur.

In the following discussion, we hope to at least quantitatively show how analytical losses overestimate actual loss by not accounting for the above.

Logic as well as analytical calculations (Chapter 2, Reference 2) indicate that the vapor space at the fuel surface will be saturated with vapor concentrations decreasing to the initially present vapor concentration as we move farther from the fuel surface. The amount of evaporation during refueling varies with the turbulence and type of refueling (Reference 2, Chapter 3). With bottom loading evaporation is minimized because agitation and fuel surface area is minimized, nevertheless, a rich vapor layer exists above the fuel surface. Since tanks have some vapor space remaining following refueling, this rich layer tends to reduce the amount of unsaturated vapor; consequently, a smaller amount of fuel will be vaporized by fuel sloshing during transit. As might be expected the refueling evaporative effect is larger with smaller vapor spaces.

This effect is shown in Data Sheet 6 for transport following refueling of air filled tanks and in Data Sheet 13 for transport following refueling of tanks with mixed vapor. A summary is shown below.

Maximum Tank Pressure Vs Refueling Conditions

Compartment No.	1	2	4	6
% Vapor Space above fuel	18.4	4.9	17.0	15.0
		Data Sheet 6		
Initial Vapor Space Condition	Air	Air	Air	Air
Max Truck Transit Pres(In. H_2O)	50+	24.	43	44
Average % Vapor Saturation	71	86	75	75
		Data Sheet 13		
Initial Vapor Space Condition	VR	No VR	No VR	VR
Max Truck Transit Pres(In. H_2O)	3	7	35	0
Average % Vapor Saturation	98	96	80	100

Note:

Average % vapor saturation is calculated assuming vapor losses are small in the time period that these maximum pressures are generated so that maximum pressure is related to saturated pressure of a closed initally partially saturated tank. Tank initial pressure (P) is

$$P = P_A + S_1 P_H^\circ$$

where S_1 is initial saturation; P_H° is fuel vapor pressure; and, P_A is the air partial pressure. By assuming little air absorption during saturation, the final tank pressure (P_F) can be expressed as

$$P_F = P_A + P_H^\circ$$

Eliminating P_A between equations and solving for S_1 we have

$$S_1 = 1 - \left(\frac{P_T - P}{P_H^\circ} \right)$$

The assumption that leakage and air absorption are negligible during the time saturation takes place is justified by noting maximum pressure is achieved in 30 seconds whereas leakage + air absorption causes pressure drops of less than 7 inches in this time. In addition our calculations are conservative since leakage increases average % saturation.

The table shows high vapor percentage saturation in vent spaces after refueling of even initially air filled tanks; and, that the concentration is significantly higher for smaller vapor space percentages. With vapor return from the service station,the tank vapor space after refueling is virtually saturated. Any vapor growth occurring will be initially contained by the pressure/vacuum valves and in most cases saved because of air absorption taking place at the fuel surface.

Factors 2 and 3, that is the fact that the truck valves do not fully open at 27 inches of water and the fact that significant air absorption takes place, further reduces possible truck transit losses following refueling.

Air absorption takes place because fuel is refined in the absence of air. If the fuel is stored and blended over a short period of time in floating roof tanks and shipped via pipeline, the fuel does not come into equilibrium with air. Since fuel in equilibrium with air can hold about 20% by volume air,considerable air can be and at times is absorbed.

However air absorption is slow compared to evaporation of fuel components. This is the reason that evaporation dominates on leaving the terminal until equilibrium is attained. The slower air absorption process however continues and is the eventual cause of the vacuum experienced in the tank trucks (see Data Sheets 6 and 13).

Note:

The reason air absorption takes place slower than fuel absorption is there is less air in the fuel than the various fuel components so air is governed by liquid diffusion and fuel mixing. Evaporation or fuel vapor equilibrium is usually governed by vapor diffusion, nearly a 100 times faster than liquid diffusion. The main difference is, the number of fuel molecules evaporating is small compared to the number present.

The amount of a particular fuel component available for evaporation is given by the fuel mole fraction. This is related to the partial pressure of that component in the vapor space by Raoults Law

$$P_{Hi} = P^{\circ}_{Hi} \, X_{Hi} \qquad (i = 1, 2, 3 \ldots n) \qquad (5)$$

The amount of air disolved per volume fuel is given by the Ostwald Coef. $\beta = V_{AF}/V_F$. Putting this in the form of Raolts Law we have

$$(P - P^{\circ}_H) = P^{\circ}_A \, X_A \qquad (6)$$

where X_A is the moles of air per mole of fuel

$$X_A = \frac{\dfrac{V_F \, (P - P^{\circ}_H)}{R \, T}}{(V_F \, \rho_F / M_F)} \qquad (7)$$

Substituting this expression for X_A into Equation 6 and solving for P°_A we have the pseudo vapor pressure of air in fuel as

$$P^{\circ}_A = \frac{\rho_F R \, T}{\beta \, M_F} \qquad (8)$$

Using typical values P°_H = 5.865 psia, ρ_F = 47 lbm/ft^3, T = 520°R, β = 0.2, M_F = 95 lbm/lbmol Liq.

$$P^\circ_A = \frac{47(10.7315)(520)}{0.2(95.0)} = 13,800 \text{ psi}$$

$$X_A = \frac{(14.7 - 5.865)}{13,800} = 6.4 \times 10^{-4}$$

In contrast mole fractions of fuel components are several percent. For example normal butane may represent 40% of the fuel vapor vapor pressure. At 60°, normal butane has a vapor pressure of about 25.4 psia, so its mole fraction in the fuel is

$$\frac{.4(5.865)}{25.4} = X_{nC_4} = .092$$

~~Another~~ In other words $_nC_4$ fuel concentration is about 144 times that of air.

In conclusion, with vapor return from the service station and bottom loading, very little vapor growth will occur due to fuel saturation on leaving the terminal. Any small pressure increase will be trapped at least temporarily by the pressure vacuum valve and in all probability saved by the fuel air absorption effect which will cause a vacuum to be drawn on the vapor space. The small amount of vapor lost by leakage in the interim is nearly negligible.

5.4 Truck Unloading Losses

Truck unloading losses were not considered as part of the transit losses by CARB however our analytical work indicated that truck leakage versus vapor return path pressure drop is the major determinate of transfer leakage. For this reason we have included calculations in this area in our previous discussions.

Truck vacuum leakage diameters were found to be quite small. (see Table 2). Correspondingly our calculations in Section 2 and correlation Section 2 Figure 1 indicate vapor loss should be 0.2% (Compartment 1) and 0.4% (Compartment 6). Actual volumes accumulated in 42 inch circumference bags were 74.7 gal. in Compartment 1 and 153.1 gal. in Compartment 6. Dividing by the amount of liquid dropped we find 74.7/2075 = 3.6% loss for Compartment 1 and 153.1/2050 = 7.5% loss for Compartment 6.

According to the above either leakage is occuring at other than the truck or the analytical correlation does not account for all terms contributing to leakage. We suspect that some leakage may be occuring near the truck liquid connection however this leakage should be noted on truck test since the hoses are similarly connected. We are also planning on investigating the second possibility although as shown in Appendix A our truck loss approximate and computer solution seems to correspond quite closely. Enough data was derived to make the correlation.

One factor which is not taken into account in our analytical model is evaporation from the fuel surface during defueling. As is shown in the next section using a diffusion model, between 0 and 1.6% vapor growth could occur for this reason. If tank turbulence is sufficient even this amount may be low. 1.6 + .2 = 1.8% which is fairly close to the Compartment 1 measured value of 3.6%. However a major portion of the 7.5% loss on Compartment 6 still appears to be caused by air injestion at the truck transfer fitting. Air injestion has been known to occur at this fitting and steps are being taken to solve the problem.

5.5 Transit Vapor Loss Following Fuel Drop

Truck compartment pressures during transit after a fuel delivery are shown on Data Sheet 11. Tests were run on compartments following fuel drops with and without vapor transfer.

Data taken seems to indicate that pressures were at their highest or nearly so on leaving the service station and that there was little pressure change during transit.

Truck leakage data indicates, that at the truck compartment pressures measured (less than 6 inches of water), leakage will be a maximum of 5% of the leakage measured at the CARB leak test level (18 or 22 inches of water). Most truck compartment pressures measured showed zero leakage at the 6 inch of water pressure level although they showed 1 to 4 inches of water pressure drop in 5 minutes at a 22 inch starting pressure level.

