WIND TUNNEL MODELING OF LNG SPILLS

by

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Paper Presented

Session 18
Tuesday, May 9 1:30 p.m.
Liquid Natural Gas II

AMERICAN GAS ASSOCIATION
TRANSMISSION CONFERENCE

Montreal, Canada
May 8-10, 1978

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CEP77-78RNM-DEN-JEC49

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ABSTRACT

Motion in the atmospheric boundary layer can be simulated with sufficient accuracy to make laboratory studies of the dispersal of cold methane plumes resulting from LNG spills useful for planning measures. Performance envelopes have been prepared to identify LNG spill scenarios which may be simulated in meteorological wind tunnels. Satisfactory agreement between diffusion characteristics in the simulated and real atmosphere has been found whenever field data have been available for making comparisons.

Key Words: Vapor, Liquid natural gas, Spill, Hazards, Wind tunnel,
Simulation, Models, Dispersion

WIND TUNNEL MODELING OF LIQUID NATURAL GAS SPILLS

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I. INTRODUCTION

The primary purpose of this paper is to show through basic similarity analysis and comparisons of model and full-scale data that atmospheric transport of dense, cold natural gas clouds can be physically modeled in "meteorological" wind tunnels for a range of real boundary conditions which have great practical importance with respect to liquid natural gas (LNG) spill hazard analysis. The scales most accurately simulated will depend upon model scale, thermal stratification, and wind tunnel characteristics. Comparisons of natural gas concentrations for laboratory model tests of LNG spill configurations ranging in scale from 1:106 to 1:666 and an atmospheric prototype support the arguments for similarity of the physical model. Performance envelopes of a typical large meteorological wind tunnel indicate situations where physical modeling is credible.

A number of controlled laboratory experiments have been prepared previously to evaluate the significance of density on gaseous plume dispersion. Sakagami and Kato (1968) measured diffusion and vapor rise from a small 5 x 10 cm LNG well in the floor of a 50 x 50 cm cross-section x 200 cm length wind tunnel. They confirmed a tendency for the gas to remain concentrated at ground level. Boyle and Kneebone (1972) released LNG on water, precooled methane, and propane in a specially built 1.5 x 1.2 m cross-section by 5 m long asbestos-wall wind tunnel. No attempt was made to scale the atmospheric surface layer velocity profile or turbulence. They concluded room-temperature propane simulated a LNG spill quite well, but the pre-cooled methane runs lofted suggesting to the authors incorrect release temperature or exaggerated heat transfer from the ground surface. Hoot and Meroney (1974) and Hall (1975) considered point source releases of heavy gases in wind tunnels at ground level. Hoot and Meroney found that releasing gases with specific gravities as great as 3.0 only slightly shifted the decay of maximum concentrations with distance despite significantly different plume cross-sections. Hall considered transient and continuous releases on a rough surface (plume height - roughness height) and on up and downhill slopes. Hall reported shallow, wide plumes whose shapes were considerably altered by 1 in 12 ground slopes.

Tests were conducted by Neff, et al., (1976) in wind tunnel facilities to evaluate the rate of dispersion and the extent of downwind hazards associated with the rupture of typical large LNG storage tanks. Concentration and temperature measurements, and photographic records were obtained for different wind speeds, wind direction and constant boiloff rates under both neutral and stable atmospheric stratifications. Subsequent measurements by Meroney, et al., (1977) examined transient releases in similar configurations as well as dense plumes on uphill slopes, and buoyant plume liftoff situations. Different model release gases were used to simulate the behavior of the cold methane plume - heavy isothermal gas mixtures (CO_2, Freon-12 and air, or Argon) or light-cold mixtures (He and N_2).

Since in many parts of the Nation there is the perception that current and planned LNG operations and facilities present an unacceptable risk to the public, the Division of Environmental Control Technology, Department of Energy, has proposed a comprehensive integrated RD & D program. The DOE (1978) program proposes to resolve the LNG safety and contral issues by developing a capability to predict the consequences of an accidental release of LNG.

Further tests to illuminate the missing physics of LNG spill behaviour would be appropriate. The purpose of this paper is to provide guidance for the planned use of wind tunnels to study the structure of vapor plumes resulting from LNG spills on land for a realistic range of meteorological variables, plus source and site features. Wind tunnel laboratory measurements permit a degree of control of safety, meteorological, source and site variables not often feasible or economic at full scale. Nonetheless simulation of dense plume behavior is not automatic, a discussion of some of the problems associated with this approach follows.

II. LABORATORY SIMULATION OF DENSE GAS PLUMES

The reliability of the use of wind tunnel shear layers for modeling atmospheric flows has been demonstrated by several investigators (Cermak, 1975). Specific problems associated with the dispersion of cold natural gas plumes have been previously discussed by Meroney, et al., (1976).

Wind tunnel flow characteristics and physical size are such that most of the requirements for similarity with the atmosphere can only be approximated with varying degrees of accuracy. This does not eliminate the possibility of making useful studies of diffusion by means of small-scale models but limits the range of length scales and thermal conditions for which the studies are feasible. Each similarity requirement will be examined in an effort to determine the necessary approximations imposed by the physical model and the resulting limitations imposed upon the dispersion studies.

Grouping independent variables which govern LNG vapor dispersion into dimensionless parameters with air density, ρ_a, wind velocity at tank height, U_H, and tank height, H, as reference variables and where Q is volume boiloff rate of methane and ρ_g is methane gas density yields

$\frac{U_H H}{\nu}$ - Reynolds number

$\frac{\rho_a U_H^2}{g(\rho_a - \rho_g)H}$ - Modified Froude number

$\frac{\rho_g Q^2}{\rho_a U_H^2 H^4}$ - Momentum ratio

$\frac{\rho_g - \rho_a}{\rho_a}$ - Gas density ratio

$\frac{Q}{U_H H^2}$ - Non-dimensional spill rate

$\frac{g(T_H-T_o)H}{T\,U_H^2}$ - Bulk Richardson number of inverse atmospheric Froude number

$\frac{\delta}{H},\frac{D}{H},\frac{h}{H},\frac{k}{H}$ - Various length scale ratios associated with shear layer thickness, δ, dike diameters, D; dike height, h; and roughness length, k.

For a model test to be completely representative of the full-scale event, values of at least these ten dimensionless numbers plus similarity in approach flow velocity and turbulence profiles should be the same in the model test as at full-scale. Since it is not possible to retain exactly the same values of all these numbers at full- and model scale some latitude must be tolerated. (Indeed in many cases the full-scale values are not even well defined.) One may accept variation in these parameters to the extent that such lassitude does not jeopardize the representativeness of the model.

The Reynolds number cannot be made equal for model and prototype for scales ranging from 1:100 to 1:600. Fortunately equality is not required if the magnitude and quality of the shear layer turbulence is similar to the full-scale--hence the use of specially designed meteorological wind tunnels (Cermak, 1975). It is possible to obtain full-scale values of the remaining non-dimensional parameters by reducing the reference velocity, U_H, to very low values (of the order of 0.2 m/s to simulate a 3 m/sec full-scale wind) and increasing the atmospheric temperature difference (T_H-T_o) as necessary. In some cases investigators modify the density ratio $\rho_a-\rho_g/\rho_a$ to permit the use of larger and more convenient values of U_H (Hall, et al., 1975). Unfortunately this also modifies inertial effects, time scale ratios, and volume dilution rates so this is not proposed herein.

