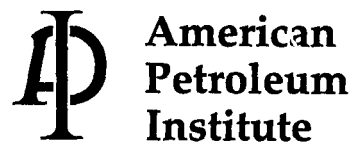


Wind Tunnel Testing of External Floating-Roof Storage Tanks

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LIST OF SYMBOLS

<u>Symbol</u>	<u>Description</u>	
C_p	Coefficient of Pressure	(-)
D	Tank Diameter	(ft)
$f(\theta)$	Frequency of Wind Direction Sector	(-)
F	Evaporative Loss Factor	(lb mole/ft/yr)
H	Tank Height	(f)
K	Product Loss Factor	(-)
L	Stock Loss	(lb/yr)
m	Evaporative Loss Factor	(-)
M	Molecular Weight	(g/g-mole)
n	Wind Power Law Exponent	(-)
N	Number of Fittings	(-)
P^*	Vapor Pressure Function	(-)
q	Dynamic Pressure	(lb/ft ²)
r	Tank Radius	(ft)
R	Roof Height	(ft)
U_{mean}	Average Wind Speed at fitting	(mph)
U_{ref}	Reference Wind Speed	(mph)
U_{rms}	Root Mean Squared Wind Speed at fitting	(mph)
x	Distance from Center of Tank Roof	(ft)
z_o	Surface Roughness Height	(ft)
ρ_a	Density of Air	(lb/ft ³)
ν_a	Viscosity of Air	(ft ² /sec)

LIST OF SYMBOLS (Continued)

Subscript

a	airport
e	effective
f	fitting, full scale
m	model scale
r	rim seal
s	standing; site
t	total
v	vapor

1.0 INTRODUCTION

The American Petroleum Institute (API) contracted with Cermak Peterka Petersen, Inc. (CPP) to conduct a wind tunnel study to determine the local wind velocities, wind directions, and roof pressures on External Floating Roof Tanks (EFRT). The results of this study are to be used to improve evaporative loss calculations for roof fittings on EFRT.

The third edition of API Publication 2517 (1989) is the first to include roof fittings as a potential source for evaporative loss. Previous publications have limited the scope to include rim seal and stock clingage losses, assuming roof fitting losses to be negligible in comparison. The loss factors used in the evaporative equations were derived from experimental data which correlated stock evaporation to the wind speed over the roof fitting.

The current procedure, as described in Section 2.2 of API 2517, specifies that an average wind speed at the tank site or from the nearest local weather station should be used as the wind speed over the roof fitting in the evaporative loss equations. This average approach wind speed may differ substantially from the actual wind speed over the fittings, from which the loss factors were derived. For lower roof levels, in particular, the inaccuracy in wind velocity may cause overestimates of the evaporative loss potential for the roof fittings.

The primary objective of this study is to develop a relationship between the airport wind speed and the wind speed at roof fittings. In addition to wind speed, the relative wind direction of air flow over the EFRT roof top will be analyzed as an aid to evaluating evaporation losses for fittings which exhibit some level of directional sensitivity. For documentation purposes and for use in future evaluations of evaporative loss, roof top pressures were also measured across the tank.

The following sections provide background into the current evaporative loss methodology and air flow characteristics, a description of the experimental program carried out during the study, results of the study, a revised method for calculating evaporation loss from roof fittings, and conclusion and recommendations.

2.0 BACKGROUND

2.1 Evaporative Loss Equation

Section 2 of API Publication 2517 describes the current procedures for estimating the total annual evaporative stock loss from EFRT. The total loss is defined as the sum of the standing storage loss, L_s , and the withdrawal loss, L_w . Withdrawal losses are primarily attributed to clingage of stock to the tank shell while the stock is withdrawn. Standing storage loss is attributed to evaporation of stock around rim seals and roof fittings. This study will focus on the latter.

The present equation for calculating standing stock losses from EFRT is as follows:

$$L_s = (F_r D + F_f) P^* M_v K_c \quad (1)$$

where:

L_s	=	Standing stock loss (lb/yr)
F_r	=	Rim-seal loss factor (lb-mole/ft/yr)
D	=	Tank diameter (ft)
F_f	=	Roof fitting loss factor (lb-mole/yr)
P^*	=	Vapor pressure function
M_v	=	Average molecular weight of stock vapor (lb/lb-mole)
K_c	=	Product factor

Equation 1 can be broken down into its two components, rim seal losses (L_r) and roof fitting losses (L_f), where:

$$L_r = F_r D P^* M_v K_c \quad (2)$$

$$L_f = F_f P^* M_v K_c \quad (3)$$

This study will concentrate its efforts on evaluating the roof fitting loss equation; however, two of the topics which will be discussed also apply to the rim seal loss equation. These include: 1) the comparison between roof top pressures measured in this study and previously published results from which F_r was derived; and 2) the relationship between the site and the nearby airport wind speeds.

The total roof fitting loss factor, F_f , from Equation 3, can be expressed as the sum of the individual loss factors for each fitting. Section 2.2.2.2 of API 2517 defines F_f as:

$$F_f = \sum_{i=1}^k N_{f_i} K_{f_i} \quad (4)$$

where:

N_{f_i}	=	Number of type i roof fittings
K_{f_i}	=	Loss factor for type i roof fitting (lb-mole/yr)
k	=	Total number of different types of roof fittings

and

$$K_{f_i} = K_{a_i} + K_{b_i} U_{\text{mean}}^{m_i} \quad (5)$$

where:

K_{a_i}	=	Loss factor for type i roof fitting (lb-mole/yr)
K_{b_i}	=	Loss factor for type i roof fitting (lb-mole/mph ^m /yr)
m_i	=	Loss factor for type i roof fitting
U_{mean}	=	Average wind speed above the fitting (mph)

The loss factors used in Equation 5 were developed using data obtained by CBI (1985) during a wind tunnel study specifically designed to measure evaporative losses from external floating

roof tank fittings. The wind tunnel tests used full scale roof fittings extending from a product reservoir into one of four 5 ft x 3 ft x 3 ft test sections. The evaporative losses from the stock reservoirs were recorded for the various roof fittings as a function of mean velocity within the wind tunnel. Exponential curve fits were applied to this data to provide the individual roof fitting loss factors.

2.2 *Air Flow Around Tanks*

A literature review was conducted to determine the current level of knowledge available concerning air flow around external floating roof tanks. The most noteworthy research (Marchmann, 1970) investigated pressure contours over open-top cylindrical tanks. It was from this data base that the rim seal equation relationship between differential pressure and approach velocity was developed. Little to no information was obtained which specifically addresses the air flow around and over EFRT.

A qualitative analysis of air flow over EFRT can be obtained using guidelines established by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE, 1989) for air flow around buildings. This analysis predicts that a cavity region will form downwind of the leading edge of each tank. The cavity, caused by flow separation at the leading edge, will expand downwind as the roof is lowered. This expansion will occur because the cavity must project deeper into the tank before the flow can reattach to the roof. At some level, depending upon the tank diameter to height ratio, the flow will not be able to reattach to the roof before encountering the trailing edge of the tank shell, causing the entire roof to be encased in a recirculation cavity. Further lowering of the roof should have minimal impact on the subsequent air flow.

A review of Marchmann (1970) confirms this qualitative analysis. The tank used in the Marchmann study was 4 ft in diameter by 1 ft tall, roughly the same height to diameter ratio as the 200 ft tank modeled in this study. The tank was installed in the 6 ft x 6 ft wind tunnel of the Aerospace Engineering Department at Virginia Polytechnic Institute. During the tests a ground board was used to simulate the approach boundary layer at the tank. Roof top pressures were measured at 81 tap locations for 5 roof top heights. In Marchmann's results (see Figure 9a), for a roof height to tank height ratio between 1.0 and 0.67, the centerline pressure coefficient profiles rapidly evolved. A relatively flat portion of the curve, which is indicative of a recirculation

cavity, is almost non-existent for the 1.0 roof height ratio. This flat region of the curve develops and expands as the roof is lowered to a roof height ratio of approximately 0.67. From this height on down to a roof height ratio of 0.23 (the lowest height for which data is presented), the centerline pressure coefficients did not vary significantly. The similarity in the profiles indicates that the cavity is no longer affected by lowering the roof height. This leads to a conclusion that the flow for roof height ratios of 0.67 and lower did not reattach to the roof after separation at the leading edge of the tank.

2.3 Wind Speeds in the Atmosphere

The wind speed, U_{mean} , in Equation 5 is the wind speed at a particular roof fitting location which, in API Publication 2517, is assumed to be the wind speed upwind of the tank location. This, in turn, is typically assumed to be equal to the wind speed at the nearest National Weather Service (NWS) station. The assumption has two problems. First, the wind speeds at the airport may not be representative of the wind speed in the vicinity of the tank, and second, the wind speed upwind of the tank is not representative of the speed near each roof fitting.

With regard to the wind speeds at the site (i.e., upwind of the tank), the following equation can be used to estimate the wind speed upwind of the tank for a given wind speed at the airport:

$$U_s = \frac{U_a Z_s^{n_s} 2000^{n_a - n_s}}{Z_a^{n_a}} \quad (6)$$

where

Z_s	=	Wind speed measurement height at the site in feet (typically 33 ft)
Z_a	=	Wind speed measurement height at the airport in feet (typically 33 ft)
U_s	=	Wind speed at the site at height Z_s in mph
U_a	=	Wind speed at the airport at height Z_a in mph
2000	=	Top of atmospheric boundary layer in feet
n_s	=	Wind speed power law exponent at the site
n_a	=	Wind speed power law exponent at the airport

The wind power law exponent is a function of surface roughness and can be estimated using the following equation (EPA, 1981):

$$n_i = 0.24 + 0.096 \log_{10} z_{0_i} + 0.016 (\log_{10} z_{0_i})^2 \quad (7)$$

where z_0 is in meters and the subscript i represents the site or the airport. For the airport, z_0 is typically 0.03 m which gives n_a equal to 0.13 while for industrial areas such as around a tank farm z_0 equals about 0.5 m which gives n_s equal to 0.21. Substituting these roughness values into Equation 6 indicates that the wind speeds at typical tank farms may be 28 percent less than those at the airport.

With respect to the wind speeds near the fittings on the roof, the speeds will generally be less than those approaching the tank when the floating roof is lower than the main surrounding tank structure. When the tank is full, the wind speeds on the roof may equal or exceed those upwind of the tank.