Since absolute temperature is about 540°R and ambient pressure about 407 inches of water and since the ideal gas laws shown absolute pressure varies inversely with absolute temperature for the same mass and volume of gas, we can deduce that a 1.3°F temperature change will cause a 1 inch of water pressure change. Temperature changes of 5 or even 10 degrees can and do occur during our tests and could easily cause the pressure changes noted.

In an effort to determine whether appreciable transit leakage is occurring the 1 inch pressure vent of Compartment 1 was removed and a pipe cap inserted. Vacuum tests on the compartment (Data Sheet 16) indicate 0 vacuum leakage at the 4.5 inch pressure level and we can surmize at below this vacuum level. Pressure measurements on the return trip are shown on Data Sheet 17. We might conclude pressure leakage except for the fact that the pressure went to vacuum. We are led to the unmistakeable conclusion that temperature effects cause most of the pressure phenomena seen and that leakage is near zero.

It follows that evaporation due to fuel remaining within the compartment is near zero which is quite different from the assumption made in our analytical calculation. On reviewing the data we find that our analytical assumption is incorrect. It is true that vapor space saturation on return to terminal following loads dropped at a single station gives vapor space saturation of about 20%. However, since tank vapor spaces for these loads averaged between 5 and 10% and since in travelling over the road these spaces become saturated, this vapor will be present in the tank on defueling and must be subtracted from the 20% initial saturation. One more effect must be taken into account. As the fuel drop occurs air is sucked into the truck tank and evaporation occurs from the receding fuel surface. Since this evaporation occurs during defueling and not from evaporation of residual fuel during transit this fractional saturation must also be subtracted from the 20% initial saturation. This implies the % saturation due to evaporation is probably 10% or less.

To refine this further a group of British Petroleum refuelings in Germany (Reference 3) having low initial fractional saturations and believed to be compartments unloaded at a single location are analyzed.

Test No.	S_1(%)	%Ullage	$S_E + S_D$(%)
20	12.0	1.0	11.0
45	14.0	3.3	10.7
51	12.0	8.6	3.4
54	22.0	19.0	3.0
69	25.0	15.0	10.0
73	15.0	4.3	10.7
74	14.0	0.0	14.0
77	21.0	17.4	3.6
78	14.0	9.1	4.9

95	16.0	9.6	6.4
100	17.0	17.2	-0.2
101	18.0	13.3	4.7
106	17.0	7.9	9.1
108	15.0	3.5	11.5
110	12.0	14.0	-2.0
111	17.0	8.3	8.7
113	11.0	4.2	6.8
114	16.0	5.3	10.7
115	17.0	9.3	7.7
Number	19	19	19
Ave	16.05	8.96	7.09
Std. Dev.	3.63	5.71	4.26
Std. Er.	0.83	1.31	0.98

S_V is the % saturation from the initially present vapor space; and, $S_E + S_D$ is used to denote the residual fuel and defueling evaporative saturation contributions.

Work done by Nichols (Reference 2) allows us to approximate the evaporative emission during defueling assuming that diffusion controls. Nichols shows that the number of moles evaporating is given by

$$W_V = 2 \frac{PS}{RT} \varphi \sqrt{D_{HA} t} \quad (9)$$

where W_V is in lbmoles; P is the pressure in psi; S is the evaporation surface area in ft^2; R is the universal gas constant 10.7315 (psi X cf)/(lbmol X °R); T is the temperature in °R; D_{HA} is the diffusion coefficient for hydrocarbon in air (88.26×10^{-6} ft^2/sec); and, t is the time in seconds.

$$\varphi = f\left(\frac{Y_{HO} - Y_{HI}}{1 - Y_{HO}}\right) \tag{10}$$

where $Y_{HO} = P_H^\circ/P$ and $Y_{HI} = P_{HI}/P$. Here, P_H° is the fuel vapor pressure in psi; P is the ambient pressure in psia; and, P_{HI} is the initial partial pressure of the vapor at the fuel interface. The functional relationship of Equation 10 is given in graphical form in Figure 7.

For an example we will choose a tank and calculate the volume of gas evaporated per gallon of tank capacity.

tank 6' x 10' x 5' high = 2244 gal.

P = 14.7psi

T = 80°F = 540°R

t = 5 min = 300 sec

$$\frac{V_E}{V_T} = \frac{W_V RT}{P} \frac{7.48}{2244} = \frac{2 \times 7.48}{2244} S\varphi\sqrt{D_{HA}t} \tag{11}$$

$$\frac{V_E}{V_T} = 6.509 \times 10^{-2}\,\varphi \tag{12}$$

where V_E/V_T is the gallons of fuel vapor evaporated per gallon of tank volume.

Three assumptions are possible for $P_{HI} = S_I P_H^\circ$.

1. Since the vapor space of the fuel compartment is saturated prior to fuel removal, and since the fuel vapors are heavier than air, we can assume the vapors remain saturated at the fuel surface. In this case $P_{HI} = P_H^\circ$; $Y_{HO} - Y_{HI} = 0$; $\varphi = 0$ from Figure 7, and, the volume of evaporated vapor is zero (i.e. $V_E/V_T = 0$).

2. The other extreme is to assume the concentration at the fuel surface is equal to the final equilibrium concentration if there was no evaporation. This would assume considerable mixing of fuel surface and the entering vapor air mixture ($P_{HI} = 0.1\ P^{\circ}_{H}$). This implies $(Y_{HO} - Y_{HI})/(1 - Y_{HO}) = 0.6$. Figure 7 is used to approximate φ ($\varphi = 0.248$). In this case $V_E/V_T = 0.01614$.

3. The alternate is to assume some average value, for example $P_{HI} = 0.55\ P^{\circ}_{H}$. $(Y_{HO} - Y_{HI})/(1 - Y_{HO}) = 0.367$. From Figure 7 $\varphi = 0.167$ and $V_E/V_T = 0.01087$.

Since by the ideal gas law PV = const at constant mass and temperature we can write

$$S_D P^{\circ}_H (V_T + V_E) = PV_E$$

$$S_D = V_E/V_T/(P^{\circ}_H/P(1 + V_E/V_T))$$

For an assumed initial interface condition $P_{HI} = S_V P^{\circ}_H$, we have

S_I	0.1	0.55	1.0
V_E/V_T	0.01614	0.01087	0.0
S_D	0.03971	0.02688	0.0
$S_D + S_V$	0.13971	0.12688	0.1
S_E	0.06029	0.07312	0.1

where S_I is the assumed initial interface concentration; S_V is the vapor space fraction; S_D is the defueling vapor fraction saturated on defueling; and, S_E is the fractional saturation assumed on the return trip.

The amount of gasoline which must be evaporated to increase the vapor space saturation by a given fraction S_E is

$$V_E = S_E \frac{P^{\circ}_H\ M_H\ V_T}{RT\ \ D\ \ 7.48} \tag{13}$$

where, P_H° is the vapor pressure in psia, M_H is the vapor molecular weight; V_T is the compartment volume; R is the universal gas constant (10.7315); T is the temperature in °R; and, D is the condensed vapor density in lbm/gal

$$D = 6.95 - \frac{120}{M_H} \tag{14}$$

By assuming

$P_H^\circ = 0.4(14.7) = 5.88$ psi

$M_H = 75$

$V_T = 2244$ gal

$D = 5.35$ lbm/gal (Eqn. 14)

Equation 13 becomes

$$V_E = S_E \frac{5.88(75)2244}{10.7315(540)(5.35)7.48} = 4.267\ S_E$$

S_E	0.0	0.025	0.050	0.075	0.100	0.150
V_E	0.0	0.107	0.213	0.320	0.427	0.640

Calculations assume about 50% of the gasoline vaporizes. M. H. Holmes (Reference 3) assumes compartments are empty if they contain less than 2 liters of fuel. Since this corresponds to approximately 10% saturation, this value seems a probable average saturation. $S_E P_H^\circ$ would then be the approximate compartment pressure rise (P_V) which would take place.

$$P_V = 27.7\ P_H^\circ\ S_E = 162.9\ S_E$$

This would say a 10% vapor saturation would lead to a 16.3 inch pressure rise; and, 5% saturation would lead to an 8.2 inch pressure rise.

Chevron data seems to indicate pressure rises of 8 inches of water or less indicating less liquid is trapped than the B.P. data. This is quite possible since the German truck delivery data indicated a high percentage of split compartment drops (i.e. the fuel in one compartment is dropped at more than one location). Since such compartments have higher vapor saturations, if there is an accounting mistake the drop load average becomes considerably higher. Since most trucks in Reference 3 had split loads and some split loads had lower vapor concentrations, we assume some mistakes occurred.