Previous experiments by Hoot and Meroney (1974), Bodertha (1961), Van Ulden (1974), and Boyle and Kneebone (1973) have confirmed that the Froude number is the parameter which governs plume spread rate, trajectory, plume size and entrainment when gases remain negatively buoyant during their entire trajectory. In the case of spills of LNG buoyancy of the plume will be a function of both mole fraction of methane and temperature. Thus, depending upon the relative rate of entrainment of ambient gases versus rate of thermal transport from surrounding surfaces the state of buoyancy may vary from negative to positive.

To clarify this point Meroney, et al., (1976) proposed a simple one-dimensional mixing model including considerations of conservation of energy and mass plus thermodynamic definitions of mixture properties. Sample computations for methane spills suggest qualitative behavior as shown in Figures 1 and 2. If the relative humidity is zero, depending upon A (heat transfer rate) the behavior of buoyancy forces will vary markedly with dilution. Figure 3 depicts the potential variation in dense plume behavior in situations where the atmosphere is dry and stable with an insulative cool boundary versus a moist unstable day with a hot conductive boundary. Thus on initial consideration it is important to model not only the initial Froude number of a plume but its characteristic variation with dilution also. Room temperatures of air-Freon-12 mixtures (or alternatetively carbon dioxide or argon) will behave like the A = 0 case, and a release of nitrogen cooled to 217°K will perform similar to a marginally buoyant methane spill (A = 1/3). For A = 0 but finite values of humidity it is seen in Figure 2 that humidities greater than 60 percent may produce marginally buoyant plumes as a result of adiabatic mixing. A mixture of helium and nitrogen ($x_{He} = 0.5$, $x_{N_2} = 0.5$) adjusted to produce a molecular weight equal to that of methane, which is cooled to methane boiloff temperatures (112°K) should simulate the variable Froude number characteristic but with a nonflammable gas.

Consideration of the heat transfer conditions suggests that surface heat transport from the ground will be a function of the Boundary Fourier Modulus function

$$\text{BFM} = \frac{\text{Plume time over surface}}{\text{Time constant to change surface temperature}}$$

Examination of the range of this term suggests that for field and wind tunnel configurations BFM << 1.0; thus, it is sufficient to maintain the surface temperature on the laboratory boundary constant. Since the turbulence characteristics of the flow are dominated by roughness, upstream profile shape, and stratification one expects that the Stanton number in the field will equal that in the model, i.e., $St_m = St_p$, and heat transfer rates in the two cases should be in proper relation to plume entrainment rates.

Earlier measurements (Neff, et al., (1976) and Meroney, et al., (1977) now suggest that heat transfer effects may be small over the significant time scales associated with non-calm situations (i.e., $U_p > 1$ m/sec); hence gas density should be adequately simulated by isothermal high molecular weight gas mixtures. This agrees with the result independently reported by Boyle and Kneebone (1972) that room temperature propane simulated an actual LNG spill quite well.

It is tempting to try to simulate the entire spill phenomenon in the laboratory including spill of LNG into the dike, heat transfer from the tank and dike materials to the cryogenic fluid, phase change of the LNG and subsequent dispersal of natural gas downwind. Unfortunately, the different scaling laws for the conduction and convection suggest that markedly different time scales occur for the various component processes as the scale changes. Since the volume of dike material storing sensible heat scales versus the cube of the length scale whereas the pertinent surface area scales as the square of the length scale one perceives that heat is transferred to a model cold plume much too rapidly within the model containment structures. This effect is apparently unavoidable since a material having a thermal diffusivity low enough to compensate for this effect does not appear to exist. Since calculations for the full scale situation suggest minimal heating of a cold natural gas plume by the tank-dike structure it suffices to cool the model tank-dike walls to reduce the heat transfer to a cold model vapor.

III. WIND TUNNEL PERFORMANCE ENVELOPE

It is instructive to consider the operational constraints on current large wind tunnels to determine those field situations which may be satisfactorily simulated. Operational limitations include:

1. The inability of most large wind tunnels to function satisfactorily at very low wind speeds (< 0.1 m/sec). At low wind speeds the wind tunnel becomes sensitive to small disturbances, both external and internal, which lead to unrealistic perturbations of the mean flow.

2. The associated inability to maintain large Reynolds number. When the characteristic Reynolds number falls below 3000 wake turbulence no larger remains similar to field conditions.
3. A minimum spatial resolution for concentration measurements of ± .25 cm. Minimum pertinant resolution in the field may be ± 1 m.
4. Lateral interference with a spreading dense plume by wind tunnel walls. Current wind tunnel facilities have widths up to about 4 m. One can estimate wind tunnel wall interference by utilizing the spread formulae proposed and tested against field spills by Van Ulden (1974). The expression relates spread to boiloff rate, wind speed, and gas density.

The four operational limitations listed above have been incorporated into the performance envelopes shown in Figures 4 and 5. Wind tunnel wall interference lines are conservative for the situation shown since they represent steady boiloff interaction at a distance of 20 diameters downwind of a 0.3 m diameter model source. Only the highest boiloff rates for the larger field situations must be eliminated from consideration and all relevant stable stratification conditions can be provided.

IV. WIND TUNNEL EXPERIMENT

Scale models (1:200 and 1:400) of two typical LNG storage tanks have been studied in meteorological wind tunnels for a neutral and stable atmosphere.

Tank facilities considered include a low dike configuration (39 m diameter tank, 36 m high surrounded by a 6.6 m high dike 93 m by 100 m in area) and high dike configuration (73 m diameter, 39 m high tank surrounded by a concentric 81 m diameter dike 24 m high). Also examined was a 1:106 scale model of Test 044 from the Capistrano Series supported by the American Gas Association (1974) which involved a spill into a 25 meter diameter by 0.5 meter high dike. The 1:200 scale models shown in Figure 6 utilized for pre-cooled He-N_2 releases incorporated liquid nitrogen reservoirs within their structure to reduce temperature difference between the gas mixture and the tank/dike walls. This device prevented exaggerated heat transfer effects as discussed previously.

Concentration measurements were performed in the Colorado State University Meteorological Wind Tunnel. This tunnel, especially designed to study atmospheric flow phenomena, incorporates special features such as an adjustable ceiling to reduce model blockage, temperature controlled air stream and boundary walls, and a large test section (1.8 m x 1.8 m cross-section by 29 m long) to permit equilibrium development of typical atmospheric shear layer characteristics.

All results presented herein are modeled with pure carbon dioxide or pre-cooled helium-nitrogen mixtures adjusted to simulate boiloff densities of methane. Turbulent diffusion of simulated LNG plumes for the three different LNG tank and dike complexes, two model gas mixtures, two atmospheric stratifications, three scale ratios, and a number of wind speed and boiloff rate combinations were studied. Mean concentration measurements were obtained for as many as 23 different sample points distributed over a ground level zone up to 250 m wide, 50 to 2000 meters long, and in the vertical over a height of 0 to 100 meters. A schematic of the model configuration and the associated concentration measuring equipment is shown in Figure 7.