3.0 EXPERIMENTAL PROGRAM

3.1 Similarity Criteria

At present, the best method available for estimating the wind speeds on the roof of external floating roof tanks is through the use of wind tunnel modeling. The wind tunnel is, in effect, an analog computer with near infinitesimal resolution and near infinite memory. The basic equations of motion are solved by simulating the flow at a reduced rate and measuring the desired quantity (in this case wind speed, wind direction and pressure). The methods for scaling wind tunnel measurements to full scale and for setting up wind tunnel experiments are summarized in EPA (1981). The criteria that were used for conducting the wind tunnel simulations to determine wind speed, wind direction and roof pressures on EFRT are as follows:

- ensure a fully turbulent wake flow — Reynolds number based on height of tank ($Re_b = U_H H_b / \nu_a$) greater than 11,000 (Actual $Re_b = \sim 60,000$);
- similar geometric dimensions;
- equality of dimensionless boundary and approach flow conditions;

where:

U_H	=	Ambient velocity at top of tank (m/s)
H_b	=	Tank height (m)
ν_a	=	Air viscosity (m^2/s)

3.2 Model Construction

Three 1:100 scale models of external pontoon floating roof storage tanks were constructed. Each model included such details that are common to all pontoon storage tanks (stairs to tank roof, wind breakers around the perimeter of the tank, and rolling ladders). The appropriate number of roof fittings were modeled for each size tank as deemed typical for EFRT in Tables 6 and 7 of API 2517. The actual number of each fitting modeled, shown in Table 1, varied slightly from the prescribed values in some instances in order to maintain geometric symmetry. The overall

full scale dimensions for the three tanks were as follows: 1) Tank 1 — 48 ft height and 200 ft outside diameter; 2) Tank 2 — 48 ft height and 100 ft outside diameter; and 3) Tank 3 — 48 ft height and 48 ft outside diameter. Figures 1 through 3 provide site and elevation plans for the three tanks. The tanks were constructed so that the roof could be adjusted to different heights.

3.3 *Wind Tunnel and Test Setup*

Appendix A describes CPP's atmospheric wind tunnel and the instrumentation that was used to collect the data. In brief, a hot-wire anemometer was used to measure the wind speed and turbulence intensity, miniature wind vanes were used to document the wind direction, and mean and fluctuating pressures were obtained using differential pressure transducers.

Prior to testing the tank models, a uniform roughness pattern was installed in the wind tunnel upwind of the location where the tank models were placed. The roughness was designed to simulate the roughness approaching a typical tank farm or industrial area (surface roughness length of 0.5 m). Mean velocity and turbulence intensity profiles were obtained using a hot-wire velocity sensor (see Appendix A for description) to verify that the profiles match those that would be observed in the atmosphere. The results of these profiles are shown in Figure 4.

Different wind directions were tested, since some of the roof details (i.e., stairs) will cause wind speeds to vary with wind direction at each point on the roof. Sixteen directions were selected to be consistent with typical wind frequency distribution summaries provided by the National Weather Service so that the results can be readily used to compute average speeds and directions on the roof for a given site climatology. North (0 degrees) was arbitrarily set for each tank as shown in Figures 1, 2 and 3, such that the gauger's platform was positioned in the southeastern quadrant.

3.4 *Wind Direction*

After the boundary layer approaching the model test area was documented, the tank models were installed, one at a time, in the wind tunnel. Initial flow visualization tests were conducted to develop a qualitative understanding of the flow over the tank roof. During the visualization tests, small flags were placed throughout the roof surface of the tanks at each of the measurement

locations shown in Figures 5a, b and c. Tests were conducted for each tank at three different roof heights for the 16 different wind directions. The local wind direction at each measurement location was recorded on videotape and still photographs. A listing of the flow visualization test plan is provided in Table 2. Subsequent placement of the velocity probes were based on the results of the visualization.

The roof top wind directions are reported in terms of the relative direction with respect to the approach flow with the tank orientated at 0 degrees (north). For example, a relative wind direction of 0 degrees indicates that the flow at that location is in the same general direction as the approach flow, while a wind direction of 180 degrees indicates complete flow reversal.

All wind direction analysis was based on visual interpretation of the still photographs. Multiple photos were reviewed to provide an estimate of the average wind direction at each location.

3.5 Wind Speed

Wind speed measurements were made at the measurement locations shown in Figures 5a, b and c using a hot-wire anemometer probe (see Appendix B for experimental procedures). Since the tanks are symmetric, except for the spiral stairway on the exterior of the tank shell, symmetry was used to reduce the total number of velocity measurements for the smaller two (100 ft and 48 ft) tanks. The tabular results presented in this report only include velocity data for locations where measurements were actually taken. The velocity profiles and contours, however, were generated by assuming that the velocity at locations where measurements were not obtained were equivalent to their symmetrical partner, where measurements were taken. On average, 20 locations were tested for each tank at each of the 16 wind directions and three roof heights. Table 3 lists the velocity measurement test plan for the three tanks.

All roof top velocities are reported in terms of a non-dimensional mean velocity. This parameter is the ratio of mean velocity at the fitting (U_{mean}) divided by the approach velocity at a nearby airport or NWS facility (U_a). The airport velocity was obtained from the reference velocity simulated in the wind tunnel using the following expression:

$$U_a = \frac{U_{ref} Z_a^{n_a} 2000^{n_s - n_a}}{Z_{ref}^{n_s}} \quad (8)$$

where:

Z_{ref}	=	Full scale reference height (328 ft)
Z_a	=	Wind speed measurement height at the airport in feet (typically 33 ft)
U_{ref}	=	Reference wind speed simulated in the wind tunnel in mph
U_a	=	Wind speed at the airport in mph
2000	=	Top of atmospheric boundary layer in feet
n_s	=	Wind speed power law exponent at the site
n_a	=	Wind speed power law exponent at the airport

The non-dimensional mean velocity (U_{mean}/U_a) is equivalent in model and full scale, therefore, the average full scale wind velocity at any location on the EFRT roof can be obtained by multiplying the average wind speed at the nearby weather station by the velocity ratio presented in this report. That is:

$$U_{mean_f} = U_{a_f} \left(\frac{U_{mean}}{U_a} \right)_m \quad (9)$$

where:

subscript f	=	full scale
subscript m	=	model scale

3.6 Roof Pressures

The pressure transducers used were Microswitch differential transducers. Reference pressures were obtained by connecting the reference sides of the 8 transducers to the static side of the pitot static probe. In this way, the transducer measured the instantaneous difference between the local pressures on the surface of the tank roofs and the static pressure at the reference velocity measurement location above the model.

All pressure measurements are reported in terms of the mean pressure coefficient:

$$C_{p_{mean}} = \frac{\Delta P_{mean}}{\frac{1}{2} \rho U_a^2} \quad (10)$$

where ΔP_{mean} is the pressure difference $(p - p_r)_{mean}$ measured by the pressure transducer and $\frac{1}{2} \rho U_a^2$ is the dynamic pressure at the airport. The mean pressure coefficient represents the mean of the instantaneous pressure differences between the roof top pressure tap and the static pressure in the wind tunnel, non-dimensionalized by the dynamic pressure at the nearby NWS facility.

The mean pressure coefficient can be used to calculate a full-scale pressure differential by multiplying the coefficient by the dynamic pressure at the nearby weather station, as:

$$\Delta P_f = C_{p_{mean}} \left(\frac{1}{2} \rho U_a^2 \right)_f \quad (11)$$

3.7 Quality Control

To ensure that accurate and reliable data were collected for the roof top velocity and pressure measurements, the following quality control steps were taken:

- calibration of flow measuring device with soap bubble meter;
- calibration of velocity device with mass flow meter (see Appendix B);
- calibration check between hot-wire and static pitot tube;
- calibration of pressure transducers with oil manometer (see Appendix B);
- comparison of wind tunnel velocity and turbulent intensity profiles with those observed in the atmosphere (see Figure 4);
- visual inspection of pressure data using X-Y plots of each measurement location to check data consistency (see Appendix E);

- visual inspection of velocity data using wind rose plots of each measurement location to check data consistency (see Appendix H).

4.0 RESULTS

4.1 General

The results of the pressure and velocity measurements collected during the course of this study are listed in Appendices C and G, respectively. Wind direction photographs are presented in Appendix F for each data set configuration at the 16 wind directions. The pressure data is reported in terms of a pressure coefficient with the nearby NWS facility used as the reference wind speed for calculating the dynamic pressure. The velocity data has been non-dimensionalized as a ratio of the measured velocity at each fitting divided by the corresponding approach wind speed at a nearby weather station. The following sections discuss the results in greater detail.

4.2 Wind Speed

Roof top contours of the non-dimensional mean velocity data are included in Appendix I. The contours provide a visual indication of the velocity distribution across the tanks. The recirculation region on each of the roof tops can be identified by large areas on the contour plots where the velocity is essentially constant. A comparison of the plots at different roof heights clearly depicts the growth of the recirculation region toward the downwind wall as the roof level is lowered.

Figures 6 and 7 are presented as a summary to Appendix I. In Figures 6a, b and c centerline velocity profiles are shown for each of the three tanks at the three roof levels. The three sets of curves depict the relative magnitude of the wind speed over the fittings from the leading edge of the tank, across the centerline, to the downwind edge of the tank. In Figures 7a, b and c the average velocity contours for the three tanks is depicted. The average contours were obtained using the average mean velocity measured at each point for the 16 wind directions.

The API literature provides no direct comparison for the centerline velocity profiles shown in Figures 6a, b and c. However, a review of the three sets of profiles produce rather interesting results. For all three tanks the wind speed across the roof top is consistently higher when the

roof is at tank height level than it is when the roof is lowered to the intermediate level. This trend does not persist when the roof top is further lowered to the lowest roof height. At this level, the velocities are generally greater than at the mid-level roof height. (A possible explanation for this behavior is presented in Section 4.3.) Figures 6b and c indicate that in certain areas the wind speeds at the lowest height actually exceed those measured at the tank top level.

If the velocity field of the EFRT roofs were independent of wind direction, each of the contours shown in Figures 7a, b and c would consist of concentric circles. It can be noted from the figures that overall the flow is fairly symmetric except for an area near the rolling ladder where the velocity is reduced.

4.3 Wind Direction

The relative roof top wind directions are shown graphically in Figures 8a, b and c and numerically in Table 5. A qualitative analysis of the results indicates that the air flowing over the top of the tanks when the roof height ratio is set at 1.0 (roof at tank height level) remains in the same general direction as the approach flow over the entire span of the roof. For the lowest roof heights the flow has completely reversed, but remains fairly constant over the entire roof. The flow on the intermediate roof heights is mixed. Some flow reversal has begun but it has not fully developed. This mixture of flow direction may result in the reduced wind speeds for the mid-level roof height discussed in Section 4.2. Along the sides of the tanks, for all roof heights and diameters, an annular flow exists where the air generally flows parallel to the tank shell. Exceptions to this are at the leading and trailing edge of the tank where the flow tends to be perpendicular to the tank shell.

4.4 Roof Top Pressures

Initial pressure measurements were made at five roof heights with the tanks orientated at 0 degrees (north) so that three representative roof heights could be selected for the remainder of the testing (see Table 4). The lowest roof height was established as the first height at which the pressure coefficient profiles remain relatively constant as the roof is moved to lower heights (see discussion in Section 2.2). The top roof height was established as the height of the tank, and the

third height was taken as an intermediate height. The results of these preliminary tests are shown in Figures 9a through 9c. The centerline pressure profiles for the 200 ft diameter tank, shown in Figure 9a, indicate that the profiles varied throughout the entire range of roof heights tested. Therefore, roof height ratios of 0.35, 0.8 and 1.0 were selected for all remaining tests of the 200 ft tank. Figure 9b shows a similar trend for the 100 ft tank. Roof height ratios of 0.5, 0.9 and 1.0 were selected for all remaining tests on this tank. With the smallest tank, 48 ft diameter, the centerline profiles for roof height ratios of 0.90, 0.75 and 0.50, as shown in Figure 9c, did not vary significantly. Therefore, roof height ratios of 1.0, 0.90 and 0.75 were selected for all remaining testing of the 48 ft tank.