Two other factors might cause Chevron trucks to have smaller evaporative emissions on the return trip than the German trucks:

1. The B.P. trucks in Germany probably meter off their load. Under such conditions fuel retains are more likely to occur since the customer may not want the full amount of fuel in the truck.

2. Vapor return in this country leads to higher initial vapor space saturations and less driving force for evaporation to occur.

Finally we would like to quote M. H. Holmes (Reference 3) observations: "The vapour phase component analysis show that the loading and preloading vapours are similar this suggests that most of the vapour is evolved from the liquid surface of the bulk gasoline during unloading rather than from the drainings or by drying of the wetted tank walls. Therefore, the true vapour pressure should have a direct effect on the vapour content. The presence of more heavy components would have indicated evaporation of a substantial portion of the liquid, in which case true vapour pressure would not be such a good parameter."

Our conclusion is that little vaporization occurs during transit following a fuel drop. The amount occurring will be at a maximum 25 to 50% of the amount assumed in our original calculations. This smaller amount will be trapped by a P/V valve at from 8 to 16 inches of pressure. Leakage of any volume of vapor so formed will be considerably less than that indicated by an orifice calculated from a CARB leakage test.

5.6 Test Temperature Observations

Below are summarized 2/15/77 Test Temperature Data

	Loading Temp	Vapor Space Arrival S.S.	Vapor Space Start SS	Vapor Space Arrival Term
Truck	T_{LS} = 61.5			
Trailer	T_{LR} = 58.5	T_{VS} = 78°F	T_{VS} = 85°	T_{VS} = 75°
	Data Sheet 5	T_{VR} = 77°F	T_{VR} = 78°	T_{VR} = 76°
		T_A = 75°F	T_A = 76°F	
		Data Sheet 6	Data Sheet 11	

	Loading Temp	Vapor Space Lv Terminal	Vapor Space Arrival St.
Truck	T_{LS} = 62.5°F	T_{VS} = 72°F	T_{VS} = 62°F
Trailer	T_{LR} = 59°F	T_{VR} = 71°F	T_{VR} = 65.5°F
	Data Sheet 12	T_A = 76°F	T_A = 64°F
		Data Sheet 13	Data Sheet 13

These observations seem to indicate that vapor space temperatures during transit lie close to ambient. This may be explained by the fact that air movement over the truck (convection heat transfer) dominates either radiant heat transfer or cooling from bulk liquid temperature. This latter observation may be justified by the warm fuel layer effect seen in storage tanks. Here the surface fuel is warmed and remains at the surface due to its lighter specific gravity.

It should be observed that tank truck vapor space temperatures can vary appreciably from ambient in non-moving tankage. Under these circumstances the radiant heating effect of the sun can be appreciable.

6.0 REFERENCES

1. Nichols, R. A. Comments On Proposed CARB Tank Truck Leakage Criteria. R. A. Nichols Engineering, 519 Iris Avenue, Corona del Mar, CA. Jan 18, 1977.

2. Nichols, R. A. Draft Report of A Survey of Emissions From Gasoline Distribution Systems, Chapter 2. EPA Contract No. 68-02-001. Parker Hannifin Corporation, Irvine, CA. 92664 (1975)

3. Holmes, M. J. Emission of Gasoline Vapour when Loading Transport Media in Germany. Part 2. Operations Service Branch. B. P. Trading Ltd., London, England. August 1973.

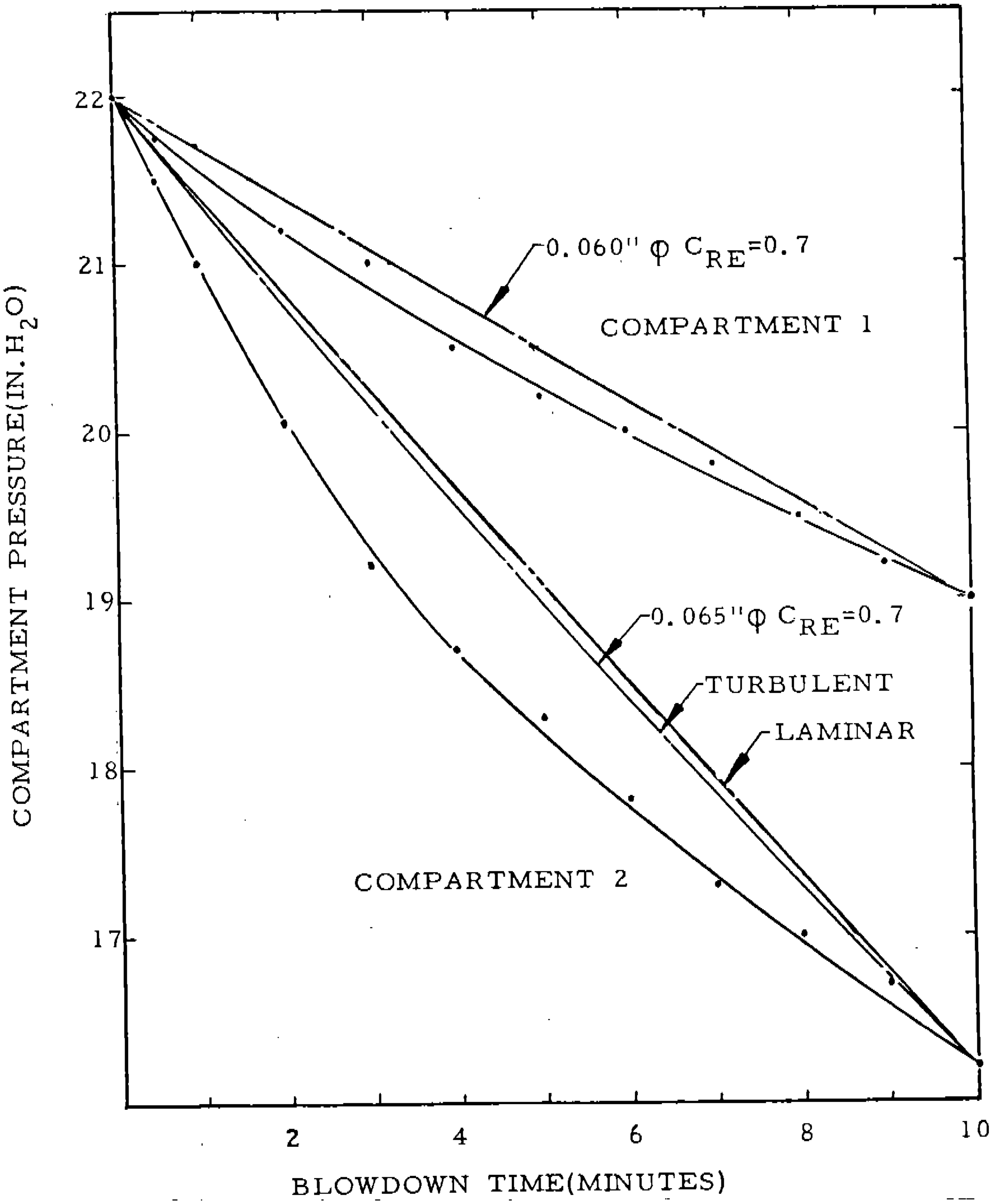

22
21
20
19
18
17
COMPARTMENT PRESSURE(IN. H_2O)
0.060" φ C_{RE}=0.7
COMPARTMENT 1
0.065" φ C_{RE}=0.7
TURBULENT
LAMINAR
COMPARTMENT 2
2
4
6
8
10
BLOWDOWN TIME(MINUTES)

