LFL Estimates for Crude Oil Vapors from Relief Tank Vents

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In 1970, the Alyeska Pipeline Service Company was formed to manage the design, construction, operation and maintenance of the Trans–Alaska Pipeline System. The 800 mile long pipeline carries crude oil from Prudhoe Bay on the North Slope to Port Valdez on Prince William Sound. There are 11 pump stations located along the pipeline, each of which is equipped with a crude oil relief tank. Because of the potential flammable nature of the crude oil vapors being vented from the tanks, Alyeska wanted to determine the region surrounding the tanks within which the lower flammable limit (LFL) could be exceeded. Because numerical models cannot accurately model the flow near structures, especially for dense gases (as is the case here), wind tunnel modeling was conducted to provide more accurate distance to LFL estimates. The wind tunnel model simulations were also used to judge the effect of various modeling parameters (i.e., site specific configurations, release scenarios and meteorological conditions), and to assist in possible future refinements to numerical models. Field observations were also obtained at one of the pump stations for the purpose of validating the wind tunnel modeling. The project, wind tunnel scaling methods, experimental methods, concentration measurement results, distance to LFL estimates and comparison between the field and wind tunnel observations are described in this paper..

INTRODUCTION

To obtain the LFL estimates, 1:50 scale models of both a simplified and actual relief tank were designed and constructed and positioned in a boundary layer wind tunnel. In addition to the relief tanks, model surroundings were constructed so site specific effects could be evaluated. A heavier-than-air tracer gas mixture was then released from the model tanks for various simulated meteorological conditions to include stable low wind speed conditions. Time varying concentrations were measured at various downwind locations so that peak and mean concentrations could be determined, and so that the distance to LFL could be specified. Wind tunnel simulations were also conducted for two cases evaluated during a field experiment conducted at one of the pump stations.

Since wind tunnel modeling of dense gas plumes under light wind conditions also poses some difficult constraints upon wind tunnel scaling, various tests were conducted to evaluate the wind tunnel simulation method. Tests were conducted to evaluate the effect of Reynolds number, Peclet/Richardson number, distorted density scaling and atmospheric stability (i.e., Richardson number).

This paper describes the project, wind tunnel scaling methods, experimental methods, concentration measurement results, distance to LFL estimates and comparison between the field and wind tunnel observations.

PROJECT INFORMATION

Physical Model And Site Description

To evaluate the dispersion of vapors released from crude relief tanks in advance of the field evaluation, a 1:50 scale model of a typical tank that closely matches the design of the tanks used at 9 of the 11 pump stations was constructed. The typical tank has 7 vents that are not symmetrically located about the tank. Figure 1 shows the tank and a portion of the surroundings that were modeled. Most pre-field tests were conducted with only the tank present.

Field tests were conducted at Pump Station #3 on September 20 and 23, 1994 as described in Quest [4]. The purpose of the field test program was to determine the concentrations due to the venting of tank vapors in the vicinity of the relief tank and tank containment berm during light wind and stable atmospheric conditions. Figure 1 shows an isometric view of the area around the tank to

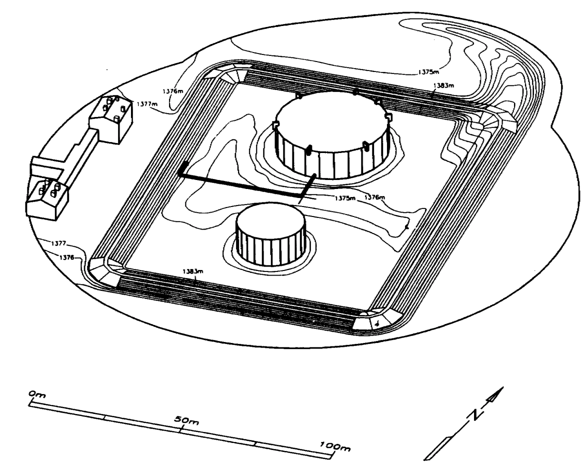

FIGURE 1 Isometric view of area modeled in wind tunnel.

include the berm. This is that area that was modeled in the wind tunnel for the field/wind tunnel comparison tests.