The centerline pressure profiles shown in Figures 9a, b and c provide a direct comparison between the results presented in this report to those reported by Marchmann (1970). The pressure profiles in Figure 9a can be directly comparable with the profiles presented by Marchmann since the tank diameter to tank height ratios are similar. An evaluation of Figure 9a, which shows both sets of data, indicates that the general shape of the pressure coefficient profiles are equivalent but that the magnitudes differ. There are two possible explanations for this discrepancy. First, the pressure coefficient value is dependent upon the reference wind speed location. The pressure coefficients in this study are based on a wind speed at a nearby NWS facility assuming a 33 ft anemometer height. Marchmann does not specify the reference wind speed location. If it was obtained in an area of slower flow (at a lower anemometer height, for example) this would explain the higher coefficient values. Second, and a more likely explanation, is that Marchmann's tests were conducted using a ground board to simulate the presence of the ground induced boundary layer. While the ground board may replicate the shape of the mean velocity profile, it may not match the atmospheric turbulence intensity. Increased turbulence will enhance mixing of the flow over the top of the tanks, thereby reducing the magnitude of the gradients (and resulting pressure differentials). The atmospheric boundary layer wind tunnel used in this study is specifically designed to model both the velocity and turbulent intensity profiles characteristic of full scale flow.

Roof top pressure contours by wind direction are presented in Appendix D. Figures 10a, b and c summarize the results in terms of average pressure contours for each EFRT tank configuration. The average contours were obtained in a slightly different manner than the average velocity contours discussed earlier in this report. Since the pressure contours include both positive and

negative values, an average at each location over 16 wind directions will produce meaningless results. For example, an area near the edge of the tank that experiences large fluctuations in pressure from negative to positive could have the same overall average pressure as that of a central area which experiences little or no pressure differential at any wind direction. Therefore, the average pressure contours presented in this report were created by fixing the coordinate system to the approach flow rather than to the tank roof such that the approach wind direction was always classified as 0 degrees regardless of the orientation of the tank.

5.0 REVISED METHOD FOR CALCULATING EVAPORATION FROM ROOF FITTINGS

5.1 General

The normalized velocity data presented in this report are provided in two different formats to facilitate the calculation of evaporative losses using either the complex or simple methods described below. The complex method uses the tables of non-dimensional mean velocities provided in Appendix G to determine the appropriate wind speed at a given location for a specific wind direction. The simple method uses the average velocity zones presented in Figures 11a, b and c.

The following sections describe the procedures for calculating the evaporative losses from roof fittings using either the complex or simple method.

5.2 Complex Method

The complex method for calculating evaporative loss potential from roof fittings is an expansion of the current methodology presented in Equations 4 and 5. Instead of assuming that the air flow over the entire roof is equivalent to the approach flow at a nearby airport, as specified in the current procedure, the complex method uses a distinct velocity, calculated from the airport wind speed, for each location and wind direction. The resulting procedure requires a summation of the individual loss factors $(F_{f_{ij}})$, calculated for every fitting at each wind direction sector, to determine the total loss factor for the roof fittings as shown in the following equations:

$$F_{f_{ij}} = \sum_{w=1}^{16} f_w(\theta) \left[K_{a_i} + K_{b_i} U_{\text{mean}_{j_w}}^{m_i} \right] \quad (12)$$

and

$$F_f = \sum_{i=1}^k \sum_{j=1}^x F_{f_{ij}} \quad (13)$$

where:

w	=	Wind direction sector (1 - 16)
$F_{f_{ij}}$	=	Total Loss Factor for Fitting i at location j
$f_w(\theta)$	=	Frequency of wind direction sector w
$U_{\text{mean},jw}$	=	Average wind speed at j location from wind direction sector w
j	=	Fitting location number
x	=	Number of fitting locations

Example calculations for the complex method are presented in Tables 6a and b for a roof manway and slotted guide pole. The overall procedure for calculating the evaporative loss potential using the complex method is as follows:

- Determine which of the 9 EFRT configurations most represents the tank in question, in terms of tank diameter to height ratio and average roof height to tank height ratio.
- Determine the average approach wind speed and frequency of occurrence for each of the 16 wind direction sectors. This data is typically available from nearby NWS facilities. Calm data should be treated using the EPA established procedure (EPA, 1987) by recalculating the frequency of occurrence of all wind directions without the calm data.
- Determine the orientation of the full scale tank with that of the modeled tank and adjust all wind directions accordingly.
- Determine the measurement location from Figure 5 which most represents the location for each fitting on the roof.
- Obtain the K_a , K_b , and m roof fitting loss factors for each type of fitting from Table 5 of API 2517.
- Multiply the average approach wind speed for each wind direction sector by the non-dimensional mean velocity (U_{mean}/U_a) for each location from Appendix G to determine the average wind speed at the roof fitting.

- For wind directional sensitive fittings, consult Figure 8 to determine the wind direction at fitting for each approach wind direction and adjust loss factors as appropriate.
- Calculate the roof fitting loss factor for each fitting and sum together to obtain the total roof fitting loss factor using Equations 12 and 13.
- Calculate the total roof fitting loss potential using Equation 3.

At this time, the complex method is presented for illustrative purposes only and is not yet developed to the point where it can be simply implemented.

5.3 Simple Method

The simple method reduces the total number of calculations required by using an average wind speed for all wind directions, instead of a wind speed for each of the 16 wind direction sectors used in the complex method. Using an average measured wind speed at each fitting and assuming a symmetric velocity distribution over the roof tanks (i.e., neglecting ladder effects) leads to the development of wind speed zones. The average wind speed within each zone can then be used to calculate the loss for a particular fitting. The resulting equation is presented in Equation 14.

$$F_f = \sum_{i=1}^k \sum_{j=1}^l \left[K_{a_i} + K_{b_i} U_{\text{mean}_j}^{m_i} \right] n_{ij} \quad (14)$$

where:

i	=	Fitting type
j	=	Velocity zone
U_{mean_j}	=	Average Velocity in zone j
n_{ij}	=	number of type i fittings in zone j
k	=	number of fitting types
l	=	number of velocity zones

The average velocity zones (Figures 11a, b and c) were created for use with the simple method to determine the average velocity predicted to occur at locations on the roof surface. These zones

were obtained by slicing the average velocity contours (Figures 7a, b and c) along four axes: 0-180 degrees, 45-225 degrees, 270-90 degrees, and 315-135 degrees. The resulting profiles are shown in Figures 12a, b and c. From the average centerline velocity profiles the maximum wind speed at $0.2r$, $0.4r$, $0.6r$, $0.8r$ and $1.0r$, where r is the radius of the tank, for the four axes was established as the wind speed for that zone.

Using the simple method, evaporative loss for an entire set of roof fittings can be calculated from a single table as indicated in Table 7. The overall procedure for calculating evaporative loss potential using the simple method is as follows:

- Determine which of the 9 EFRT configurations presented in this report most represents the tank in question, in terms of tank diameter to height ratio and average roof height to tank height ratio.
- Determine the average wind speed at the nearest local weather station. Values from Table 4 in API Publication 2517 may be used as an approximation.
- Identify the total number of each type of fitting present in each of the velocity zones.
- Obtain the K_a , K_b , and m roof fitting loss factors for each type of fitting from Table 5 of API 2517.
- Multiply the average approach wind speed by the non-dimensional mean velocity (U_{mean}/U_a) for each zone as indicated in Figure 11. The value used should be the greater of the two values on the zone boundary.
- Calculate the total roof fitting loss factor using Equation 14.
- Calculate the total roof fitting loss potential using Equation 3.

5.4 Discussion

The example calculations shown in Tables 6 and 7 provide a direct comparison of the resulting loss factors for the roof manway and the slotted guide pole, using a wind frequency distribution for the Long Beach, California, area. The examples show a difference of 25 percent to 30 percent between the two methods. The loss factors obtained using the complex method in this example were lower than for the simple method, however, this trend may not hold for other types of fittings and wind frequency distributions.

A note of caution, the tanks used in this report all correspond to a full scale height of 48 ft. Using the presented results for tanks which deviate substantially from this height may not be valid due to the non-linearity in the approach boundary layer. It may be acceptable to scale the results for different tank heights, but an investigation into the possibility is beyond the scope of this study.

This study only investigated 9 different tank configurations (3 tank diameters x 3 roof heights). Obviously, the total number of possible configurations is limitless. To obtain conservative loss estimates (i.e., higher than expected) the user should not try to extrapolate wind speed values for tank configuration which fall between those presented in this study. Rather, the configuration on either side of the actual tank which produces the largest values should be used.

6.0 CONCLUSION AND RECOMMENDATIONS

This study has developed two new procedures for calculating evaporative loss potential for roof fittings on External Floating Roof Tanks (EFRT). The first method, identified as the complex method, converts the approach wind speed, as measured by a nearby National Weather Service (NWS) anemometer, to a wind speed at a particular roof fitting for each of the 16 different wind direction sectors. Using these wind speeds, the roof fitting evaporation loss may be obtained for each individual fitting using loss factors presented in the American Petroleum Institute (API) Publication 2517. The total roof fitting loss factor is then obtained as the summation of the individual fitting loss factors. The second method, referred to as the simple method, reduces the complexity of the calculations by establishing wind speed zones on the tank roof. The loss factors for all similar type fittings within each zone can be calculated from a single expression. A limited comparison of the two methods was conducted which showed a 25 percent to 30 percent difference, with the complex method providing lower loss factors. This trend may not occur for all fitting types and wind frequency distributions.

In addition to developing a method for determining the local wind speed over roof fittings, this report also investigated roof top pressure profiles for 9 different EFRT tank configurations. This effort was undertaken to provide preliminary data which may be used in the future to evaluate the current method for determining the rim seal loss factors. The pressure coefficient profiles presented in this report are similar to the results from Marchmann (1970) from which the rim seal loss equations were derived, however, the magnitudes differ. This is primarily attributed to the discrepancy between the turbulence intensity present in the Marchmann study as apposed to the turbulence which is present in a wind tunnel specifically designed to model the atmospheric boundary layer. These new results indicate that further analysis may be needed regarding the rim seal loss equations.

An overall evaluation of the data collected indicates a need for additional testing. An unanticipated phenomena was observed in which the magnitude of the wind speed over the roof top first decreased as the roof was lowered then increased as the roof was further depressed. Additional velocity measurements at various roof height to tank height ratios are necessary to

fully understand the flow characteristics as a function of roof height. With sufficient data, it may be possible to develop a generalized equation for predicting wind speeds at the roof fittings.