Figure 1

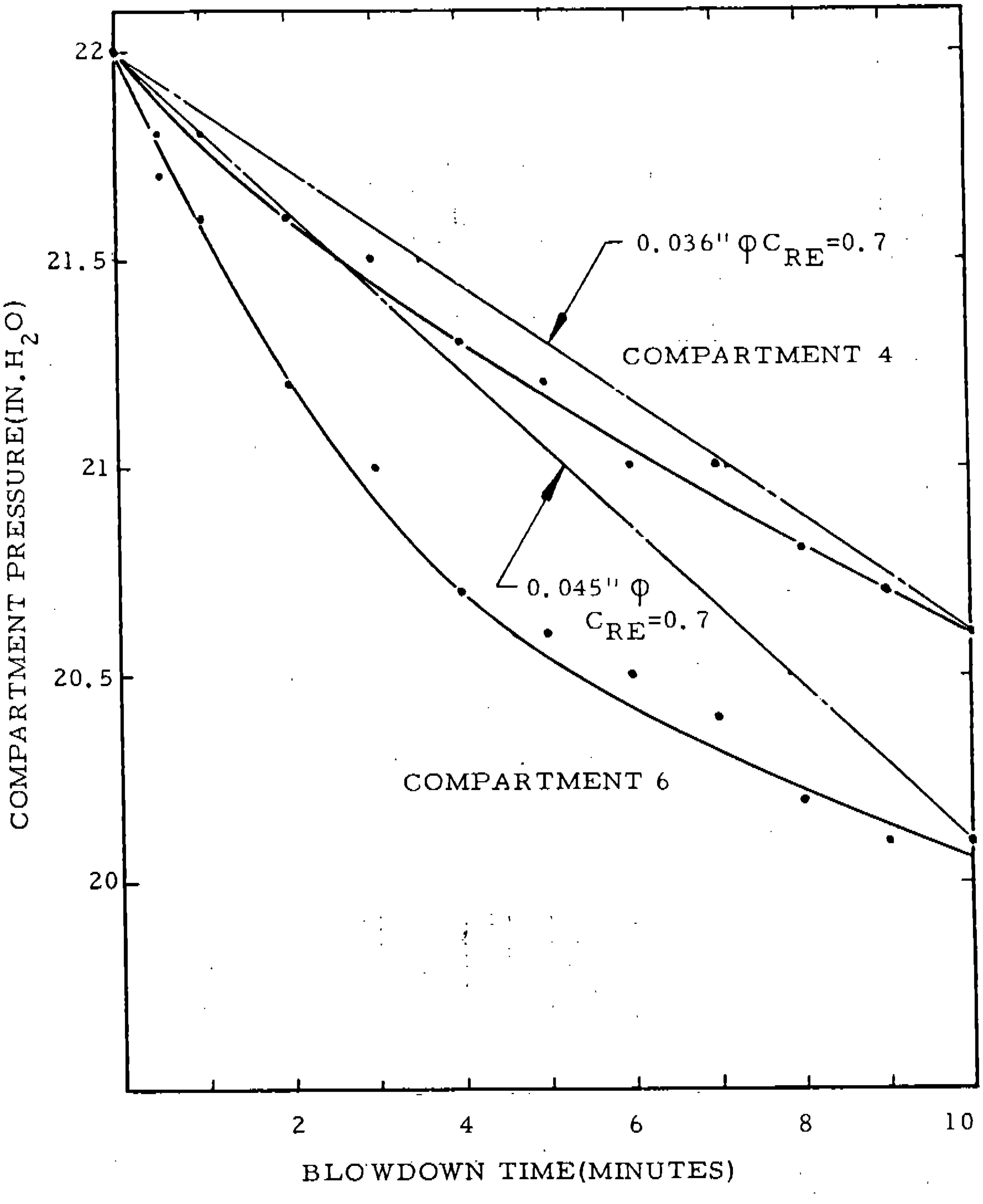

22
21.5
21
20.5
20
COMPARTMENT PRESSURE(IN. H_2O)
0.036" φ C_{RE}=0.7
COMPARTMENT 4
0.045" φ
C_{RE}=0.7
COMPARTMENT 6
2
4
6
8
10
BLOWDOWN TIME(MINUTES)

Figure 2

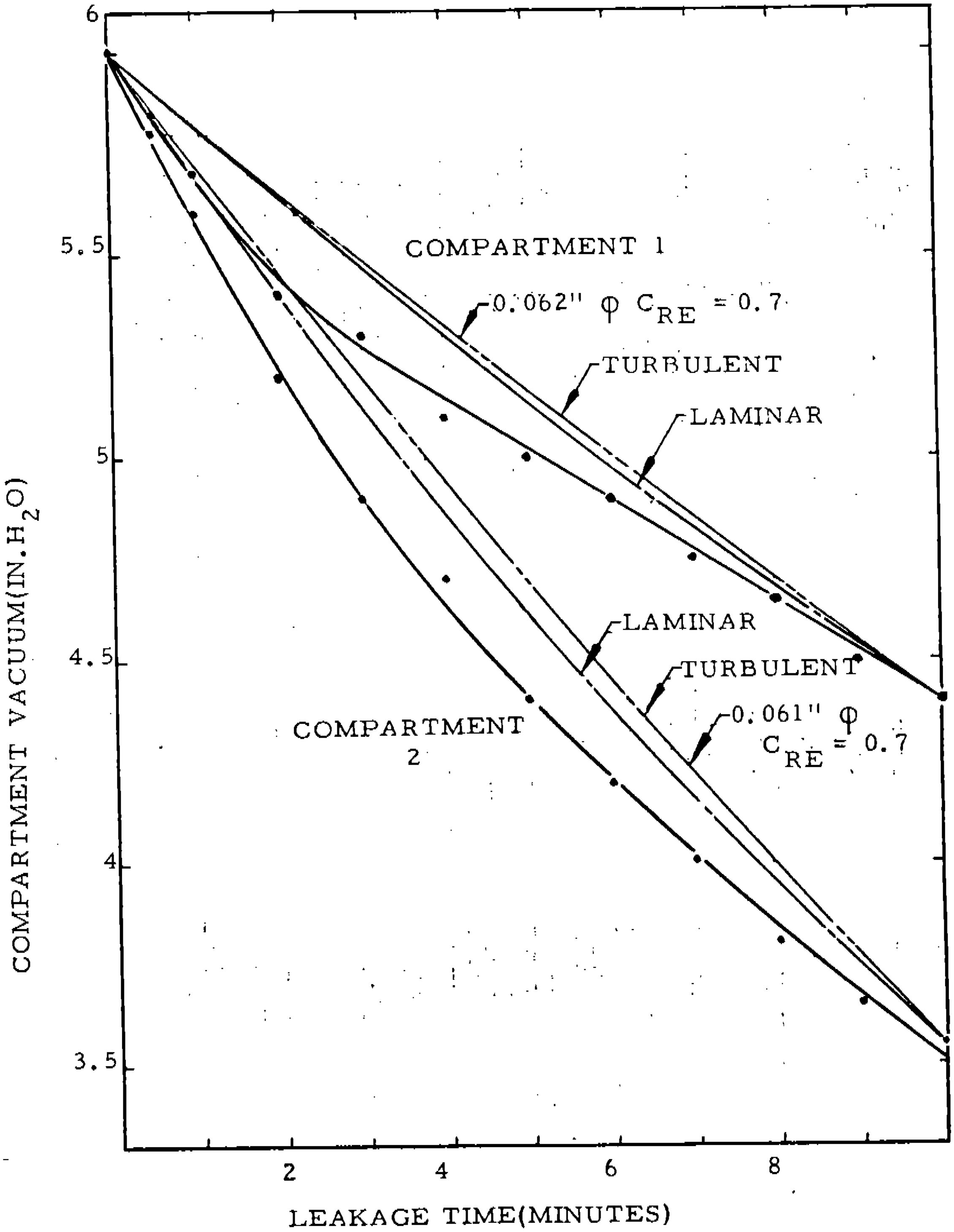

6
5.5
5
4.5
4
3.5
COMPARTMENT VACUUM(IN.H_2O)
2
4
6
8
LEAKAGE TIME(MINUTES)
COMPARTMENT 1
0.062" φ C_{RE} = 0.7
TURBULENT
LAMINAR
LAMINAR
TURBULENT
0.061" φ
C_{RE} = 0.7
COMPARTMENT
2