To obtain an accurate prediction of the extent of hazard associated with the vaporization of LNG, the model should simulate the variable boiloff rate of the gaseous methane characteristic to that of the spill configuration. Typical boiloff curves for the prototype situation along with the actual model gas release for the Capistrano Test 044 are presented in Figure 8. These gas flow rate curves were obtained by use of a programmed cam to close a micrometer needle valve controlling the flow of simulation get at a predetermined rate.

The transient nature of the boiloff rates simulated necessitated the use of a fast response, temperature compensated concentration transducer. An aspirated dual film probe was designed for this project. As noted in Figure 9, dual films operated at different current levels permitted compensation for temperature drift, while a flared inlet reduced the noise of pressure fluctuations. Calibration suggests a noise level of 0.1% by volume CO_2 and an upper frequency response of 1000 Hz.

V. TEST PROGRAM RESULTS

The purpose of this paper is to demonstrate the feasibility of utilizing wind tunnels as a tool to study dense gas spills rather than present comprehensive results. Extended discussions of the LNG spill cases examined at CSU have been prepared by Neff, et al., (1976), Meroney, et al., (1977). Meroney and Neff (1977), R & D Associates, et al., (1977), and Harsha (1976).

Test results consisted of (1) a qualitative study of the flow field around the different tank and dike localities by visual observation of the plume released from the model area; and (2) a quantitative study of gas concentrations produced by the release of a tracer from the model area.

1. Continuous Boiloff Release Results

Continuous releases of CO_2 made from the high and low tank-dike configurations agree well with the earlier Freon-12-N_2 simulations performed by Neff, et al. (1976). The dimensionless concentration coefficient $X\bar{U}H_T^2/Q$ scales with non-dimensional downwind distance x/H_T (Figure 4). The dimensionless concentration coefficient curves asymptotically approach the slope of those given by the appropriate Pasquill diffusion category for both neutral and stable flow. No significant differentiation appeared between CO_2 and pre-cooled HeN_2 simulation gases.

2. Variable Boiloff Release Results

Figure 5 displays the dilution time history of the Capistrano Model Test and the field situation superimposed for the typical test position (320', 0', 0'). The time and magnitude of highest concentrations observed at most of the test locations is in good agreement. The arrival time of the transient plume at the measurement location is reasonably close. The model does not, however, predict the large and intermittent concentration peaks at late times as observed in the field. Such variations are likely due to gustiness and changes in wind direction recorded for the field case but not present in the wind tunnel, or possibly the long time response of the field sensors utilized (10 seconds).

Transient measurements made downwind of the typical high and low dike configurations reveal that mean concentration measurements made at constant boiloff rates appear to upper bound conditions to the maximum concentrations detected during a transient boiloff situation.

Motion in the atmospheric boundary layer can thus be simulated with sufficient accuracy to make laboratory studies of cold methane gas dispersal useful for planning measures. Satisfactory agreement between diffusion characteristics in the simulated and real atmosphere has been found whenever field data have been available for making comparisons.

VI. SUMMARY

The wind tunnel can simulate a range of conditions associated with vapor transport and dispersion downwind of LNG spills. Scaling criteria suggest that existing size facilities can simulate spills boiling from areas up to 150 meters diameter. Wind speeds at a 10 m reference heights may be simulated from lower magnitudes of 0.7 m/s for spills of 15 m diameter (scale ratio = 1/50) or 3.0 m/s for spills of 150 m diameter (scale ratio = 1/500) upwards. A desirable local resolution of 1 m limits model scale ratios to ~ 1/500 or less. Lateral spreading in a typical 4 m width wind tunnel may further limit maximum equivalent volume production of cold vapor at a given wind speed (i.e., for scale ratios = 1/200 a liquid boiloff rate of 25.4 mm/min produces wall interference effects beyong downwind distances of 300 m for velocities less than 3.0 m/sec). For rates less than liquid boiloff rates of 2.5 mm/min there should be no additional constraint. Vapor dispersion downwind of LNG spills has been reproduced for selected cases of the 1974 AGA landspill program. Wind tunnel simulation provides a design tool to pre-scale trajectories and dispersion of cold LNG vapor clouds. This method will provide guidance for instrument placement and numerical model development during the 50 million dollar program planned by DOE to guide LNG hazard analysis.

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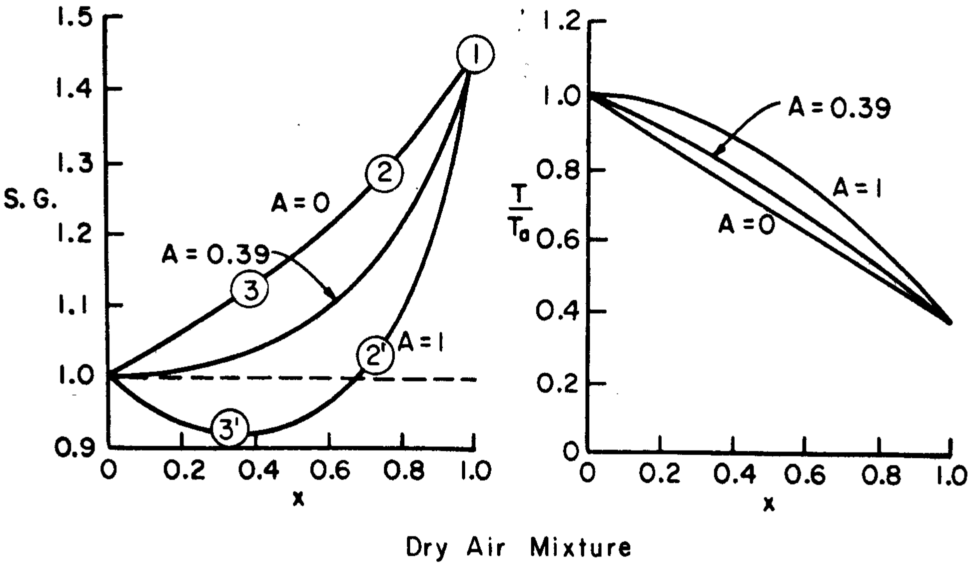