7.0 REFERENCES

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FIGURES

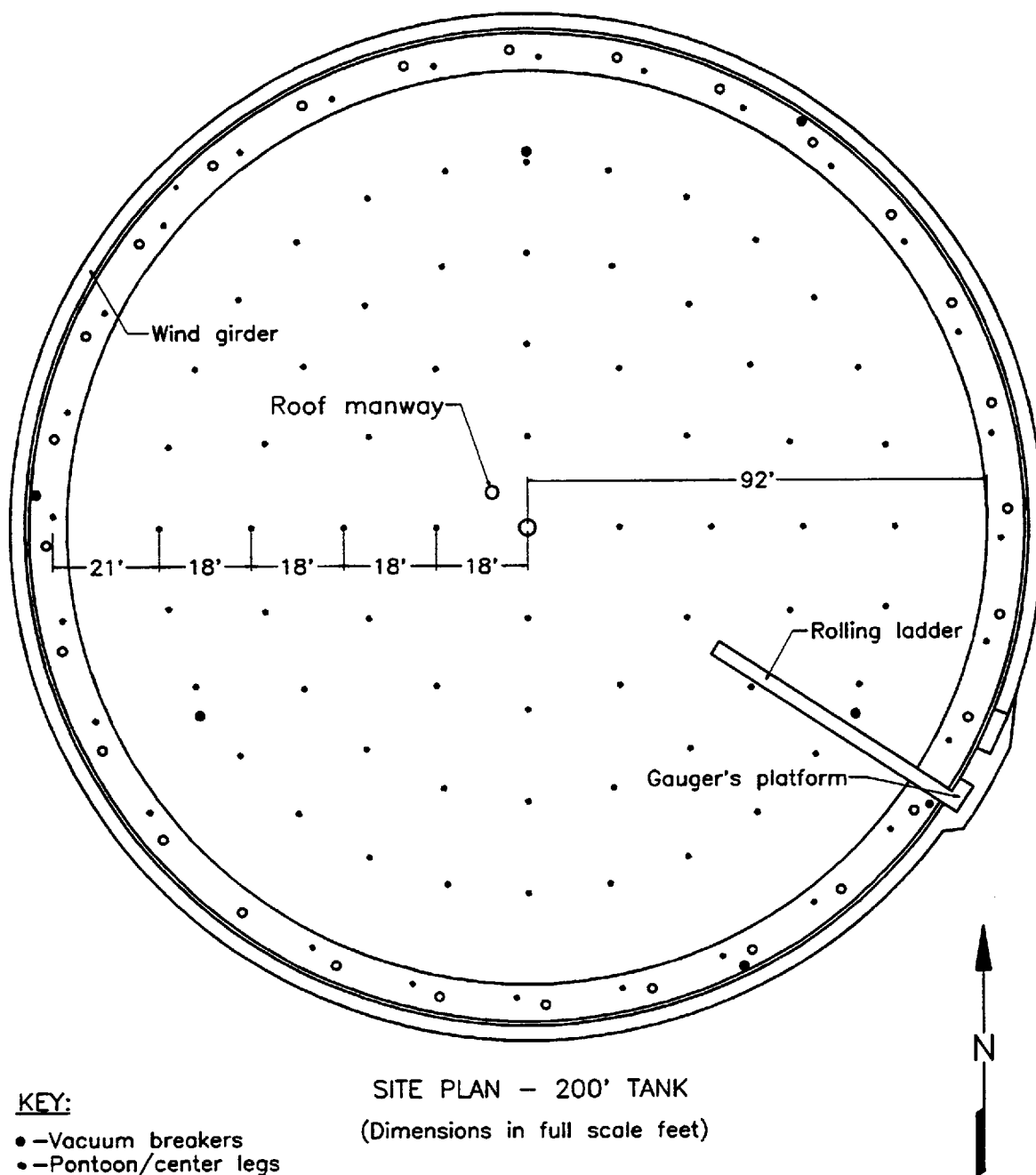
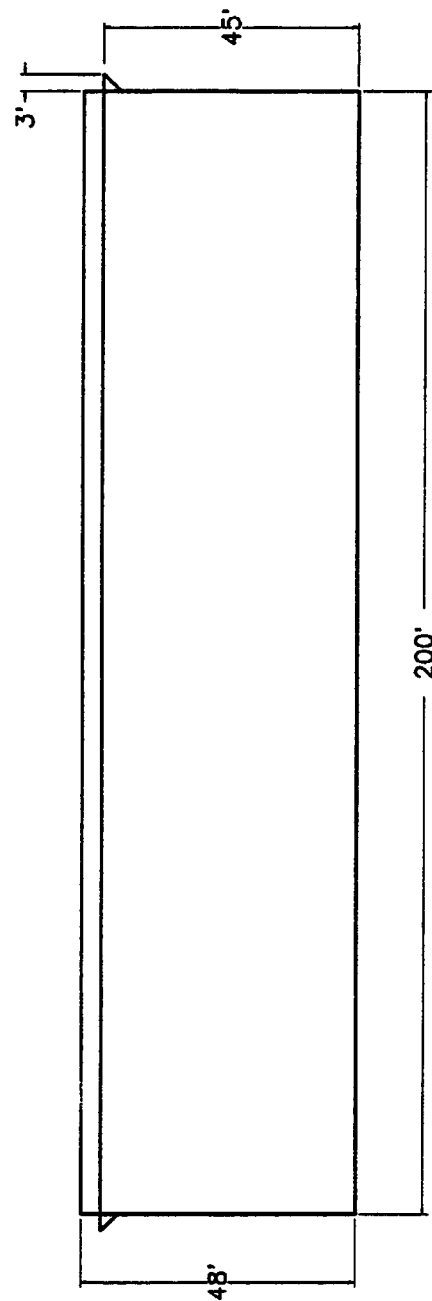
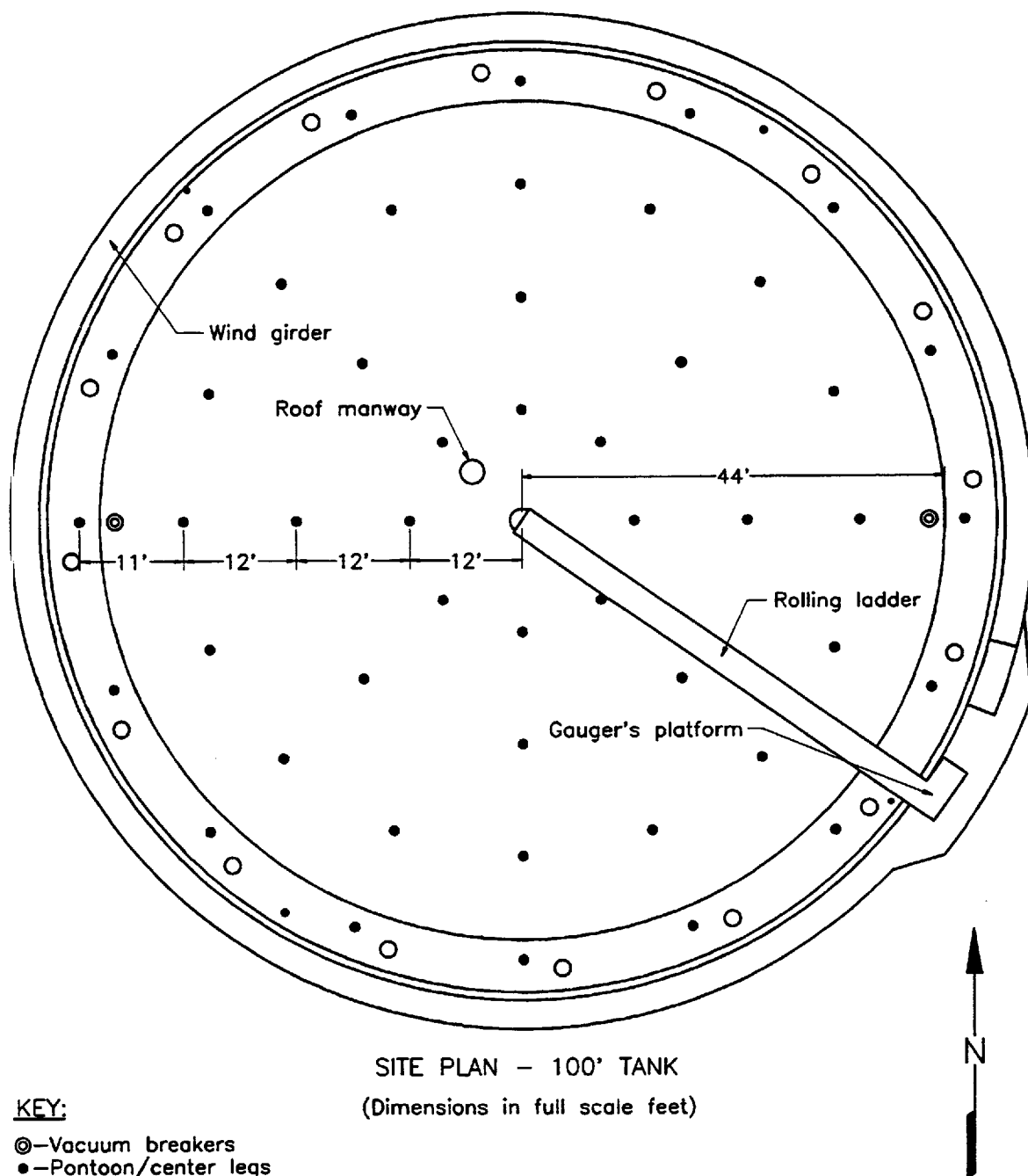


Figure 1a. Site Plan — 200 ft Tank.



ELEVATION — 200' TANK
(Dimensions in full scale feet)

Figure 1b. Elevation — 200 ft Tank.

**KEY:**

- ⊙—Vacuum breakers
- Pontoon/center legs
- Pontoon manways
- ⊙—Gauge well/guide pole
- Rim vent
- ⊕—Gauge hatch

Figure 2a. Site Plan — 100 ft Tank.