Figure 3

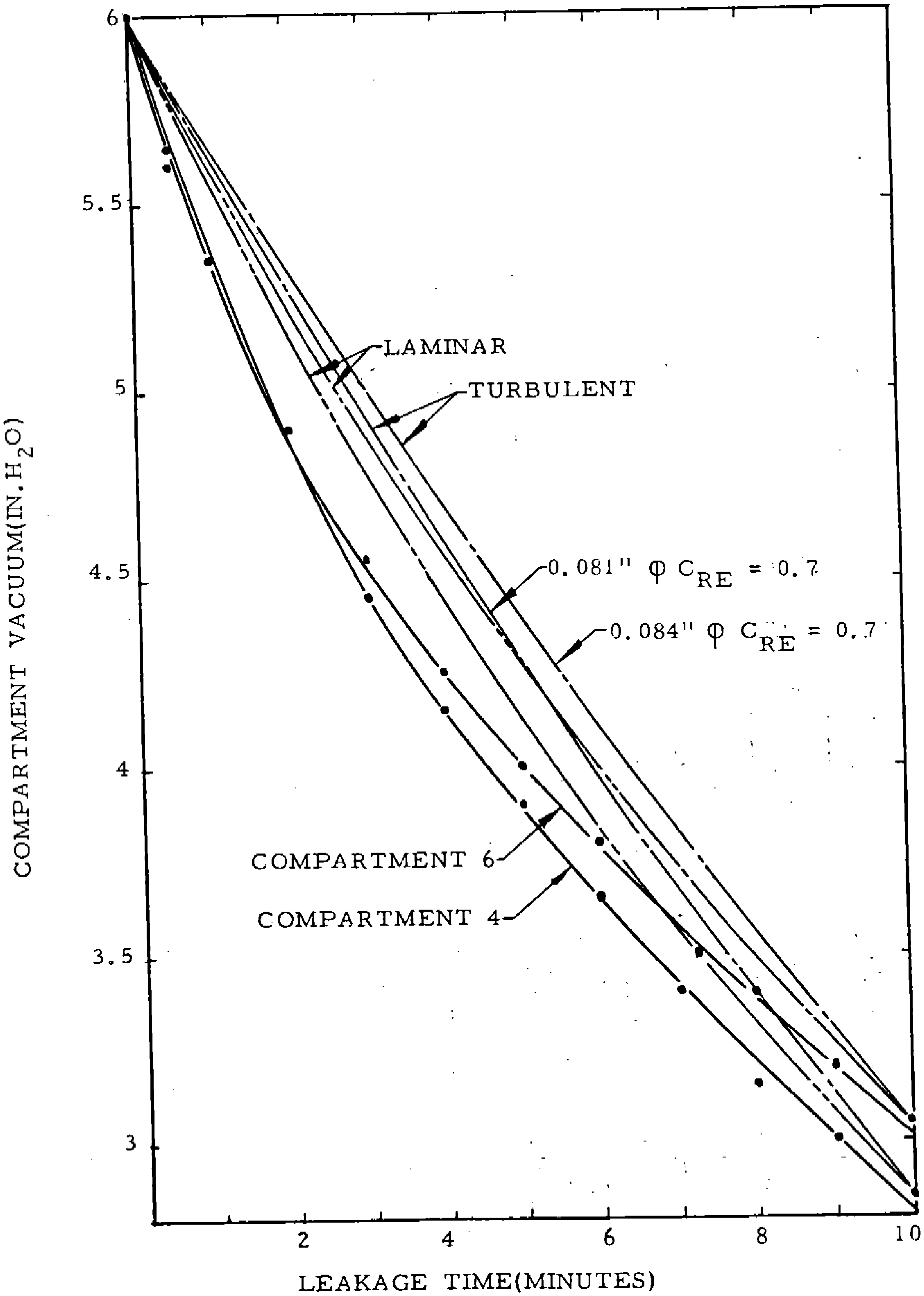

6
5.5
5
4.5
4
3.5
3
2
4
6
8
10
COMPARTMENT VACUUM(IN. H_2O)
LEAKAGE TIME(MINUTES)
LAMINAR
TURBULENT
0.081" φ C_{RE} = 0.7
0.084" φ C_{RE} = 0.7
COMPARTMENT 6
COMPARTMENT 4

Figure 4

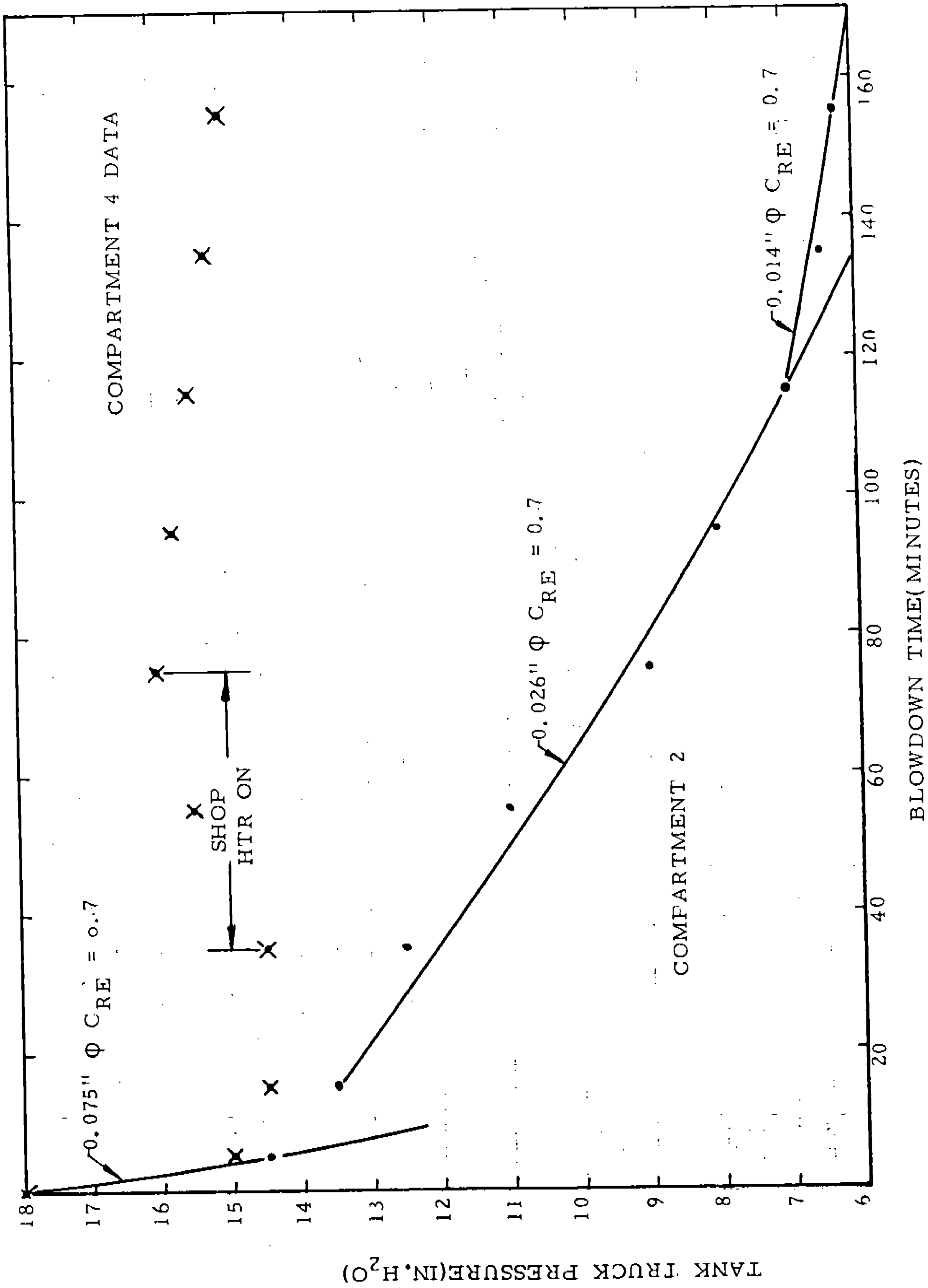

COMPARTMENT 4 DATA
COMPARTMENT 2
SHOP HTR ON
0.075" Φ C_RE = o.7
0.026" Φ C_RE = 0.7
0.014" Φ C_RE = 0.7
BLOWDOWN TIME(MINUTES)
TANK TRUCK PRESSURE(IN. H2O)
20
40
60
80
100
120
140
160
18
17
16
15
14
13
12
11
10
9
8
7
6