Figure 1. Theoretical Behavior of LNG Plumes

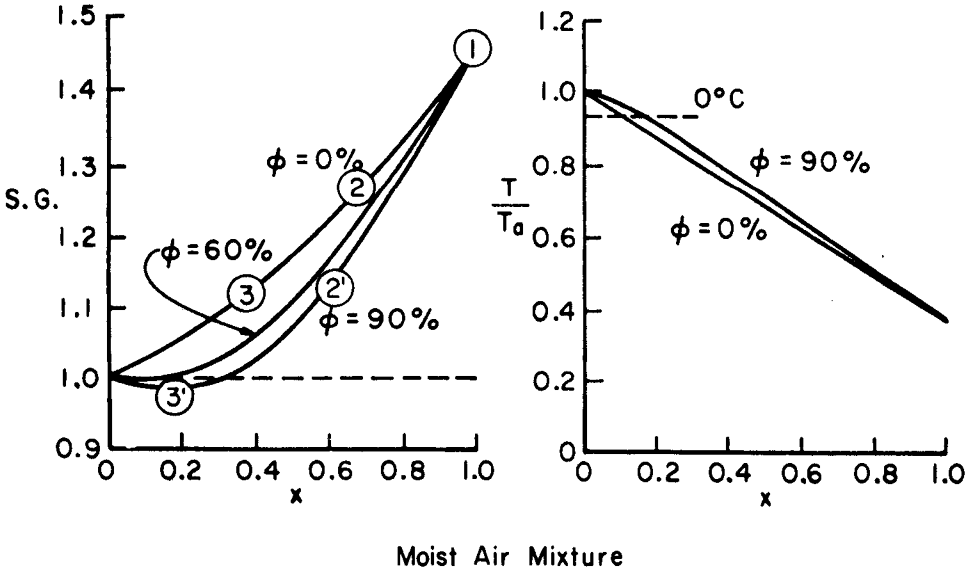

Figure 2. Theoretical Behavior of LNG Plumes

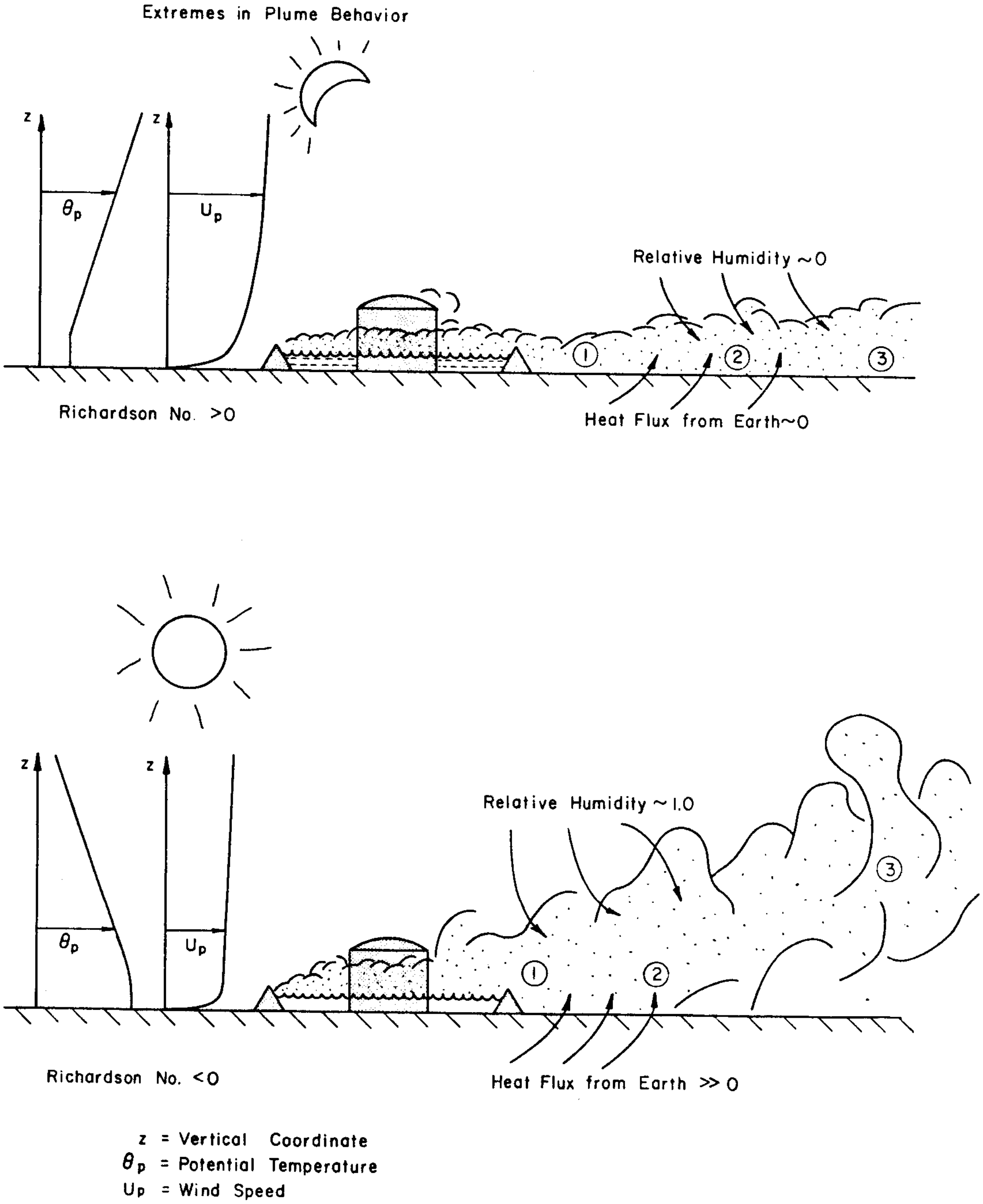

Figure 3. Extremes in Natural Gas Plume Behavior