Release Scenarios

Four different release scenarios were modeled during the pre-field study and the source characteristics for these scenarios are provided in Table 1. The scenarios are referred to as Maximum Light Ends–Warm (MaxLEW), Minimum Light Ends–Warm (MinLEW), Minimum Light Ends–Cold (MinLEC) and Maximum Light Ends–Cold (MaxLEC).

The Quest [4] report provided information on initial release conditions for the two field tests. These conditions are also summarized in Table 1. It should be noted that the volume flow rate from the vents was not measured during the field experiment but was based on estimates provided by Alyeska Pipe Line Service Company. Watson [7] believes that the specified volume flow rates are most likely a high estimates and the actual flow rate is probably closer to 0.8 times the specified value.

Meteorological Conditions

The meteorological conditions evaluated during the pre-field study depicted a neutrally buoyant atmosphere with high wind speeds (namely, "D" stability and 4 and 9 m/s wind speeds), and a stably stratified atmosphere and near calm conditions (Pasquill–Gifford category E/F and a 1 m/s wind speed).Other wind speeds under both neutral and stable conditions (1.5, 2 and 3 m/s) were also evaluated during the study to assess the sensitivity of the results to this variable.

For the purpose of setting the wind tunnel experiment for the simulation of the field experiment, the wind speed and direction measured at a 10 m height in the field were used. The wind direction and wind speed did vary during each field condition. For Field Test 1, the average wind direction was 11.2 degrees and the average wind speed was 3.2 mph. For Field Test 2, the average wind direction was 23.8 degrees and the average speed was 2.2 mph.

Test Matrix

The test matrix consisted of: 1) atmospheric dispersion comparability (ADC) tests; 2) Reynolds number independence tests; 3) simulation sensitivity tests; 4) tests to define distance to LFL, and 5) tests to replicate the field experiment. The ADC tests were conducted to demonstrate that the dispersion in the wind tunnel is comparable to that described for the atmosphere by the basic Gaussian plume equation. The results of these tests demonstrated that representative neutral and stable atmospheric boundary layers were simulated. The Reynolds number independence tests were designed to define minimum acceptable operating conditions where Reynolds number effects are not significant. The next series of tests were designed to evaluate the sensitivity of the wind tunnel concentration predictions to wind speed, atmospheric stability, the simulation method (i.e., density ratio distortion), and molecular diffusion effects (i.e., Peclet/Richardson number). The final series of pre-field tests were conducted to determine distance to LFL estimates.

After the field experiment, a series of tests were conducted to replicate Field Tests 1 and 2. Some of the runs were carried out using the average wind speed and direction observed during the field test and some were run using the two minute average wind speeds and wind directions observed during the field release duration. A series of tests were also conducted to evaluated the sensitivity of the resulting ground level concentrations to volume flow and wind speed. For most of the simulations a steady state release was simulated and steady state average concentrations (2 to 15 minute averaging time) were recorded. Two cases were run using the average wind speed and wind direction but the release duration was also simulated (referred to as a finite duration release). For this test instantaneous concentrations were measured at each receptor. lowest Reynolds number (2691), the maximum ground level concentrations are more than 30% lower at all distances.

TABLE 1. Selected Source Parameters for Pre-Field and Field Relief Tank Wind Tunnel Simulations

Release Type	Min LEW	Min LEC	Max LEW	Max LEC	Field Test 1	Field Test 2
Exit Velocity, V_e (m/s)	2.962	3.147	3.202	3.335	3.213	2.690
Density ratio of effluent/air	1.280	1.069	1.396	1.152	1.218	1.269
Lower Flammability Limit, LFL (%vol)	4.76	6.28	3.65	4.74	1.76	1.76

WIND TUNNEL SIMILARITY

An accurate simulation of the boundary-layer winds and heavier-than-air gas dispersion is an essential prerequisite to meet the objectives of this study. The techniques for simulating the boundary-layer winds and gas dispersion have been well established [1,6] and the basic requirements are discussed in detail in Petersen and Parce [3]. The basic scaling relations used during the study were: 1) match (equal in model and full scale) source Buoyancy ratio, B_o; 2) match the source momentum ratio, M_o; 3) match (and distort) relative density, λ; 4) maintain a Peclet/Richardson number ratio $\left(Pe/Re = \rho_a U_2^3/[g(\rho_s - \rho_a)\varepsilon]\right)$ greater than 1500; 5) ensure a fully turbulent boundary layer—surface Reynolds number greater than 2.5; 6) maintain a sufficiently high tank height Reynolds number; 7) identical geometric proportion; 8) equivalent stability—measured by the atmospheric Richardson number; and 9) equality of dimensionless boundary and approach flow conditions.