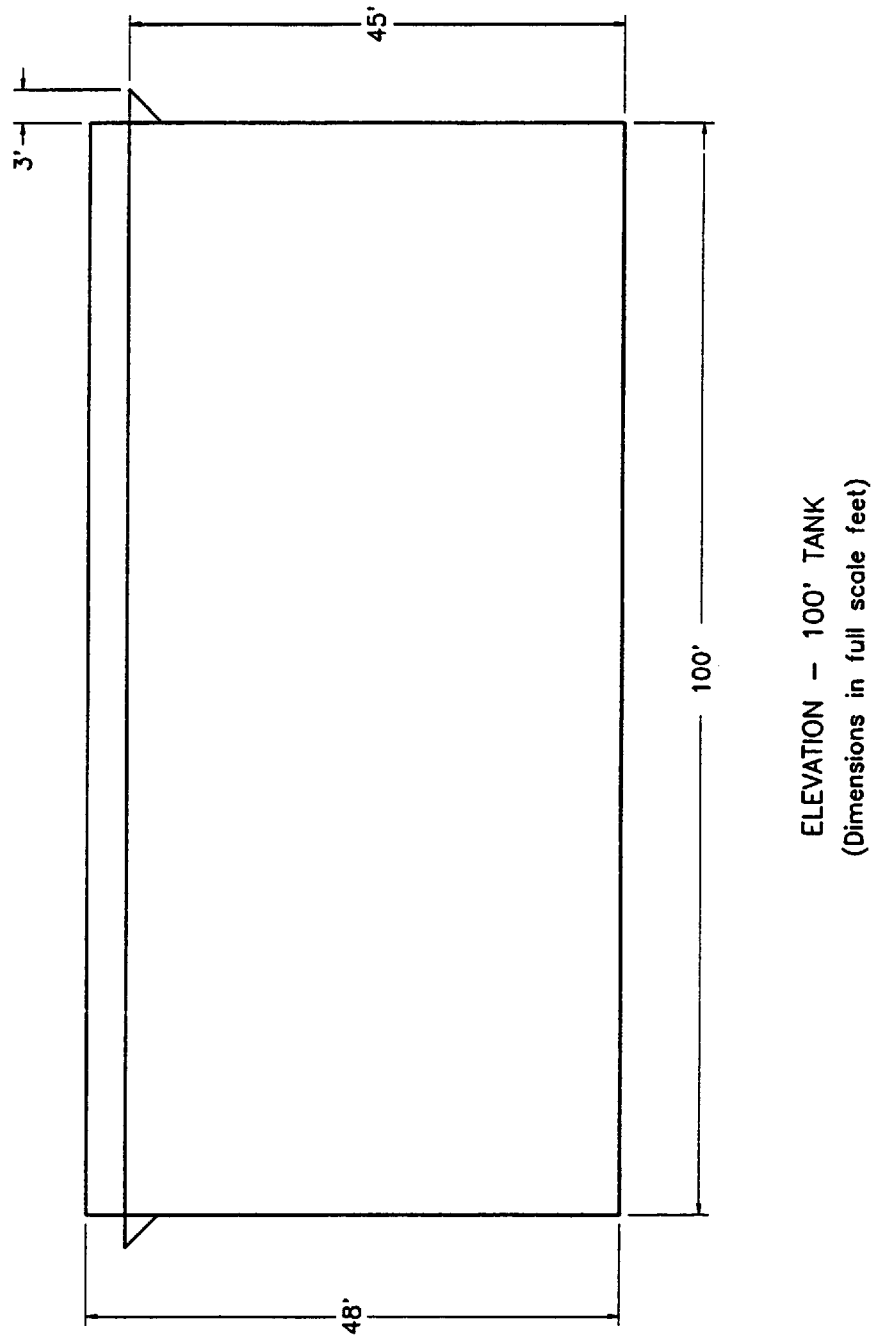


Figure 2b. Elevation — 100 ft Tank.

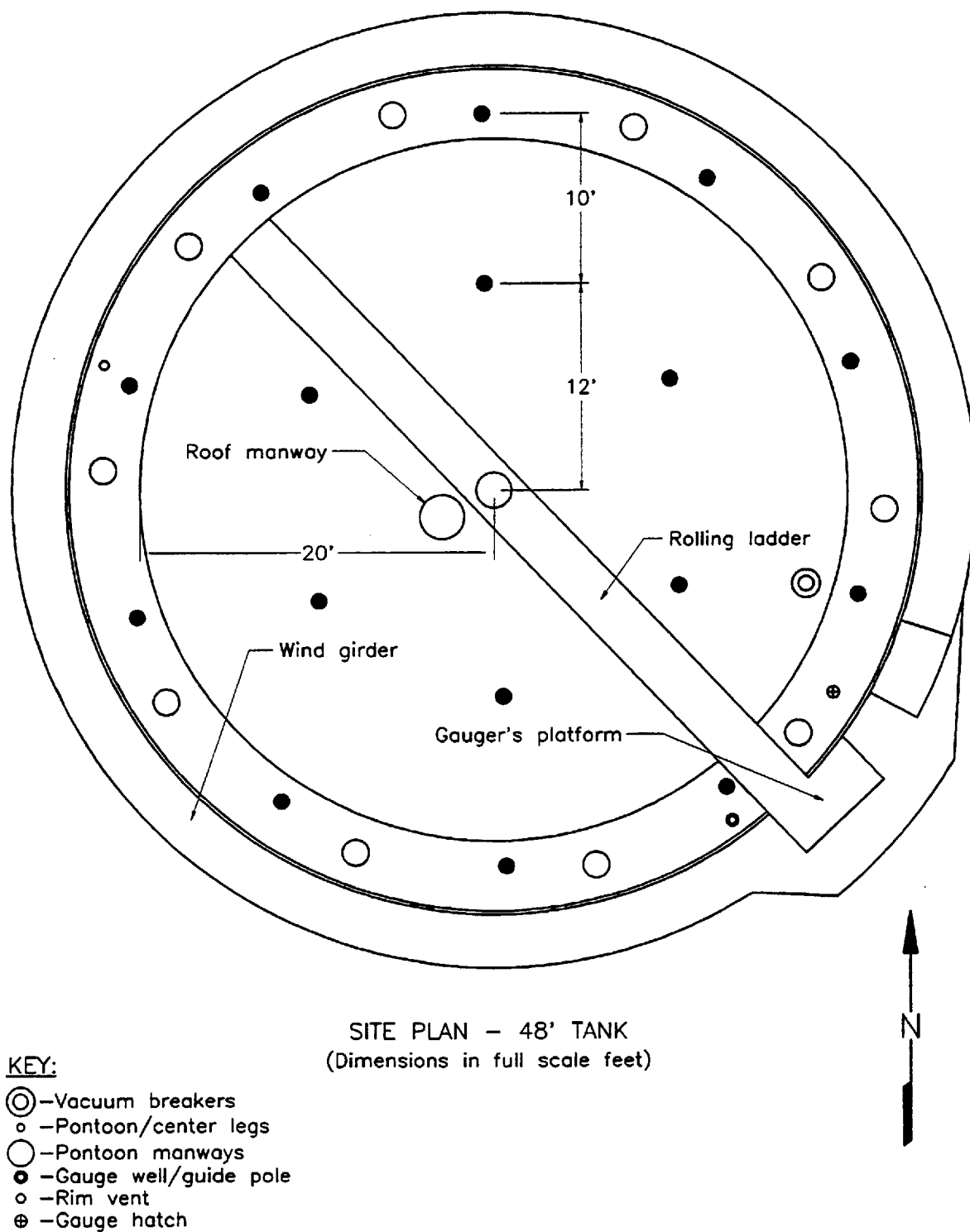


Figure 3a. Site Plan — 48 ft Tank.

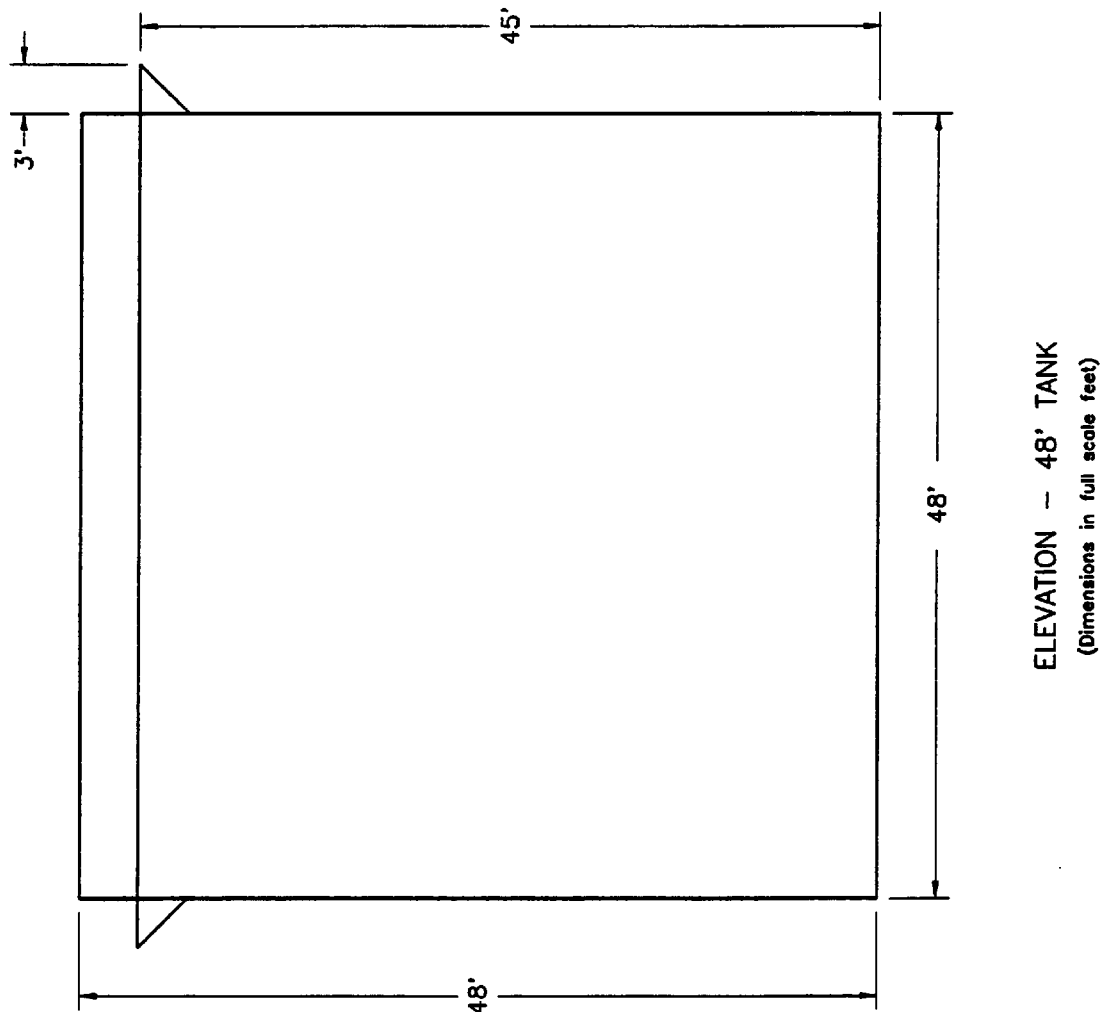


Figure 3b. Elevation — 48 ft Tank.