Figure 5

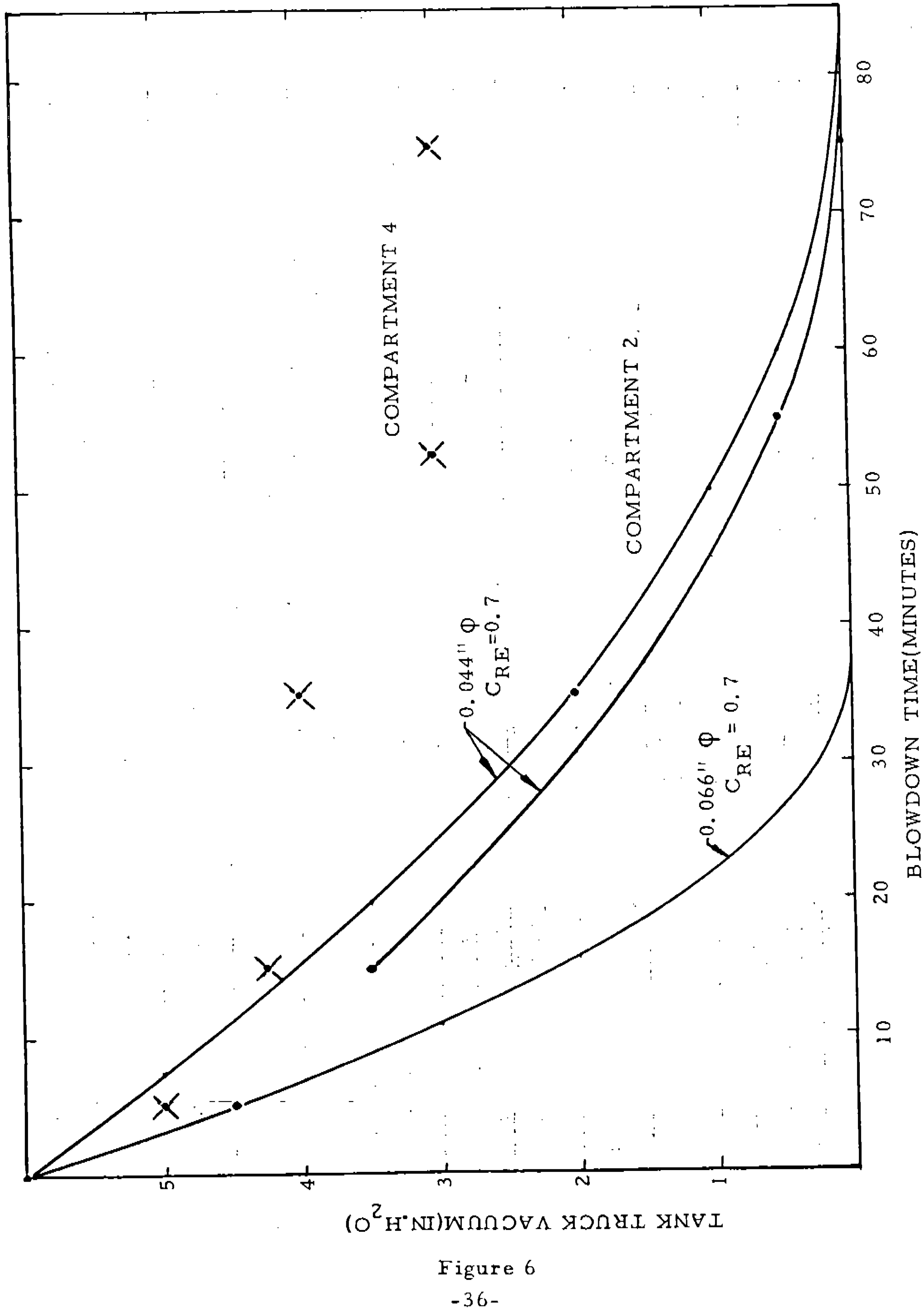

COMPARTMENT 4
COMPARTMENT 2
0.044" Φ
C_{RE}=0.7
0.066" Φ
C_{RE} = 0.7
BLOWDOWN TIME(MINUTES)
10
20
30
40
50
60
70
80
TANK TRUCK VACUUM(IN.H_2O)
1
2
3
4
5

Figure 6

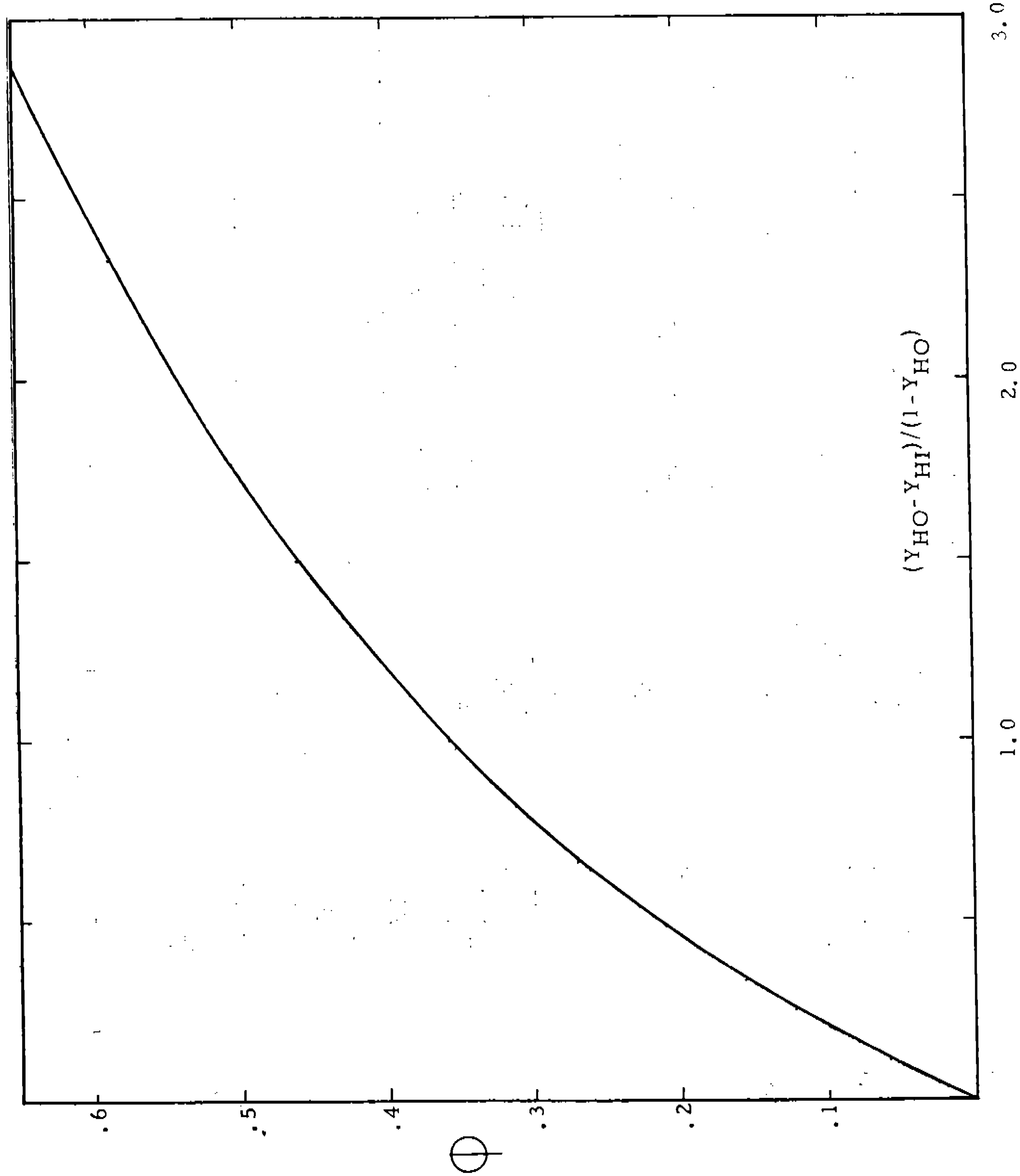


Figure 7

TABLE 1

PRESSURE LEAKAGE END POINT CORRELATION

Comp. No.	Tank Volume Gal.	End Point Pressure In. H_2O	Leakage Dia. (In.) Turbulent C_{RE}=0.7	Leakage Dia. (In.) Laminar .5 InPath
1	2543	19.0	0.060	0.035
2	1525	16.2	0.065	0.036
4	2017	20.6	0.036	0.027
6	2329	20.1	0.045	0.030

Initial Pressure 22.0" H_2O

Blowdown time 10 minutes

TABLE 2

VACUUM LEAKAGE END POINT CORRELATIONS

Comp No.	Tank Volume Gal.	End Point Vacuum In. H_2O	Leakage Dia. (In.) Turbulent C_{RE} =0.7	Laminar .5 InPath
1	2543	4.4	0.062	0.033
2	1525	3.55	0.061	0.033
4	2017	2.85	0.081	0.038
6	2329	3.05	0.084	0.039

Initial Vacuum 6.0 In. H_2O

Blowdown time 10 minutes

DATA SHEET 1

TRUCK LEAK RATE TEST

TIME 10:40 A.M.