EXPERIMENTAL METHODS

CPP's open circuit atmospheric boundary layer wind tunnel was used for all testing. For all tests, a flat aluminum floor was placed within the tunnel. Above the floor, rows of roughness flaps were placed laterally across the tunnel to establish either a grassland or rural surface roughness length (z_o = 2 or 20 cm). The roughness was only installed upwind of the tank to ensure that the roughness elements would not enhance plume mixing. A trip was installed at the entrance of the wind tunnel to stimulate boundary layer growth and to retard flow reversals that are often observed at low speeds under stable stratification. For stable testing, the insulated cold chambers beneath the wind tunnel floor were cooled to the desired temperature.

For the pre-field wind tunnel tests, a multipoint concentration sampling array was positioned on the wind tunnel floor. The array consisted of up to 68 ground level points arranged in concentric arcs centered on the center of the tank. For a large fraction of tests, vertical concentration distributions were measured at two downwind locations.

For replicating the field experiments, a multipoint concentration sampling array was positioned on the Pump Stations 3 model as shown in Figure 2. The array was designed to replicate the sampling grid that was used during Field Tests 1 and 2 [4].

For the majority of the tests, concentration measurements were obtained using a fast response flame ionization detector (FID) with two detectors. At each receptor, a concentration time series was generally obtained of sufficient duration to obtain an estimate of the 15 minute average full scale concentration. This averaging time was assumed to be sufficiently long to be the steady state average. The concentration time series were stored on a computer file and subsequently analyzed to determine the concentration over various averaging times.

RESULTS OF PRE-FIELD WIND TUNNEL TESTS

Reynolds Number Independence Tests

Reynolds number independence tests were conducted to define the minimum acceptable Reynolds number (or wind speed) at which testing could be conducted. Tests were conducted under both neutral and stable stratification and only the results for the neutral testing will be reported here. Meroney [1] and Snyder [6] noted that roughness can be added to the surface of a round circular cylinder (a tank in this case) to increase the turbulence and thereby extend the lower limit for Reynolds number independence. Hence, 1.6 mm square roughness strips were added to the surface of the tank.

Figure 3 provides a graphical illustration of the neutral results. The figure shows the maximum concentration versus downwind distance for each run as well as 30% error bars about the high Reynolds number case (Run 208). The figure shows that the concentrations agree well at all downwind distances for cases with a Reynolds number greater than 5382 or a model wind speed greater than 0.5 m/s. At the

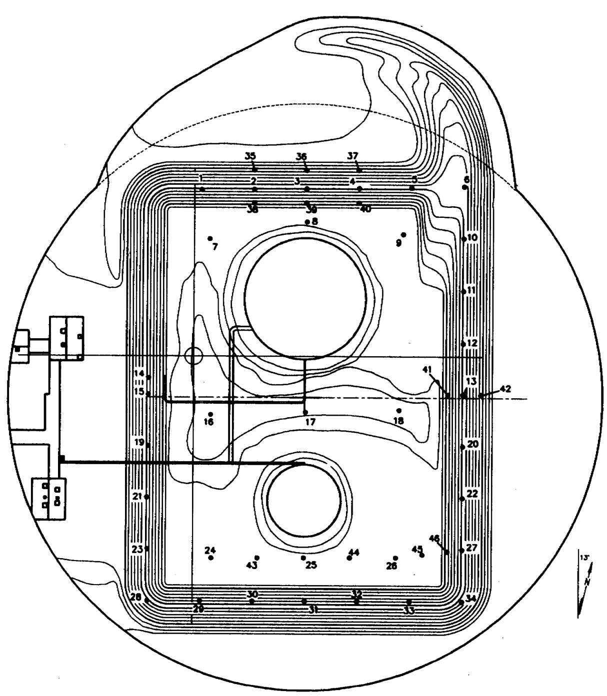

FIGURE 2 Wind tunnel concentration measurement sampling array for replicating field tests.