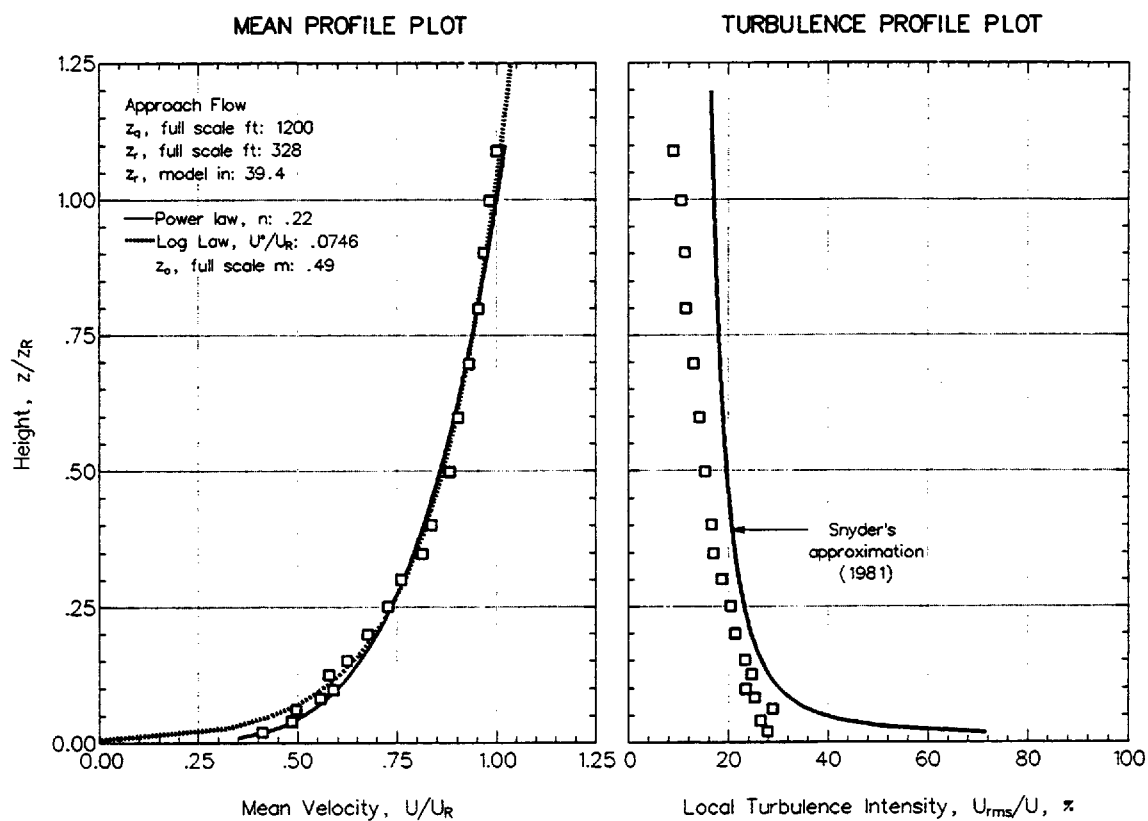


Figure 4. Velocity and Turbulent Approach Profiles.

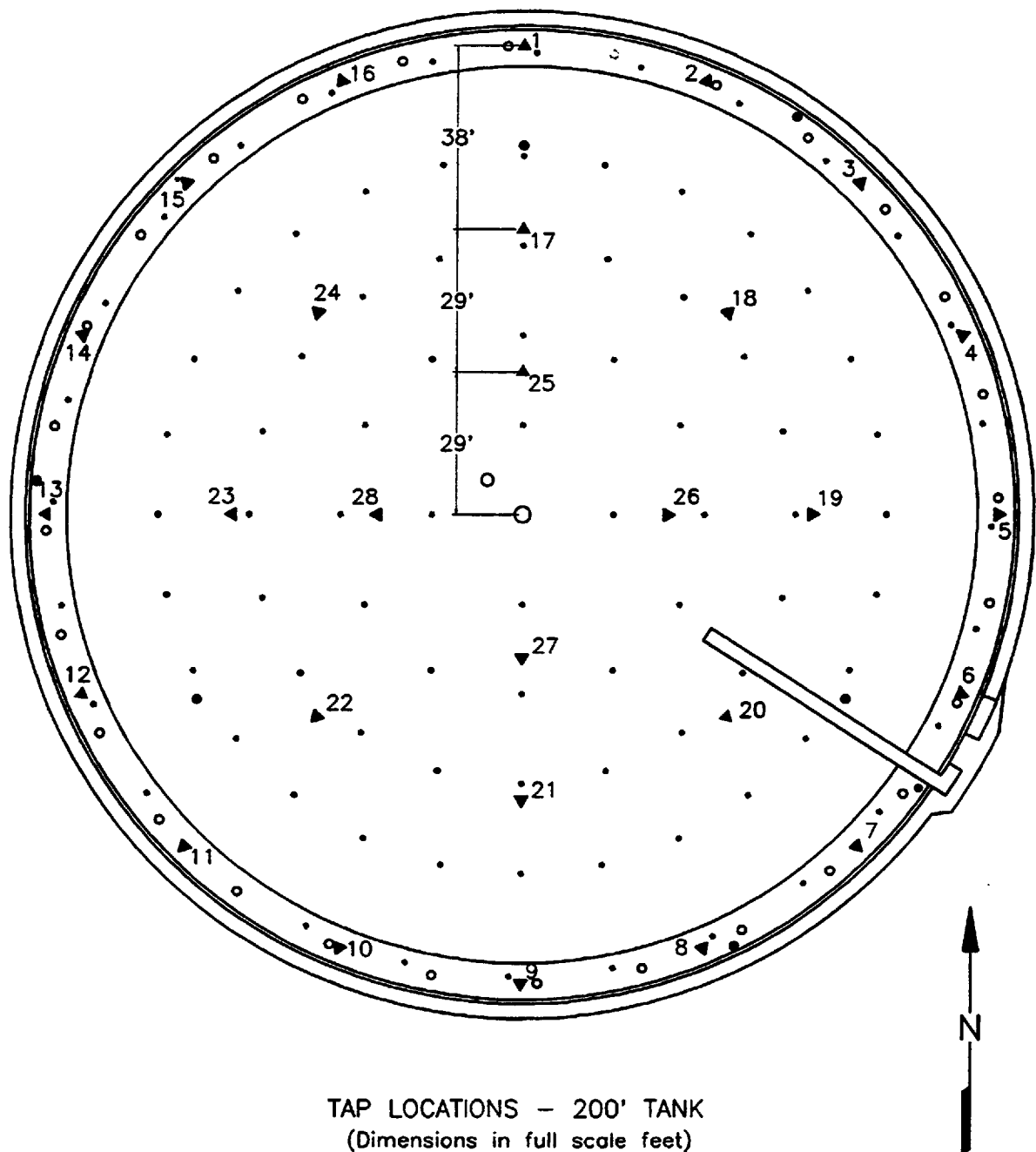


Figure 5a. Wind Speed, Wind Direction and Roof Pressure Measurement Locations —
200 ft Tank.

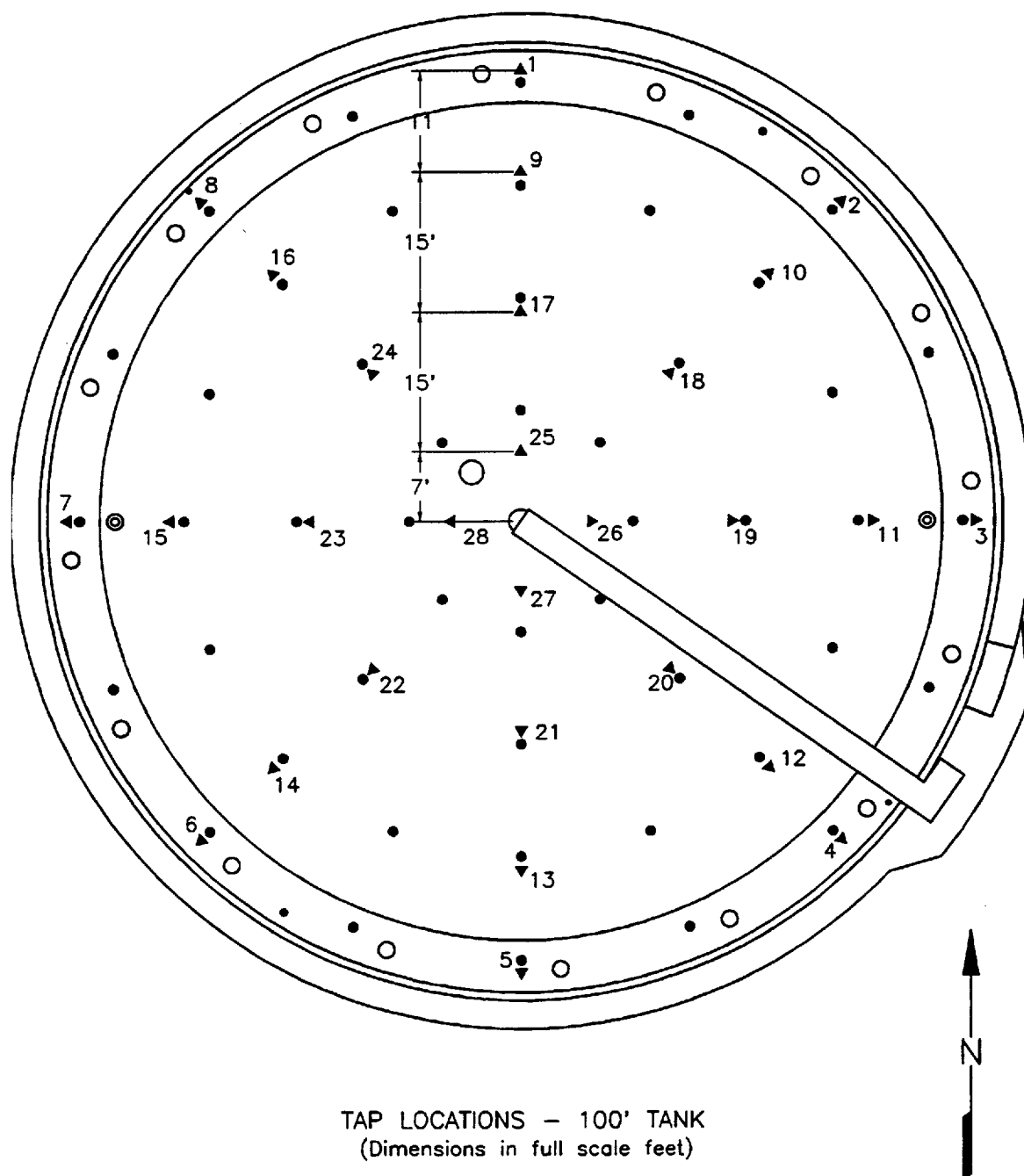


Figure 5b. Wind Speed, Wind Direction and Roof Pressure Measurement Locations —
100 ft Tank.