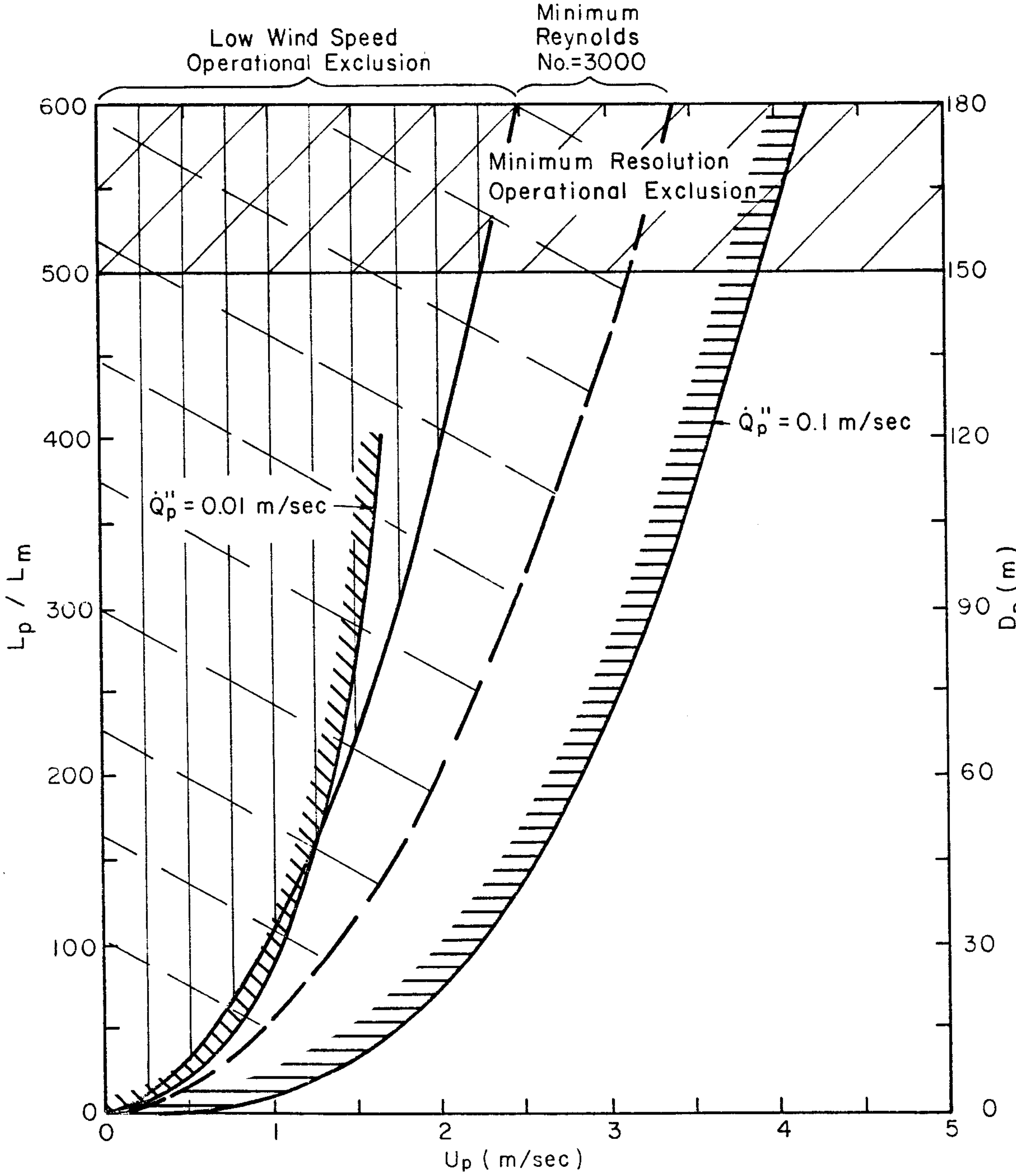

Figure 4. Performance Envelope to Simulate LNG Spills - Constant Boiloff Conditions

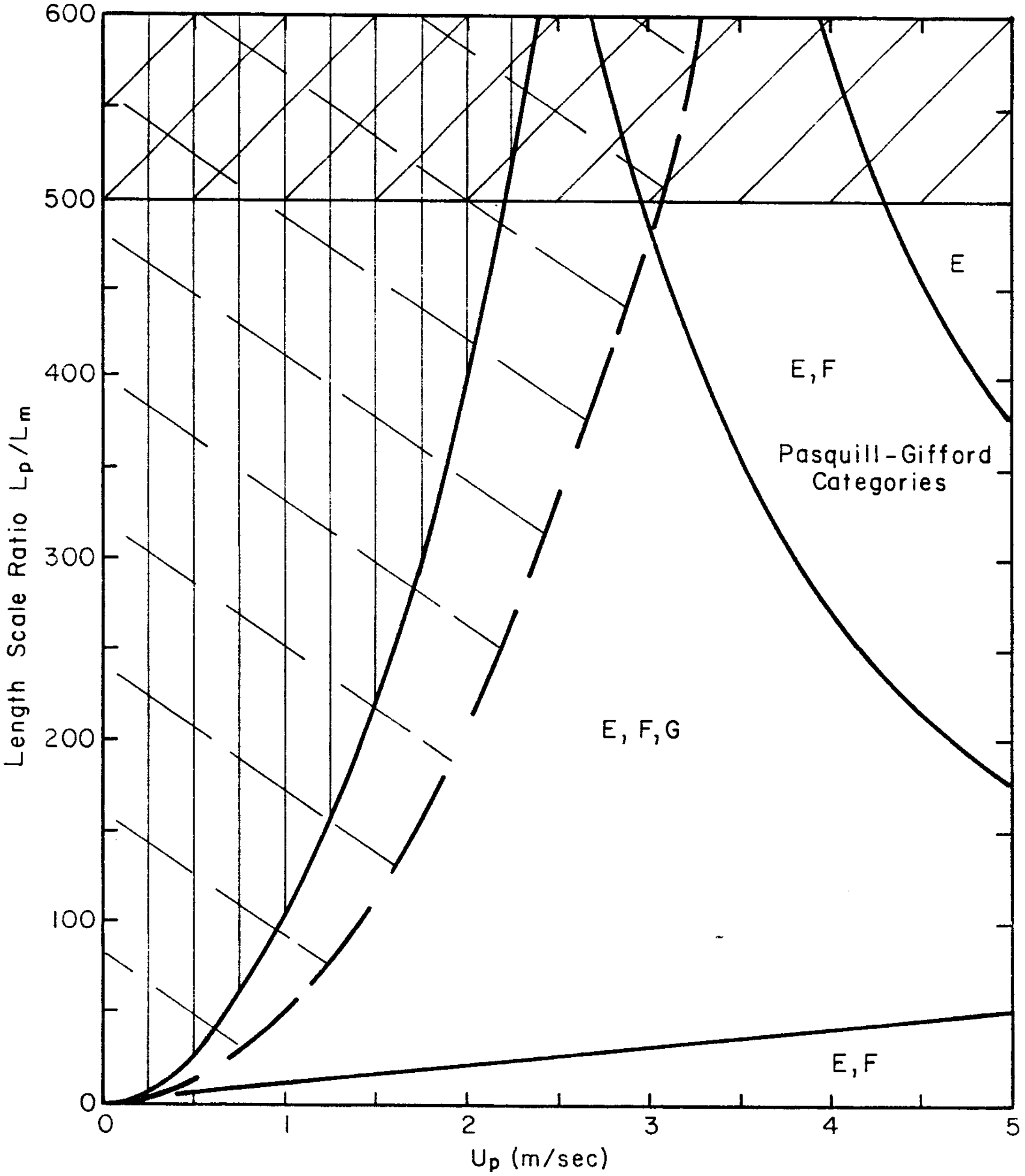

Figure 5. Performance Envelope - Atmospheric Stable Stratification on Envelope for Dm = 0.3 m