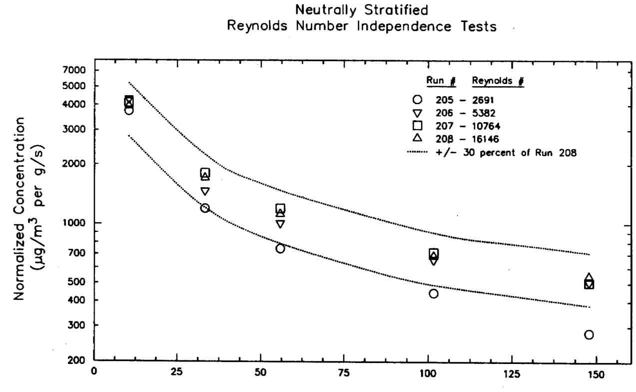

FIGURE 3 Reynolds number independence tests.

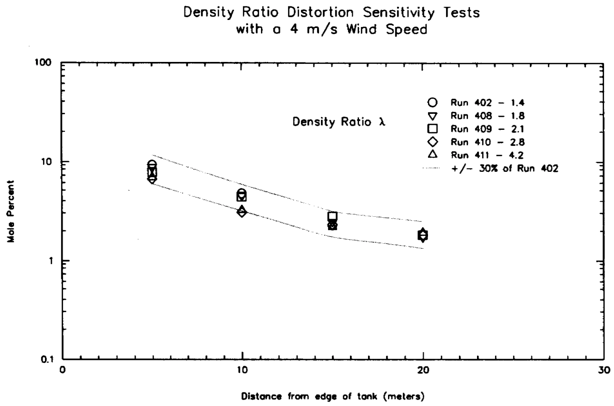

FIGURE 5 Effect of initial density ratio on wind tunnel predicted concentrations (4 m/s wind speed at 10 m).

Based on the neutral Reynolds number tests, a lower limit where Reynolds number independence can be assured at all distances out to 150 m was about 5382 or a wind tunnel speed of 0.5 m/s at a 1:50 model scale. For distances within 30 m, a lower Reynolds number limit of 2691 was found to be acceptable.

Simulation Sensitivity Tests

Density Ratio Distortion

The effect on the concentration results of distorting the density ratio was evaluated at three simulated wind speeds, 2, 4 and 9 m/s. For each modeled wind speed density ratios of 1.4, 1.82, 2.10, 2.80 and 4.2 were used to see if the results would be similar. A 1.40 density ratio would result in exact matching for all simulations. This ratio could not be tested at the 2 m/s wind speed since the resulting model wind speed would give a Reynolds number below the acceptable minimum.

Maximum concentrations versus downwind distance for the 4 m/s case are plotted in Figure 4. The figure also shows a 30% error bar about the undistorted density ratio case. The figure shows that concentrations are within 30% for all cases (except at one distance). This result suggested that density ratio distortion, up to a 4.2 density ratio, could be used and the results will be similar to the undistorted density ratio case.

Peclet/Richardson Number Ratio

The critical *Pe*/*Ri* ratio has been specified in the literature to be 1500 [1]. Wind tunnel experiments conducted with initial source properties below this limit may be impaired and will tend to provide underestimates of the concentrations. Tests were conducted to evaluate the effect of relaxing this requirement. These tests showed a *Pe*/*Ri* value as low as 227 could be used [3] without significantly impairing the results.