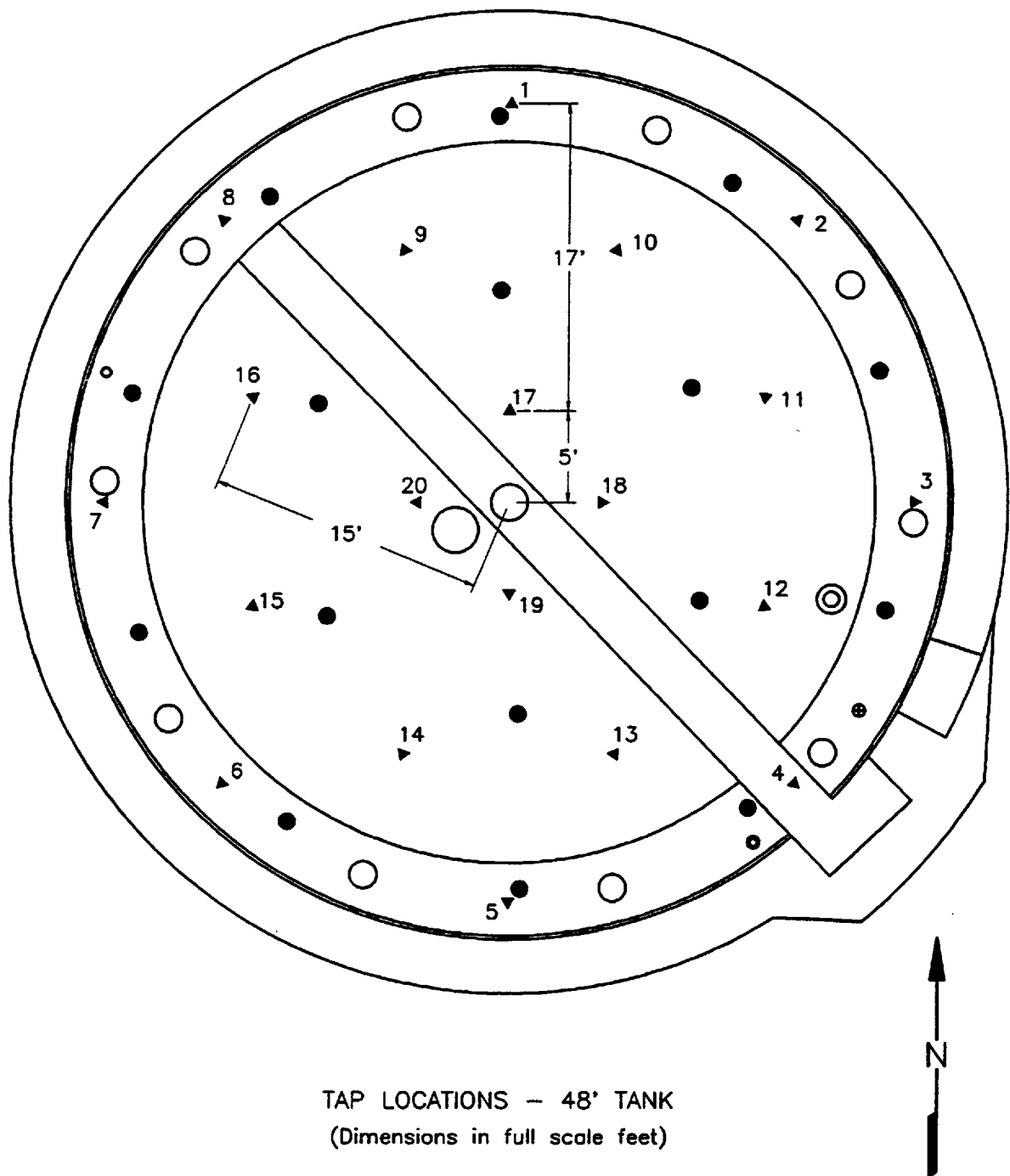


Figure 5c. Wind Speed, Wind Direction and Roof Pressure Measurement Locations — 48 ft Tank.

CENTERLINE VELOCITY PROFILES 200ft Dia Tank

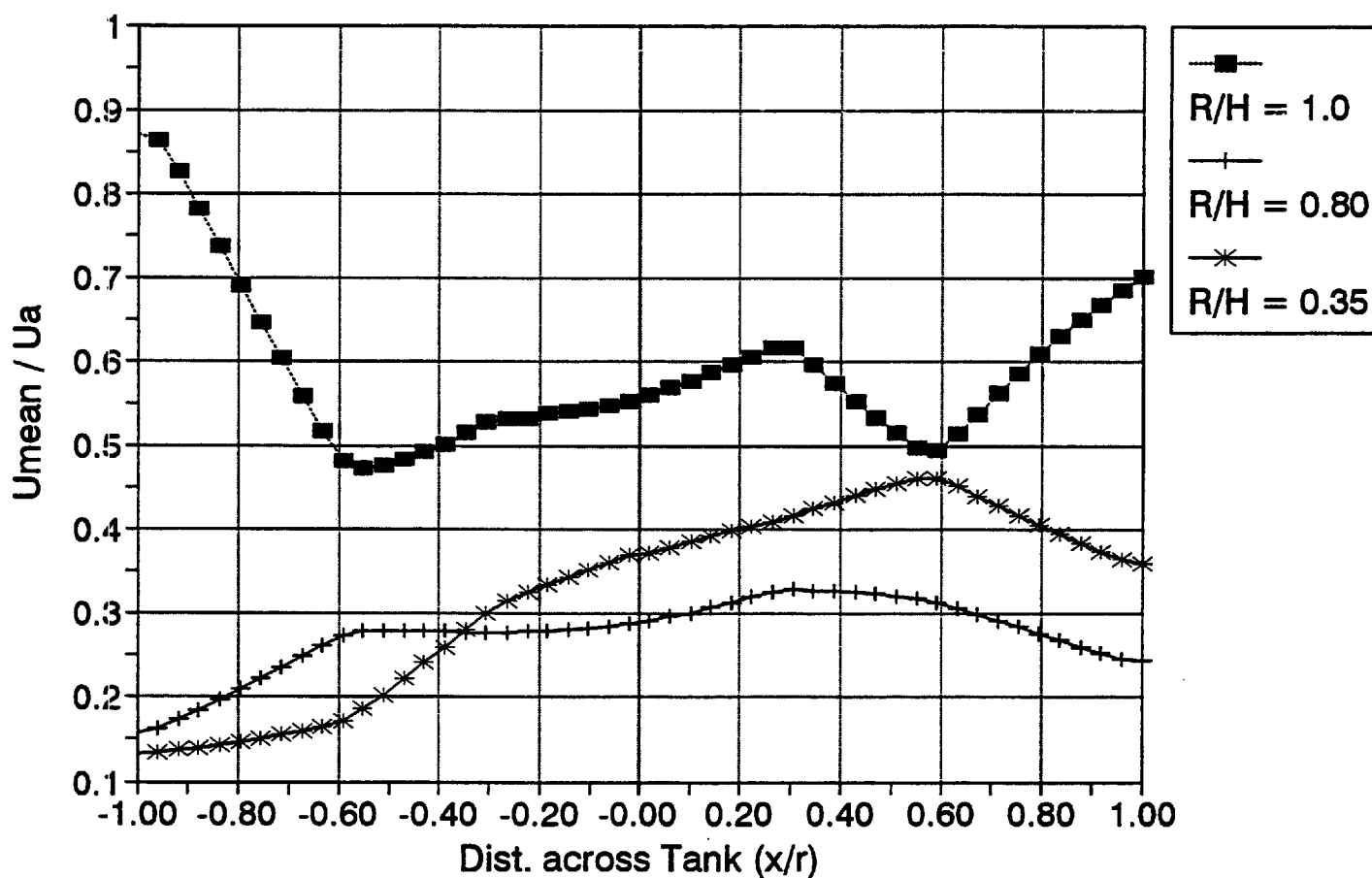


Figure 6a. Non-dimensional Mean Velocity Centerline Profiles — 200 ft Tank.

CENTERLINE VELOCITY PROFILES 100ft Dia Tank

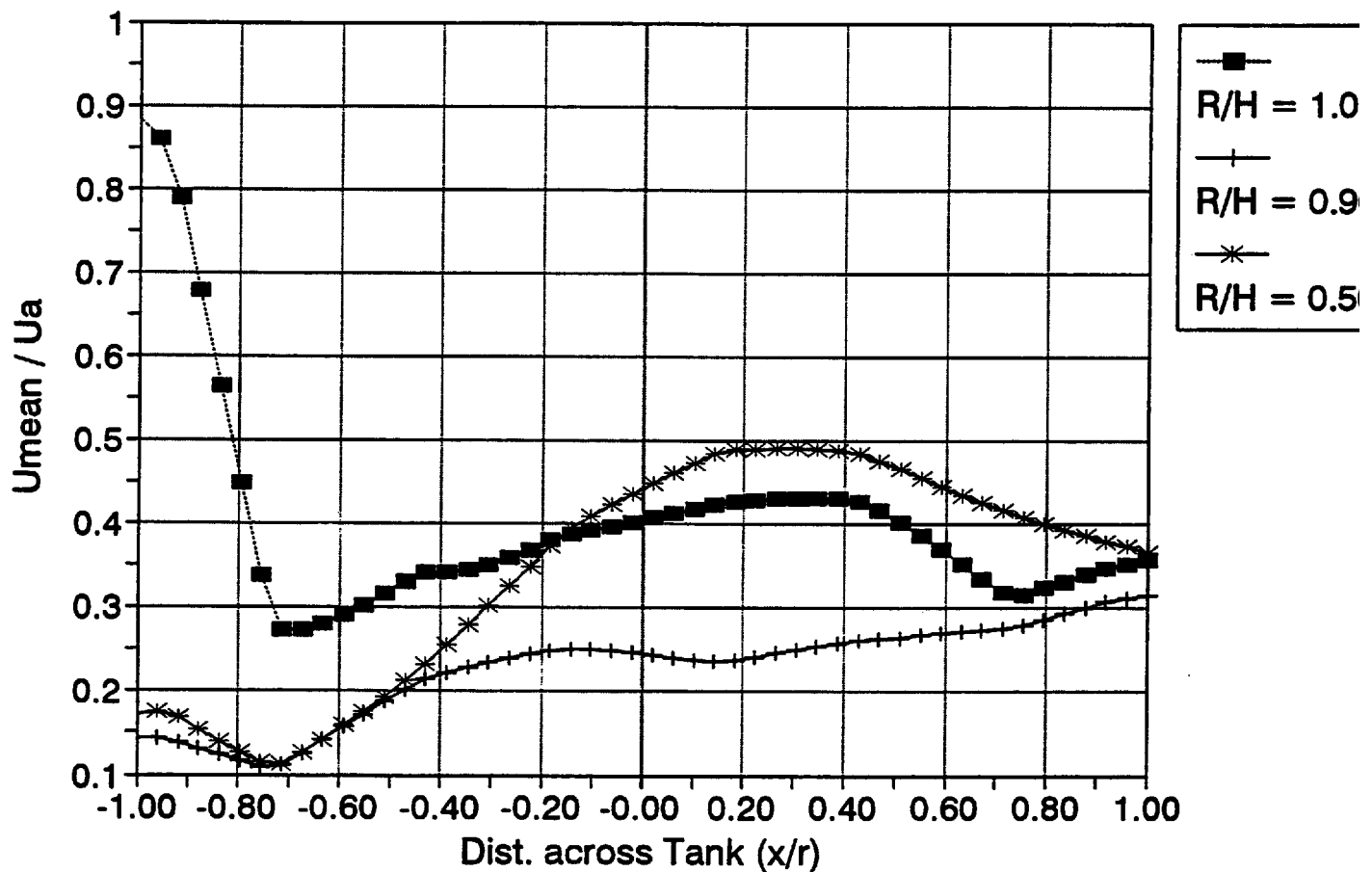


Figure 6b. Non-dimensional Mean Velocity Centerline Profiles — 100 ft Tank.