DATE 2/15/77

TRUCK # 68-177

COMPT.# 1 COMPT. CAP (SHELL FULL) 2543 Gals.

	PRESS	VAC.
TIME 0	22" H_2O	6" H_2O
30 Sec.	21.75	5.85
1 Min.	21.70	5.7
2	21.2	5.4
3	21.0	5.3
4	20.5	5.1
5	20.2	5.0
6	20.0	4.9
7	19.8	4.75
8	19.5	4.65
9	19.2	4.5
10	19.0	4.4

DATA SHEET 2

TRUCK LEAK RATE TEST

TIME 11:00

DATE 2/15/77

TRUCK # 68-177

COMPT. # 2 COMPT. CAP (SHELL FULL) 1525 Gals.

		PRESS	VAC.
TIME	0	22" H_2O	6" H_2O
	30 Sec.	21.5	5.8
	1 Min.	21.0	5.6
	2	20.1	5.2
	3	19.4	4.9
	4	18.7	4.7
	5	18.3	4.4
	6	17.8	4.2
	7	17.3	4.0
	8	17.0	3.8
	9	16.7	3.65 $\pm$
	10	16.2	3.55

DATA SHEET 3

TRUCK LEAK RATE TEST

TIME 11:55

DATE 2/15/77

TRUCK # 68-177

COMPT.# 4 COMPT. CAP. (SHELL FULL) 2017 Gals.

	PRESS	VAC.
TIME 0	22"H_2O	6"H_2O
30 Sec.	21.8	5.6
1 Min.	21.8	5.35
2	21.6	4.9
3	21.5	4.45
4	21.3	4.15
5	21.2	3.9
6	21.0	3.65
7	21.0	3.4
8	20.8	3.15
9	20.7	3.0
10	20.6	2.85

DATA SHEET 4

TRUCK LEAK RATE TEST

TIME 12:10

DATE 2/15/77

TRUCK # 68-177

COMPT.# 6 COMPT. CAP. (SHELL FULL) 2329 Gal.

	PRESS.	VAC.
TIME 0	22"H_2O	6"H_2O
30 Sec.	21.7	5.65
1 Min.	21.6	5.35
2	21.2	4.9
3	21.0	4.55
4	20.7	4.25
5	20.6	4.0
6	20.5	3.8
7	20.4	3.6
8	20.2	3.4
9	20.1	3.2
10	20.1	3.05

DATA SHEET 5

TRUCK LOADING DATA

(TEMPERATURE MEASURED COMPARTMENTS ARE NO. 3 AND 5)

TIME 1:05

DATE 2/15/77

TRUCK # 68-177

SUBSTANCE IN COMPARTMENT AT START OF LOADING

TRUCK	1	Air
	2	Air
	3	Air
TRUCK	4	Air
	5	Air
	6	Air

TRUCK LOADING TEMP. 61.5°F PRODUCT LOADED IN TRUCK SUPREME

TRAILER LOADING TEMP. 58.5°F PRODUCT LOADED IN TRLR. REGULAR

LOADING PRESSURES	TRUCK		TRAILER	
TIME	COMPT.#1	COMPT.#2	COMPT.#4	COMPT.#6
0	0	0	0	3.0 (3)
30 Sec.	2"H_2O	2.5	3.5(2)	3.0
1 Min	2 (1)	2.5	2.0	3.5
2	2	2.5	2.0	1.0
3	2.5		0	

NOTES:

(1) Single Hose Loading

(2) Two Product Loading

(3) Multiple Truck Loading

DATA SHEET 6

TRUCK TRANSPORT DATA

TIME STARTED 1:30

TIME FINISHED 2:10

DATE 2/15/77

TRUCK # 68-177

AMBIENT TEMP. 75°F

CARGO TANK CONDITION Loaded

VAPOR SPACE TEMP.(START) IN CONTROL COMPT(#3)

VAPOR SPACE TEMP.(FINISH) IN CONTROL COMPT(#5)

TRANSPORT PRESSURES

	TRUCK		TRAILER	
TIME	COMPT.#1	COMPT.#2	COMPT.#4	COMPT.#6
0	25	24	14.5	17
30 Sec.	50+	24	43	44
1 Min.	43	20	40	39
2	35	15	34	32
3	31	10	30	29
4	29	5	28	26
5	27	1	26	25
6	24	-?(1)	21	23
9	19	0	14	19
10	17	-?	14	17
13	13	-?	10	15
15	11	-?	8	13
18	7	-?	4	10
21	5	-?	2	8
24	3	-?	1	6
27	3	-?	1	5

DATA SHEET 6 (CONT.)

TIME	TRUCK COMPT.#1	TRUCK COMPT.#2	TRAILER COMPT.#4	TRAILER COMPT.#6
30(2)	-?	-?	-?	-?
31	-?	-?	-?	-?
32	-?	-?	-?	-?
33	-?	-?	-?	-?
36	-?	-?	-?	-?
37	-?	-?	-?	-?
38	-?	-?	-?	-?
39	-?	-?	-?	-?
40	-?	-?	-?	-?

end of run (at Station #9148)

(1) Opened Dome to check

(2) Turn around truck at Milk Farm

DATA SHEET 7

TRUCK UNLOADING DATA

TIME 2:45

DATE 2/15/77

COMPT. 2 PRODUCT Sup. VAPOR RECOVERY No TRUCK#68-177

UNDERGROUND TANK

QUANTITY AT START 550 DEPTH BELOW GROUND 9'10"

QUANTITY AT FINISH 2100 DEPTH BELOW GROUND 8'10"

QUANTITY DELIVERED 1450 DELIVERY TIME 3 min. 15sec.

LENGTH OF BAG ON STATION VENT N/A

DELIVERY DATA

TIME	CARGO TANK VACUUM	UNDERGROUND TANK PRESS.
0	0	0
30 Sec.	1.15	6.6
1 Min.	1.20	8.6
2	1.20	7.2
3	1.10	6.0
3:05	1.0	2.0
3:15	0	0

DATA SHEET 8

TRUCK UNLOADING DATA

TIME 2:55

DATE 2/15/77

COMPT.# 1 PRODUCT Sup. VAPOR RECOVERY Yes TRUCK #68-177

UNDERGROUND TANK

QUANTITY AT START 2100 DEPTH BELOW GROUND 8'10"

QUANTITY AT FINISH 4450 DEPTH BELOW GROUND 7'4"

QUANTITY DELIVERED 2075 DELIVERY TIME 4 min. 56 sec

LENGTH OF BAG ON STATION VENT 10'3"(1)

DELIVERY DATA

TIME	CARGO TANK VACUUM	UNDERGROUND TANK PRESS.
0	0	0
30 Sec.	1.75	.05
1 Min.	1.75	.05
2	1.70	.04
2.5	1.70	.03
3.0	1.65	.025
3.5	1.60	.025
4.0	1.55	.025
4.5	1.50	.03
4:56	1.0	0

(1) 42 inch circumference bag

DATA SHEET 9

TRUCK UNLOADING DATA

TIME 3:20

DATA 2/15/77

COMPT.# 4 PRODUCT CLL VAPOR RECOVERY No TRUCK# 68-177

UNDERGROUND TANK

QUANTITY AT START 900 DEPTH BELOW GROUND 9'6"

QUANTITY AT FINISH 2650 DEPTH BELOW GROUND 8'2 1/2"

QUANTITY DELIVERED 1675 DELIVERY TIME 4 min 9 sec.

LENGTH OF BAG ON STATION VENT NONE

DELIVERY DATA

TIME	CARGO TANK VACUUM	UNDERGROUND TANK PRESS.
0	0	0
30 Sec.	.95	5.8
1 Min.	.95	7.5
1.5 Min.	.95	8.0
2.0	.95	7.4
2.5	.90	7.0
3.0	.80	6.6
3.5	.85	6.15
4.0	.78	6.0
4:09	0	0

DATA SHEET 10

TRUCK UNLOADING DATA

TIME 3:35

DATE 2/15/77

COMPT. 6 PRODUCT CLL VAPOR RECOVERY Yes TRUCK#68-177

UNDERGROUND TANK

QUANTITY AT START 2650 DEPTH BELOW GROUND 8'2 1/2"

QUANTITY AT FINISH 4700 DEPTH BELOW GROUND 6' 11"

QUANTITY DELIVERED 1980 DELIVERY TIME 4 min 23 sec.