Effect of Atmospheric Stability

At present, the scientific community has a higher degree of confidence in wind tunnel simulations conducted under neutral stratification than those conducted under stable stratification. For this reason, duplicate cases were run under neutral and stable conditions to see if the results

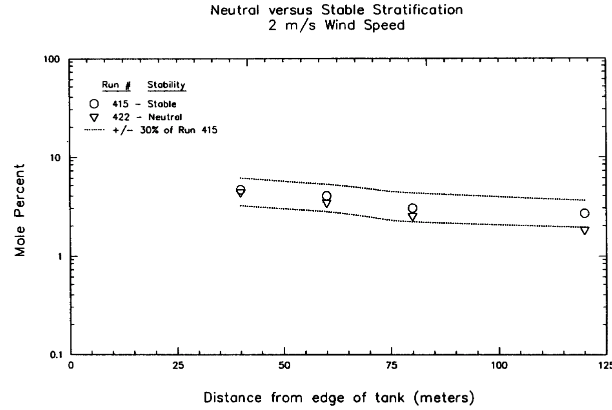

FIGURE 4 Effect of atmospheric stability on concentration (2 m/s wind speed at 10m).

showed the expected trend. The expected trend is that near the tank, the effect of the tank wake and initial source characteristics will dominate, and the concentrations will be similar under stable and neutral conditions. At greater downwind distances, the effect of atmospheric stratification will start to dominate and the concentrations should increase under stable stratification.

Figure 5 shows maximum concentrations versus distance for the stable and neutral 2 m/s simulations. Both simulations have Reynolds numbers and *Pe*/*Ri* values above the minimum limits. The figure shows that the stable case produces concentrations that are similar to the neutral case at 40 m from the tank wall, and which tend to become greater than the neutral case with increased distance from the tank. This graph shows the expected trend and would suggest that heavy gas effects are dominating the dispersion close to the release, and farther downwind atmospheric stratification effects start to dominate. At 120 m downwind, the stable concentrations are about 1.5 times as large as the neutral concentrations, again a reasonable difference due to atmospheric stratification effects. Overall, these results suggested that the stable concentration estimates show the expected trend when compared to the neutral simulation.

Actual Tank and Site Specific Sensitivity Tests

During this phase of the study, testing was conducted using the model of an actual relief tank, both with and without a surrounding berm. The purpose of these tests was to evaluate the effect of various site specific features on concentration estimates and to document whether or not the features resulted in higher or lower concentration estimates. Most of the tests were conducted with a 2 cm surface roughness approaching the model and no berm around the tank. Sensitivity tests were conducted with a berm, with a 20 cm approach surface roughness (with and without a berm), and with a model of Pump Station 3. Overall, the concentrations for all configurations showed little relative variation. The results showed that estimates obtained with a 2 cm approach surface roughness will be reasonable estimates regardless of site roughness classification.

Distance to LFL Estimates

Petersen and Parce [3] present a listing of the distance to LFL estimates for all conditions evaluated. The estimates are based on 30 second (peak) and 15 minute (steady state) averaging times. The 15 minute averaging time distance to LFL estimates were provided for the purpose of comparison with mathematical models which do not normally consider averaging times. The distance to LFL estimates based on the 30 second averaging time are the values that are typically used for actual distance to LFL estimates. For some applications, the 15 minute averaging time may be appropriate. All neutral tests with simulated wind speeds greater than or equal to 2 m/s at a 1:50 model scale met all important similarity requirements. All stable tests with a simulated wind speed greater than or equal to 3 m/s met all important similarity requirements. Tests at simulated speeds below these critical values were impaired and the distance to LFL estimates were viewed accordingly.

All neutral simulations at 4 and 9 m/s were not impaired and distance to LFL estimates for the actual tank are summarized in Table 2 (i.e., based on 30 second and 15 minute average concentrations).

Table 2. Summary of distances to LFL (m) from edge of tank for all non-impaired neutral simulations at 4 and 9 m/s.

	Distance to LFL (m)			
	4 m/s		9 m/s	
Release Type	30 sec*	5 min*	30 sec*	15 min*
MaxLEW	7–49	4–34	4–12	2–8
MaxLEC	18–23	12–16	4	3
MinLEC	12–20	8–14	4	3
MinLEW	17–30	13–19	5	3

*Concentration averaging time

As discussed above, all 1 m/s simulations were generally impaired due to Reynolds number, *Pe*/*Ri* and wind tunnel blockage effects. Hence, an alternate method was developed to estimate the distance to LFL for the 1 m/s case. The neutral 2 m/s wind speed case and the 3 m/s stable wind speed case were used to estimate the maximum concentrations at 1 m/s by assuming concentration times wind speed is a constant. If anything, this procedure would provide a conservative estimate, since the study showed that concentration times wind speed decreases with decreasing wind speed. The results are summarized below.