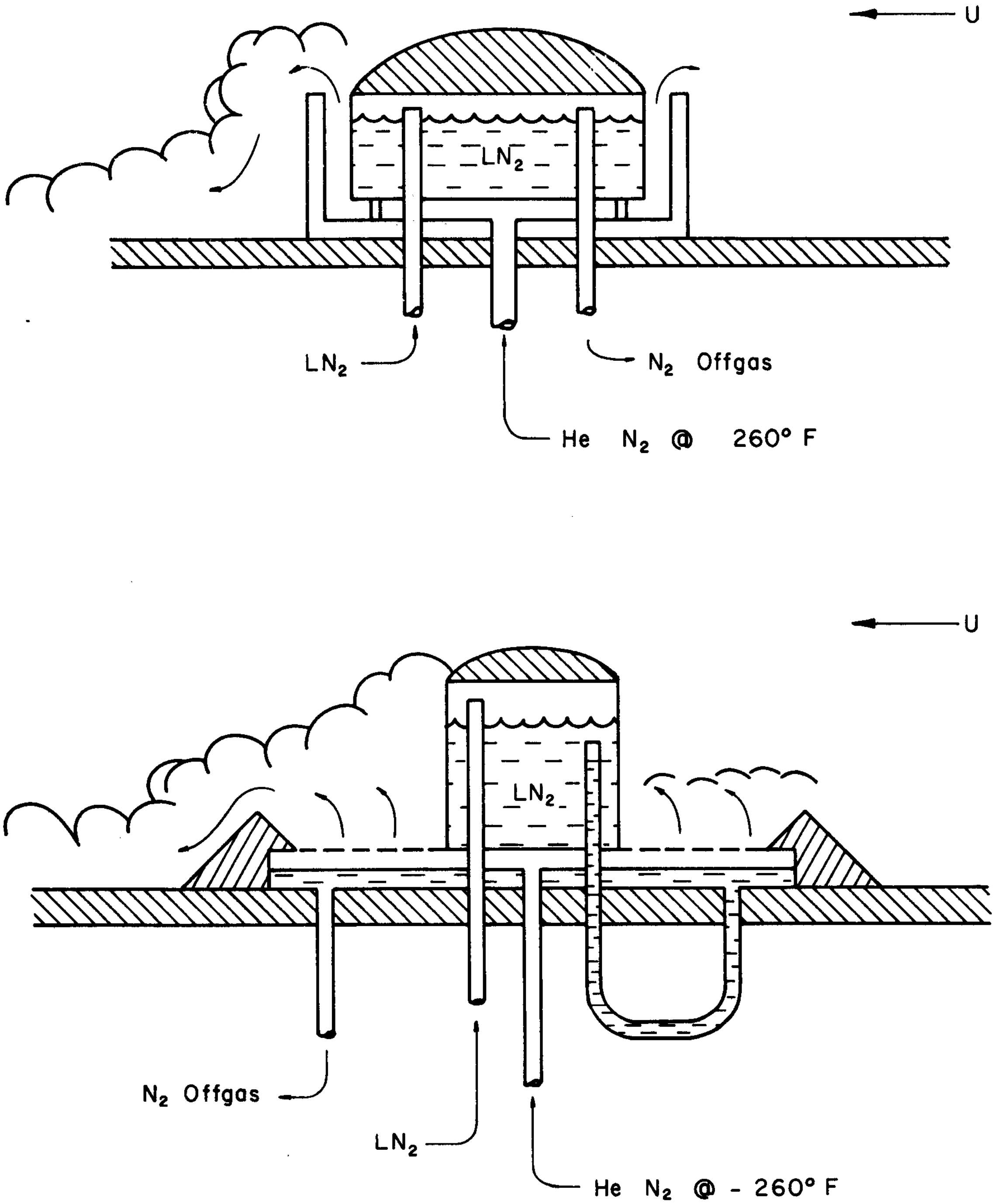

Figure 6. High and Low Dike Models for Simulation With Helium-Nitrogen Gas Mixture