LENGTH OF BAG ON STATION VENT 21' 0" (1)

DELIVERY DATA

TIME	CARGO TANK VACUUM	UNDERGROUND TANK PRESS.
0	0	0
30 Sec.	1.55	.15
1 Min.	1.52	.15
2 Min.	1.50	.08
2.5	1.45	.07
3.0	1.40	.06
3.5	1.38	.06
4.0	1.35	.05+
4.23	1.30	.05

(1) 42" circumference bag

DATA SHEET 11

TRUCK TRANSPORT DATA

TIME STARTED 4:04

TIME FINISHED 4:27

DATE 2/15/77

TRUCK # 68-177

AMBIENT TEMP. 76°F

CARGO TANK CONDTION Empty

VAPOR SPACE TEMP. (START) COMPT. (#3) TRK 85°F
(#5) TRLR 78°F

VAPOR SPACE TEMP. (FINISH) COMPT. (#3) TRK 75°F
(#5) TRLR 76°F

TRANSPORT PRESSURES

	TRUCK		TRAILER	
	V.R.	No V.R.	No V.R.	V.R.
TIME	COMPT. #1	COMPT. #2	COMPT. #4	COMPT. #6
0	5	5	3	5
30 Sec.	5	5	3	5
1 Min.	5	5	3	5.5
2 Min.	5	5.5	3	5.5
3	5.5	6	3.5	6.0
4	5.5	6	3	6
5	5.5	6	3	6
6	6	6	3	6
7	5.5	6	3	6
8	5	6	2.5	5.5
9	5.5	6	2.5	6
10(1)	5	5.5	2	5
11	5	6	2	5
12	5.5	6	3	6

DATA SHEET 11 (CONT.)

	TRUCK		TRAILER	
	V.R.	No V.R.	No V.R.	V.R.
TIME	COMPT.#1	COMPT.#2	COMPT#4	COMPT.#6
13	5.5	6.5	2.5	6
14	5.5	6	2.5	6
15	5.5	6	2.5	6
18	5	6	2	6
21	5	6	2	6
24	5	6	2	6
27	5	6	1.5	6
30	4.5	5.5	1.5	5.5
33	3.5	4.5	0.5	4.5

(1) turn around head for Sacramento

DATA SHEET 12

TRUCK LOADING DATA

(TEMP CONTROL COMPTS. ARE #3 and 5)

TIME 4:45

DATE 2/15/77

TRUCK#68-177

SUBSTANCE IN COMPT. AT START OF LOADING

TRUCK	1	Vapor	TRLR. 4	Air
	2	Air	5	Vapor
	3	Vapor	6	Vapor

TRUCK LOADING TEMP. 62.5°F PRODUCT LOADED IN TRUCK Sup

TRAILER LOADING TEMP. 59°F PRODUCT LOADED IN TRLR. CLL

LOADING PRESSURES	TRUCK		TRAILER	
TIME	COMPT#1	COMPT#2	COMPT#4	COMPT#6
0	1	1	1	1
30 Sec.	3.5	3	4	3.5
1 Min.	3.5	3	4	4
2	4	3.5	4	4
3	4			

DATA SHEET 13

TRUCK TRANSPORT DATA

TIME STARTED 5:18

TIME FINISHED 5:59

DATE 2/15/77

TRUCK #68-177

AMBIENT TEMP. 76

CARGO TANK CONDITION Full

VAPOR SPACE TEMP.(START) COMPT. (#3) TRUCK 72°
(#5) TRAILER 71°

VAPOR SPACE TEMP.(FINISH) COMPT. (#3) TRUCK 62.0°
(#5) TRAILER 65.5°

TRANSPORT PRESSURES

	TRUCK		TRAILER	
TIME	COMPT. #1	COMPT.#2	COMPT.#4	COMPT.#6
0	0	5	3	0
30 Sec	2.5	7	35	-2
1 Min.	3	4	34	-6
2 Min.	1	-5	31	-8
3	-1	-7	29	-9
4	-1.5	->10	28	-10
5	-2	-8.5	27	-9.5
6	-2	-8.5	26	-9.5
7	-3	-9	21	-9.5
8	-4	-7	20	-9
9	-4.5	-6	19	-9
10	-5.5	-7	18	-9
11	-5.5	-7.5	17	-9
12	-5.5	-7.5	17	-9

DATA SHEET 13 (CONT.)

	TRUCK		TRAILER	
TIME	COMPT. #1	COMPT. #2	COMPT. #4	COMPT. #6
13	-6	-7.5	16	-9
14	-7	-9	13	-9
15	-7	-8	12	-9
18	-8.5	-6.5	9	-9
21	-8	-5.5	8	-9
24	-8	-6	7	-9
27	-10	-10	3	-10
30	-8	-6.5	1	-9
33	-8	-5	1	-8
36	-8	-6	-1	-8

DATA SHEET 14

RVP AND FUEL D-216 DISTILLATION DATA

FOR DATA SHEETS 1 THRU 13

FUEL	REGULAR		SUPREME	
SAMPLE	1	2	1	2
RVP	11.0	11.3	11.3	11.1
RVP REPEAT	11.0	11.2	11.3	11.2
% CONDENSED	DISTILLATION TEMPERATURES, °F			
START	83	78	79	78
5%	101	100	99	99
10%	114	113	109	110
15%	124	124	118	120
20%	135	134	128	131
25%	146	144	137	140
30%	154	153	147	149

DATA SHEET 15

COMPARTMENT 2 and 4 LEAK TESTS

DATE 5/11/77

TRUCK #68-177

TRUCK COMPARTMENT 2 -1525 GAL.

PRESSURE TEST

Hr : Min	In. H_2O
0:00	18.0
0:05	14.5
0:15	13.5
0:35	12.5
0:55	11.0
1:15	9.0
1:35	8.0
1:55	7.0
2:15	7.0
2:15	6.5
2:35	6.25

VACUUM TEST

Hr : Min	In. H_2O
0:00	6.0
0:05	4.5
0:15	3.5
0:35	2.0
0:55	0.5
1:15	0.0

TRAILER COMPARTMENT 4 - 2017 GAL.

PRESSURE TEST

Hr : Min	In. H_2O
0:00	18.0
0:05	15.0
0:15	14.5
0:35	14.5
0:55	15.5 ↕ (2)
1:15	16.0
1:35	15.75
1:55	15.5
2:15	15:25
2:35	15.0

VACUUM TEST

Hr : Min	In. H_2O
0:00	6.0
0:05	5.0
0:15	4.5
0:35	4.0
0:55	3.0
1:15	3.0
1:35	3.0

Notes: (1) Vacuum Test run morning, #4 Pres over lunch, #2 pressure last
(2) Shop heater came on and was shut off when ΔP rise found.

DATA SHEET 16

COMPARTMENT 1 and 6 LEAK TESTS

DATE 5/25/77

TRUCK #68-177

TRUCK COMPARTMENT 1 - 2543 GAL

PRESSURE TEST

Min	In. H_2O
0.	18.0
5	17.0
10	16.75
15	16.5
20	16.25
25	16.25
0	7.0(1)
20	9.0
0	7.0(1)
20	7.375

VACUUM TEST

Min	In. H_2O
0	6
5	5
10	4.5
15	4.5

TRAILER COMPARTMENT 6 - 2329 GAL

VACUUM TEST

Min	In. H_2O
0	6
5	5
10	4.5
15	4.5

PRESSURE TEST

Min	In. H_2O
0	18.0
3	15.0

Notes:

(1) Tank pressure bled down to 7.0 inches water, leakage test started.

(2) Pressure tests run 1st, 1" Pressure vent plugged with pipe plug and the vacuum tests run.

DATA SHEET 17

VAPOR TRANSIT PRESSURE AFTER FUEL DROP

DATE 5/25/77

TRUCK #68-177

TRUCK COMPARTMENT 1 - 2017 GAL.

Min	In. H_2O
0	0.6
1	0.8
2	1.2
3	1.0
4	0.7
5	0.7
6	0.4
7	0.1
8	0.0
9	-0.2[1]
10	-0.4
11	-0.4
12	-0.1[2]
13	-0.5
14	-0.7[3]
15	-0.8
16	-1.3[4]

AMBIENT TEMP. 70°F

FUEL LOAD TEMP. 72°F

HAZY SUN

Notes:

(1) Minus sign means vacuum

(2) Came off freeway

(3) Stop and Go traffic

(4) Arrive terminal