WIND TUNNEL VERSUS FIELD

This section discusses the comparison of the field observations with the wind tunnel estimates for Quest [4] Field Tests 1 and 2. Several different statistical comparisons were made which are discussed more completely in Petersen and Hosoya [2]. This paper will only discuss the comparisons of peak concentrations measured in the field and those measured in the wind tunnel. The full scale averaging time for the peak concentrations was 0.8 min. Since peak concentrations are used to specify distance to LFL, these comparisons seem the most significant. The comparisons were made for concentrations measured in the

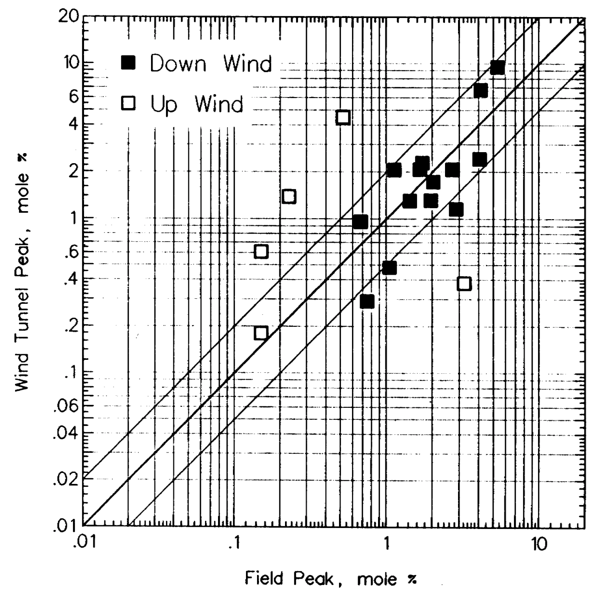

FIGURE 6 Field versus wind tunnel concentration estimates for Field Test 1 - peak concentrations and specified volume flow (V_0).

wind tunnel at the specified volume flow rate and for flow rates 1.2, 0.8 and 0.6 times the specified flow. The latter comparisons were obtained by adjusting the concentration measurements at each receptor obtained at the specified flow using flow correction factors developed during the study.

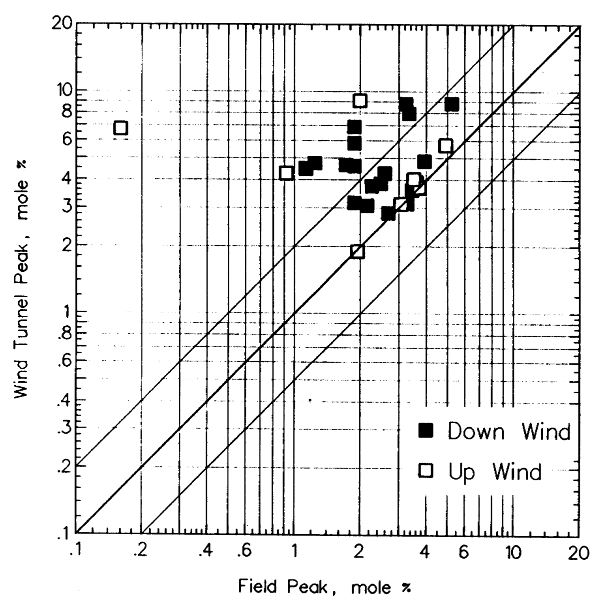

FIGURE 7 Field versus wind tunnel concentration estimates for Field Test 2 - peak concentrations and specified volume flow (V_0).

Table 3. Summary of LFL estimates for 1 m/s wind speed

Release Type	MaxLEW	MaxLEW
Stability	D	E/F
Wind Speed (m/s)	1	1
Distance to LFL (m) 30 sec/15 min*	133/100	195/160

*Concentration averaging time

Figures 6 and 7 show a scatter plots of wind tunnel versus field peak concentrations for Field Tests 1 and 2. The figures shows that most wind tunnel predictions are within a factor of two of field observations. The average bias was found to be less than about 15% for Field Test 1 and about a factor of 2 for Field Test 2. If the actual flow rate from the tank were 0.8 times that specified (a likely case), the agreement between the field and wind tunnel would improve.