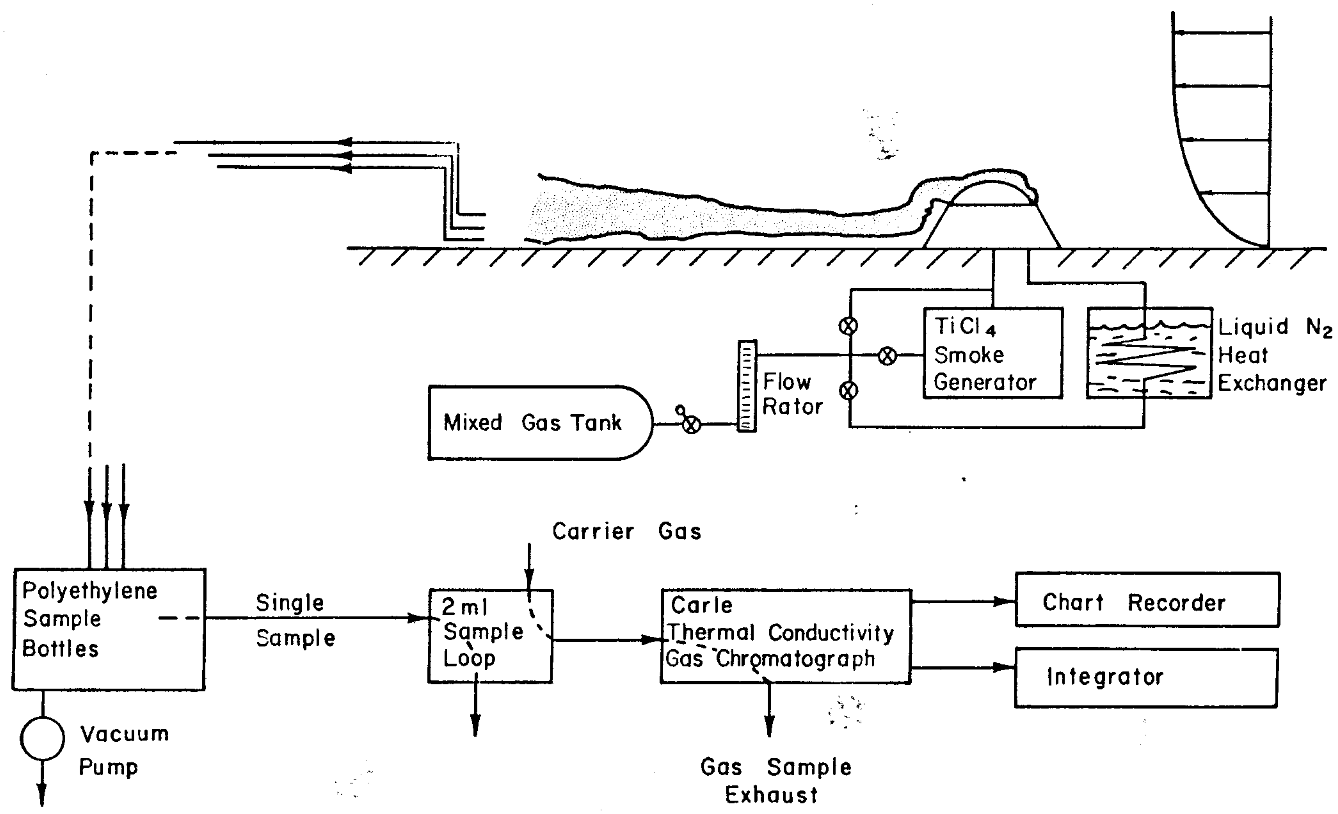

Figure 7. Flow Chart of Mean Concentration Sampling System

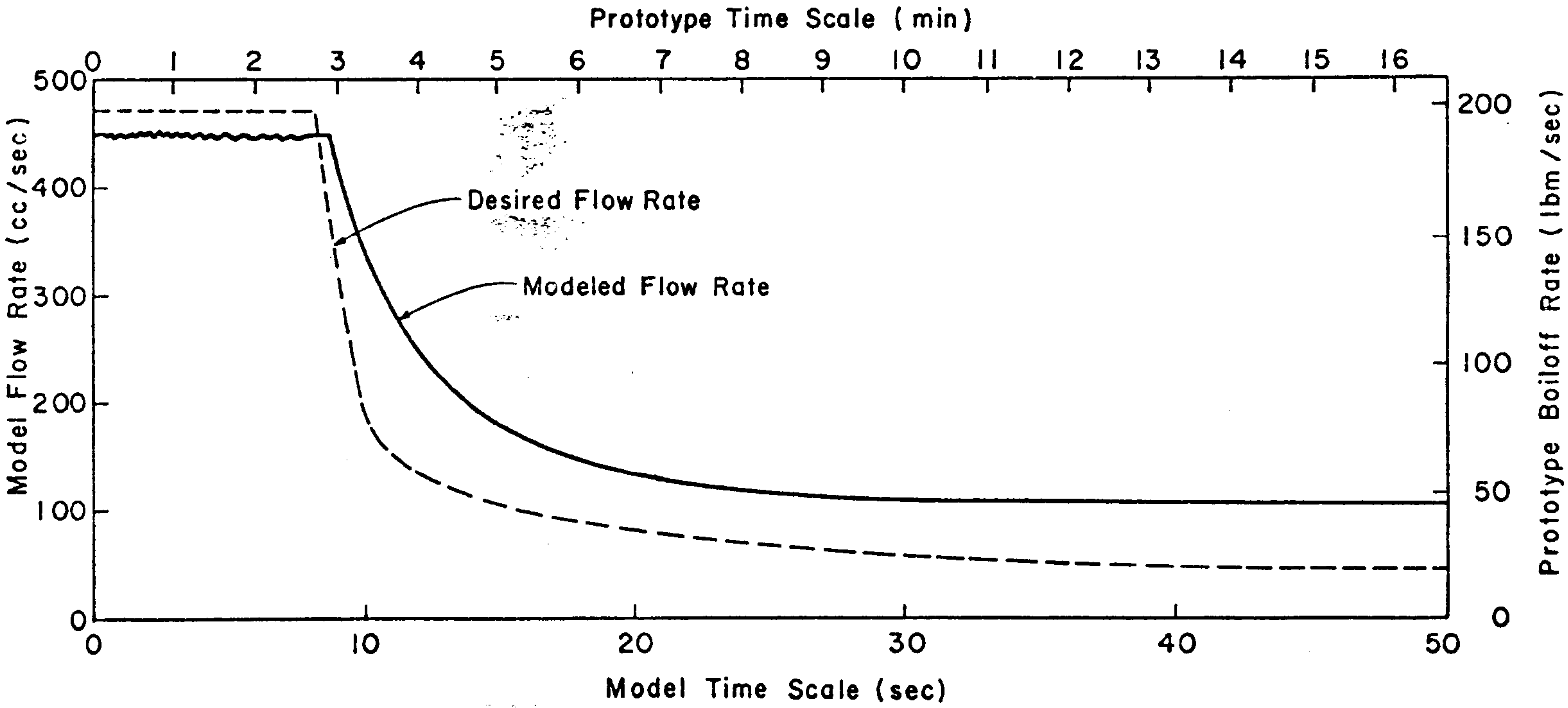

Figure 8. Capistrano 044 Gas Release Rates for Model and Prototype

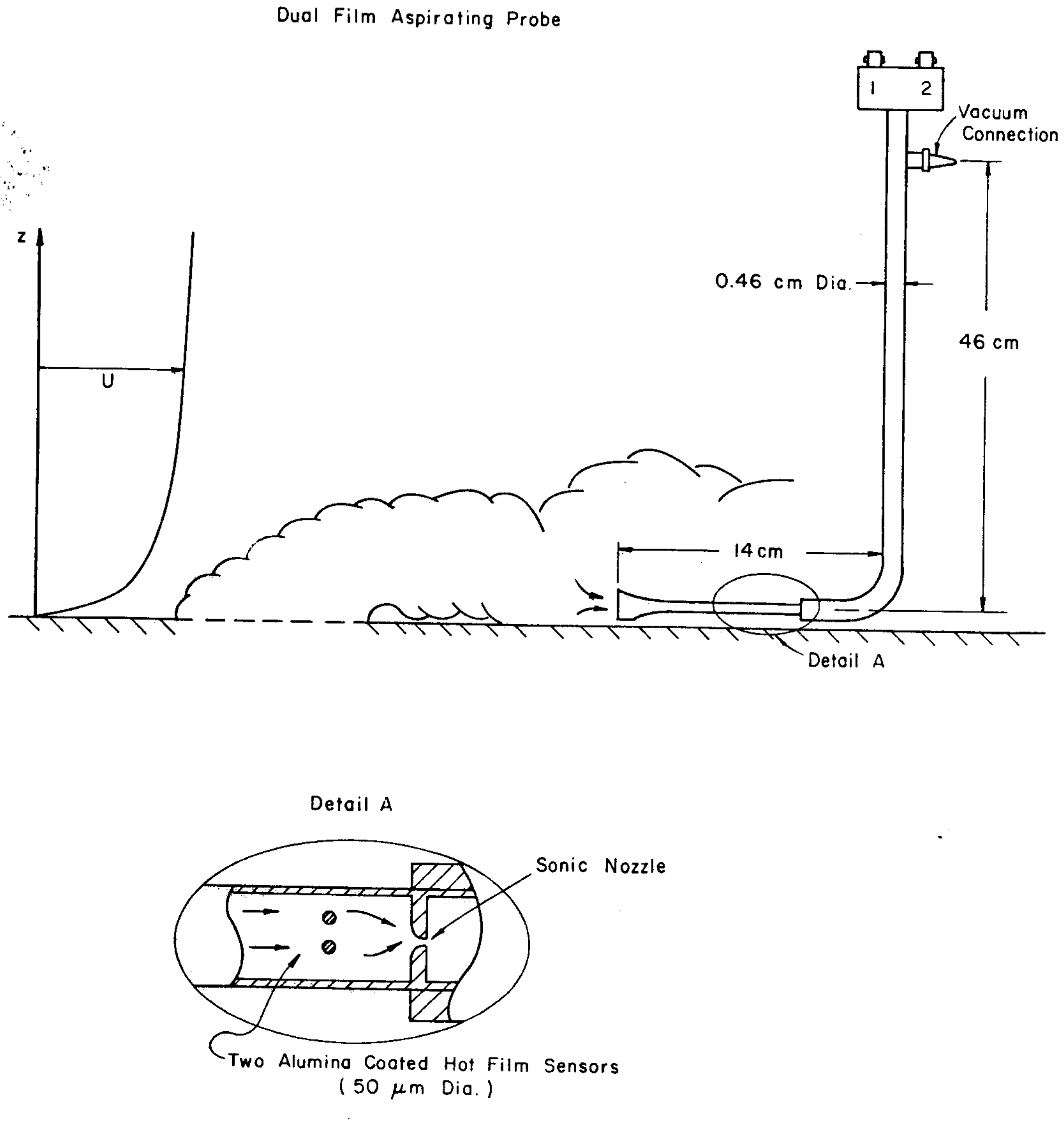

Figure 9. Dual Film Aspirating Concentration Probe