CENTERLINE VELOCITY PROFILES 48ft Dia Tank

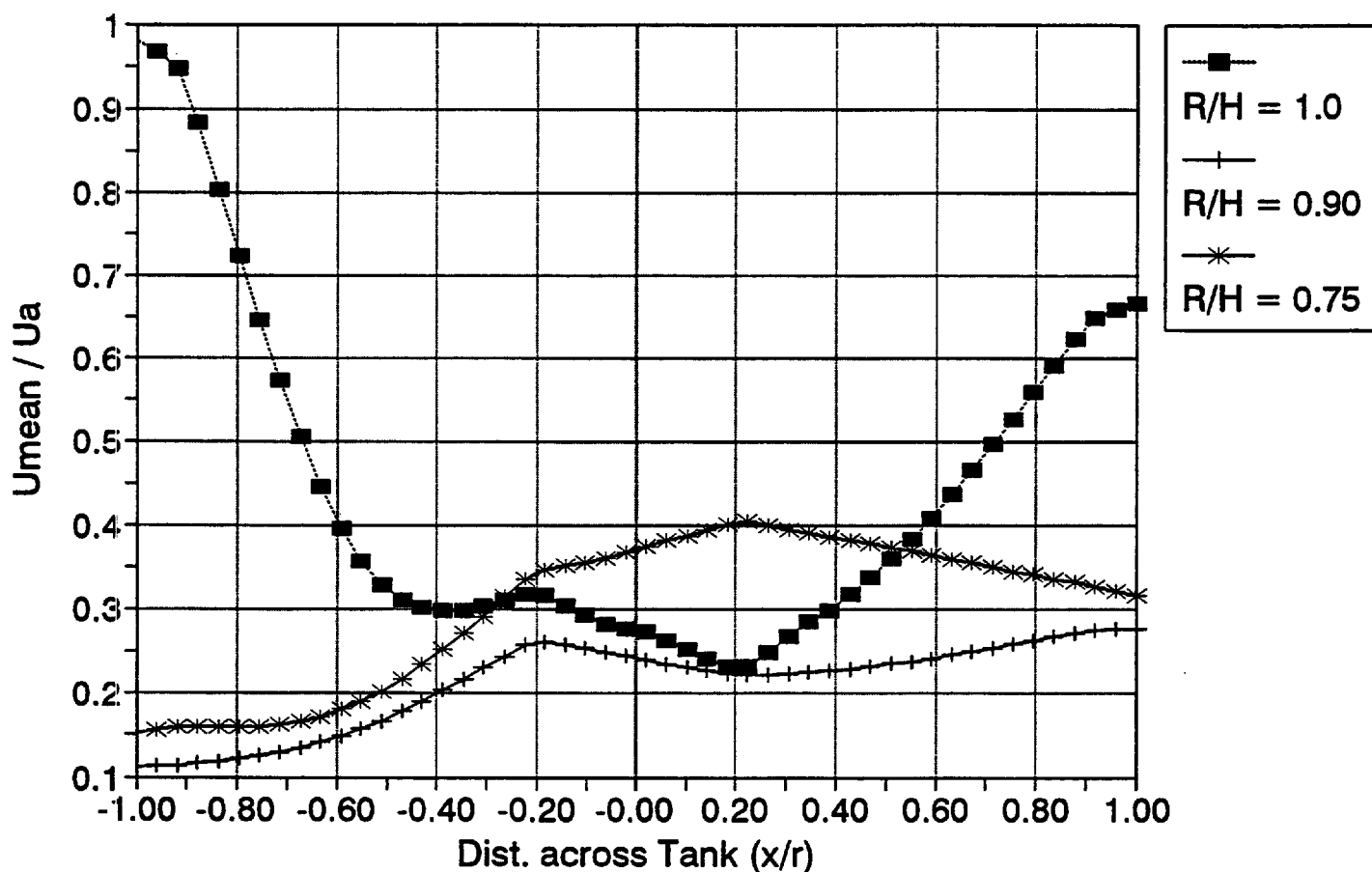


Figure 6c. Non-dimensional Mean Velocity Centerline Profiles — 48 ft Tank.

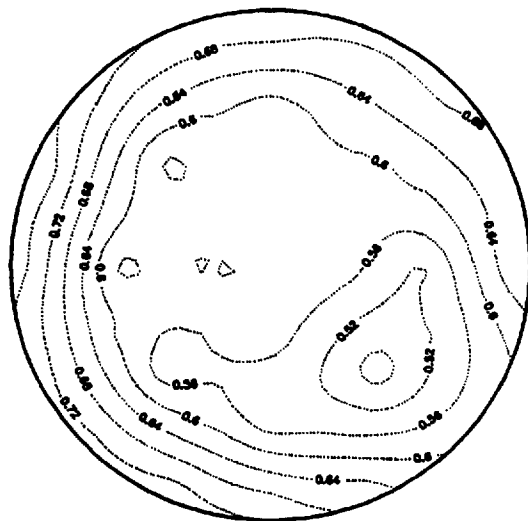
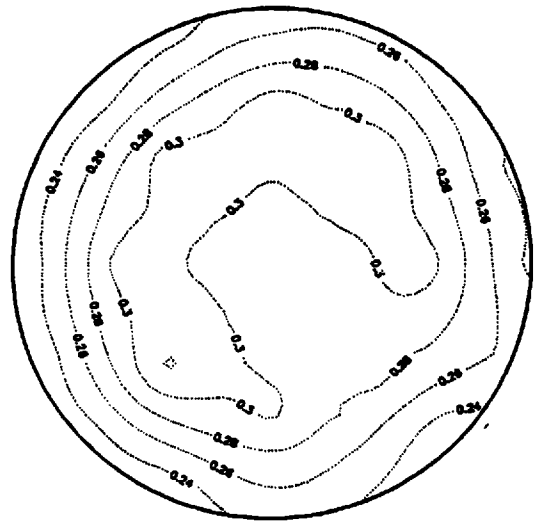
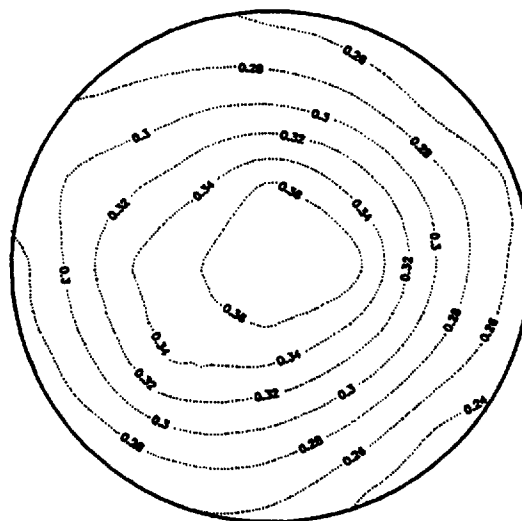
 $R/H = 1.00$  $R/H = 0.80$  $R/H = 0.35$

Figure 7a. Average Non-dimensional Mean Velocity Contours — 200 ft Tank.

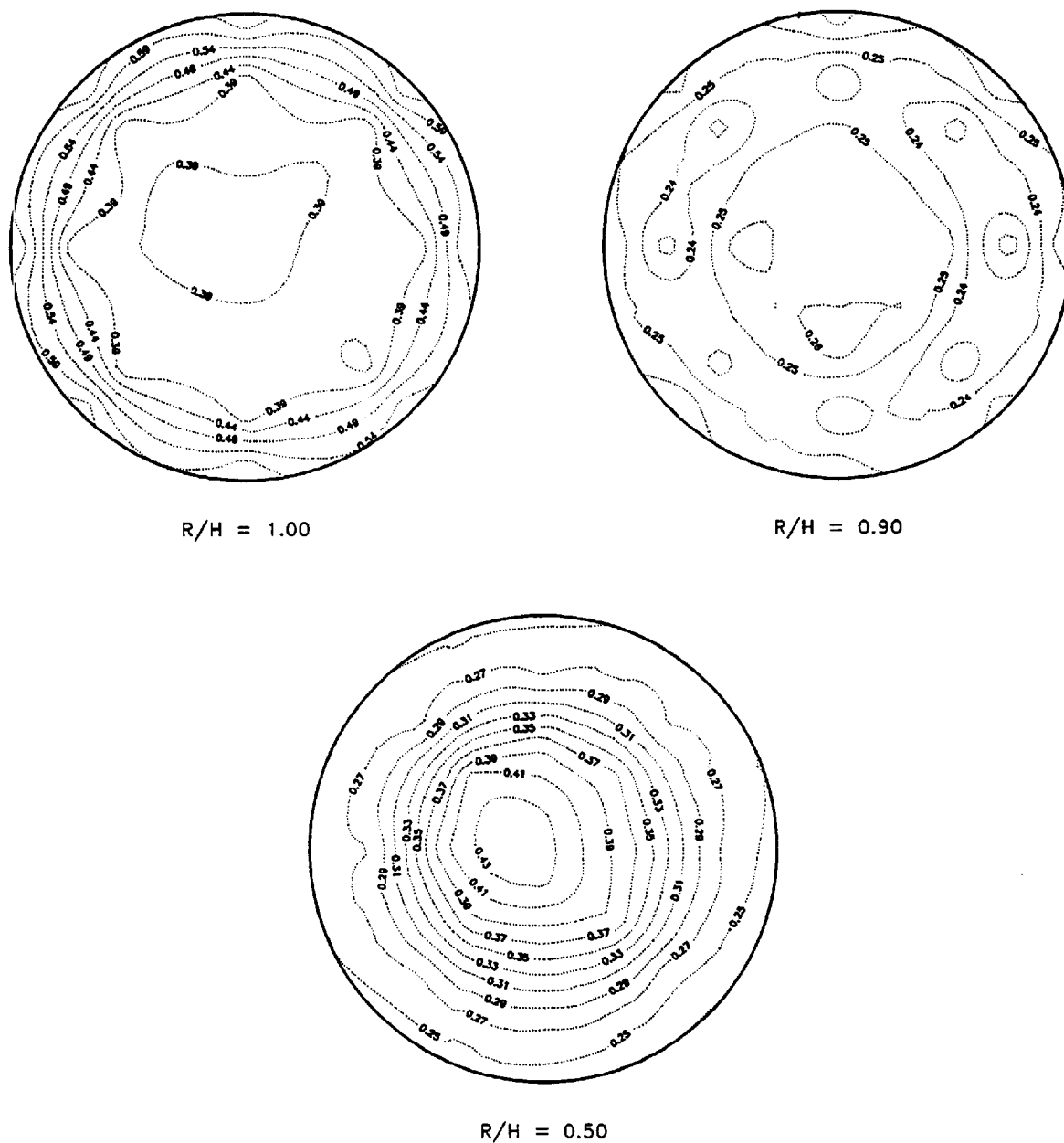


Figure 7b. Average Non-dimensional Mean Velocity Contours — 100 ft Tank