Comparisons are presented in Figures 8 and 9 which show the field and wind tunnel observations ranked from highest to lowest for Field Tests 1 and 2. Wind tunnel predictions are presented for the specified volume flow rate (V_o), and for flow rates 0.8 and 0.6 times that specified. These comparison do not consider the measurement location but just how well the wind tunnel predicts the concentration ranking. This comparison will tell whether the wind tunnel overpredicts high values and underpredicts low values or has no tendency toward over or under prediction. The figures shows that wind tunnel predicts the hightest values reasonably well and shows a slight tendency to underpredict.

The figure again shows that the best agreement is achieved for the case with a volume flow equal to 1.0 times that specified. The figure also shows that maximum concentrations will only be underpredicted at a couple points for this condition. The figure again shows that the best agreement is achieved for the case with a volume flow equal to 0.8 times that specified.

CONCLUSIONS

This study has provided valuable information regarding the range of applicability of the wind tunnel for predicting distance to LFL estimates downwind of relief storate tanks. The study also provided worst case estimates for the distance to LFL. These distances were 133 m for neutral stability and 195 m for stable stratification based on a 30 s concentration averaging time and a 1 m/s wind speed. For more typical meteorological conditions (neutal stability and 4 to 9 m/s wind speeds), the distance to LFL estimates were from 3 to 34 m downwind of the tank.

Wind tunnel predicted peak (0.8 minute averaging time) concentrations were also compared with corresponding field observations. This comparison showed that the wind tunnel estimates of peak concentration compared well with field observations for Field Test 1 (i.e., within 10 th 20%) with a slight tendency to overpredict. For Field Test 2, the agreement was not as good as that for Field Test 1 using the specified volume flow rate from the tank. Using the more likely flow rate from the tank, the agreement improved significantly for Field Test 2. Using the more likely flow rate from the tank for Field Test 1, the agreement between the field and wind tunnel still remained exceptionally good.

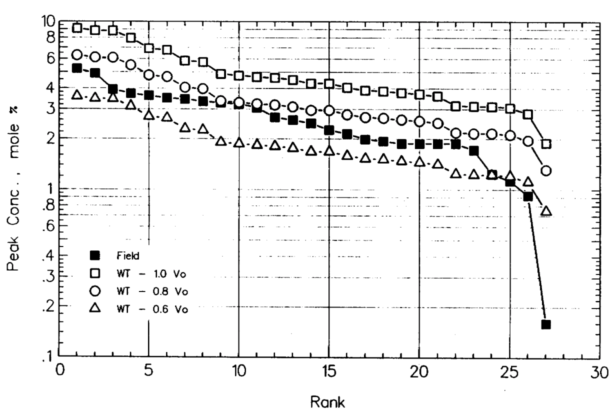

FIGURE 8 Observed field concentrations ordered from highest to lowest for Field Test 2 compared to ordered wind tunnel concentration estimates using specified volume (V_0), $0.8V_0$ and $0.6V_0$.

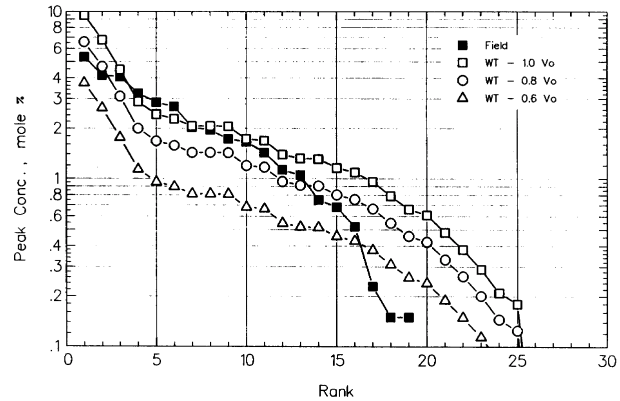

FIGURE 9 Observed field concentrations ordered from highest to lowest for Field Test 1 compared to ordered wind tunnel concentration estimates using specified volume (V_0), $08V_0$ and $0.6V_0$.

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