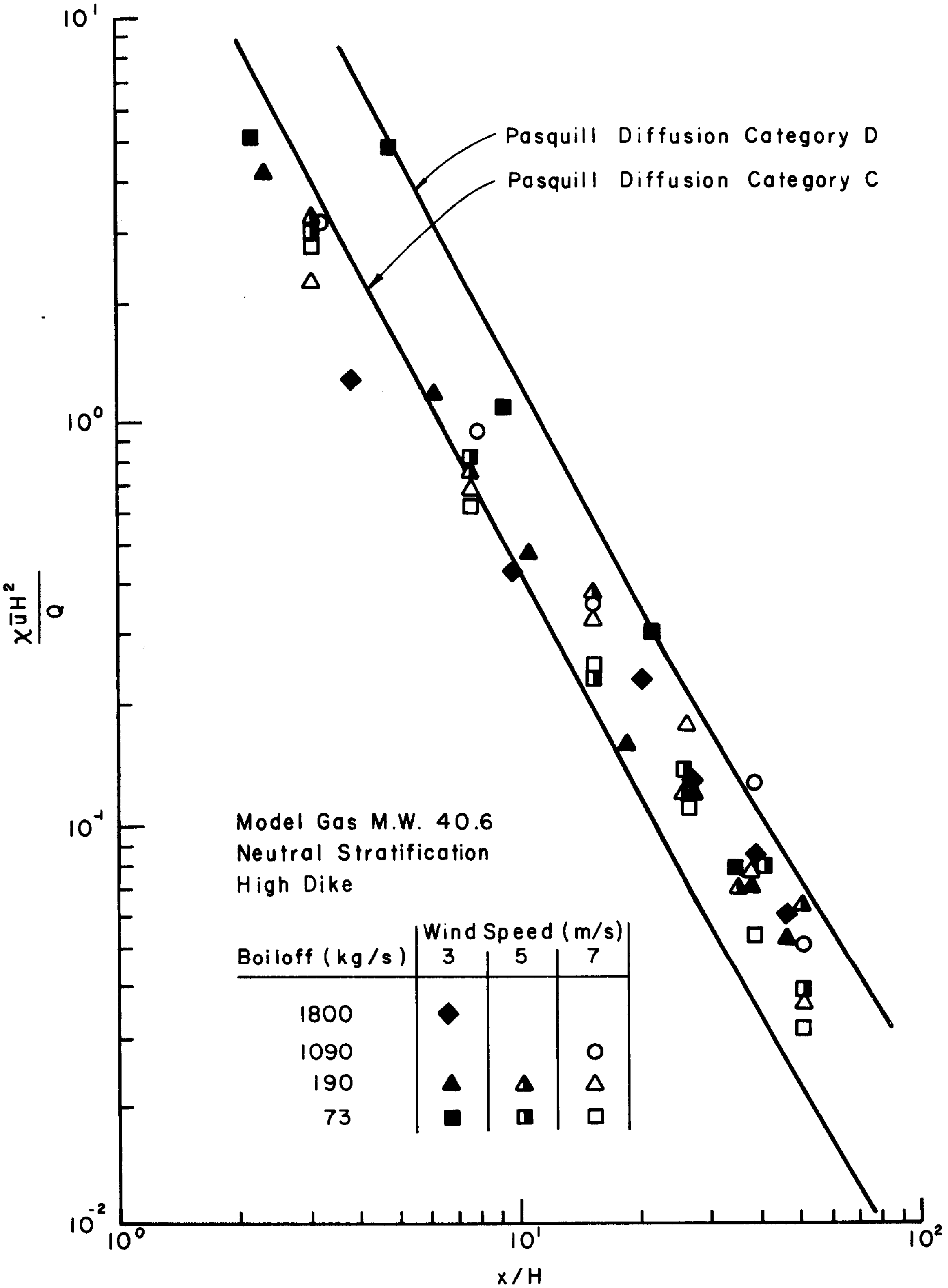

Figure 10. Dimensionless Concentration Coefficient Versus Non-Dimensional Downwind Distance

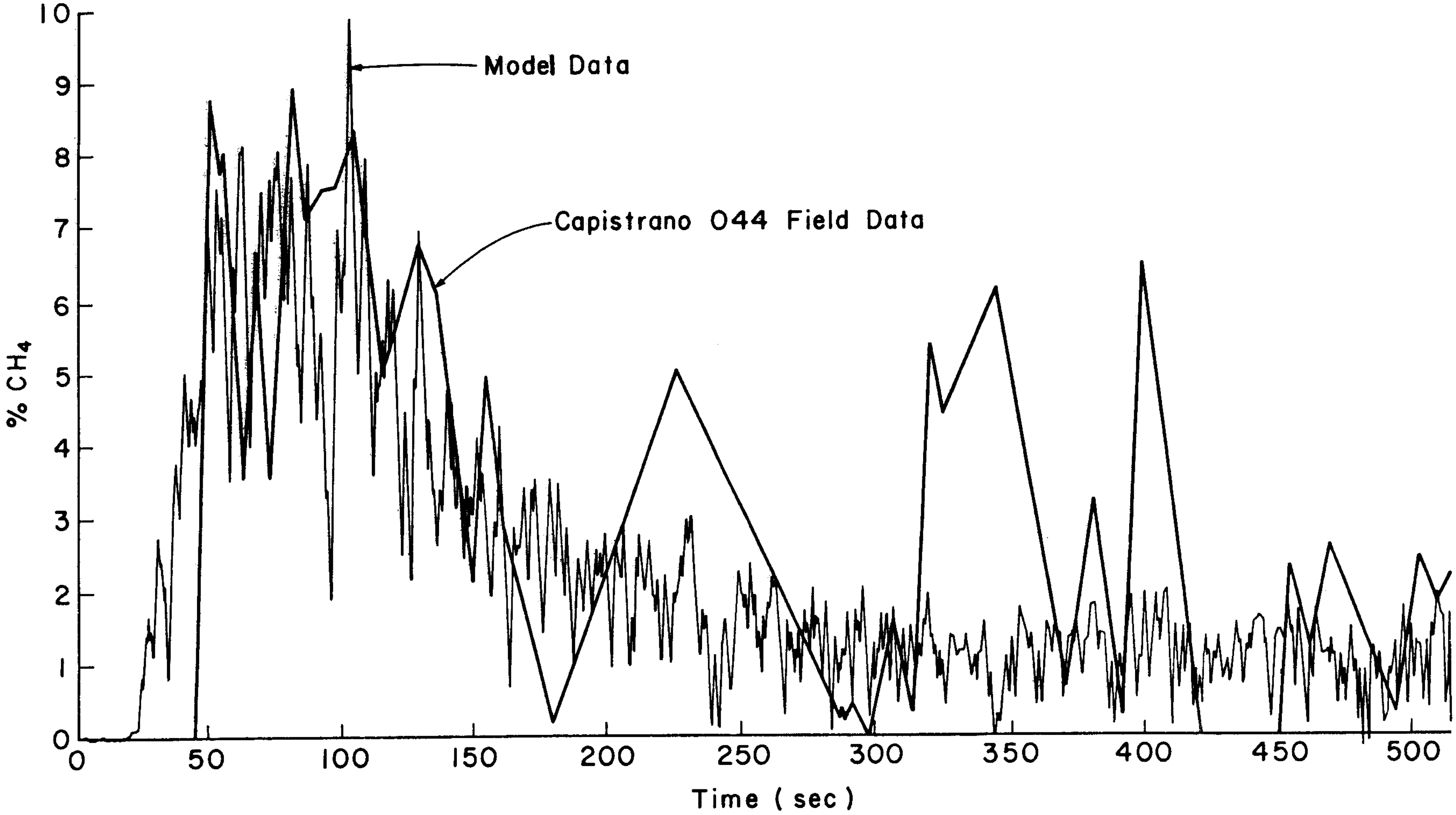

Figure 11. Comparison of Model Data With Capistrano 044 Field Data for a Sample Location at (320', 0', 0')