LABORATORY SIMULATION OF LIQUID NATURAL GAS VAPOR DISPERSION OVER LAND OR WATER

by

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SUMMARY

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.

1. INTRODUCTION

The capability of the wind tunnel to model the gravitational effects associated with negatively buoyant gas discharges in the earth's boundary layer has been established and underlies important potential applications of wind tunnel testing, such as the simulation of the vapor dispersion from large full-scale LNG spills and the generation of gravitationally dominated check cases for theoretical models. Such wind tunnel data can be correlated in a manner that yields an empirical prediction of vapor dispersion resulting from full-scale spills. However, certain facility-specific limitations must be considered in planning and executing an experimental program.

2. PRIOR EXPERIENCE: LABORATORY SIMULATION OF DENSE GAS AND CRYOGENIC SPILLS

In the event of a liquid natural gas (LNG) release, the dense gas boils from the spilled liquid at the source and is carried downwind in the form of a plume with gas concentration decreasing with distance and height from the

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source. The negative buoyancy produced by the high density of the cold gas tends to exaggerate lateral movement and inhibit vertical mixing. Hence the spatial distribution of methane dilution is generally found to be quite different from that predicted for neutral density plumes.

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.[1] 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.[2] 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, 1977) considered point source releases of heavy gases in wind tunnels at ground level.[3,4,5] 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.[6] 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 lift off situations.[7,8] 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).

Currently research on LNG spill behavior over irregular terrain is being performed at Colorado State University for the U.S. Coast Guard Program. Small scale models of the LNG Release Pond and surrounding topography at China Lake, Naval Weapons Testing Center, California, are being examined in a meteorological wind tunnel. Mean and transient concentration contours have been mapped. Overall plume geometry and behavior have been recorded photographically. Results will be used to plan a field experiment and validate tunnel methodologies.

3. LABORATORY SIMULATION OF CRYOGENIC SPILLS

The reliability of the use of wind tunnel shear layers for modelling atmospheric flows has been demonstrated by several investigators.[9] Specific problems associated with the dispersion of cold natural gas plumes have been previously discussed by Meroney et al. (1976, 1978).[10,11] The Froude number is the primary parameter which governs plume spread rate, trajectory, plume size and entrainment when gases remain negatively buoyant during their entire trajecory. Earlier measurements suggest that heat transfer effects may be small over the significant time scales; hence gas density should be adequately simulated by isothermal high molecular weight gas mixtures.[6,7,8] Visualization of similar tests for the range of model scales used (1:130 to 1:666) indicate a similar plume geometry. Concentration results of the different model scales agreed to within the experimental accuracy of approximately ±20%. Similarly, identical tests also show good agreement; hence the Reynolds number must play a minor part in the dense gas dispersion situations considered.

The major practical limitations of accurate wind tunnel simulation of LNG dispersion are operational constraints, particularly the inability to obtain a steady wind profile or to accurately simulate atmospheric turbulence at the lowest wind speeds of interest, and Reynolds number constraints (as yet somewhat ill-defined) associated with the proper scaling of near-field turbulence. When combined with estimates of the restraint of plume expansion by the tunnel sidewalls, these considerations permit the development of a performance envelope for a particular wind tunnel facility, examples of which are given in the following Sections.

4. PERFORMANCE ENVELOPES: LAND BASED SPILLS

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 perturbation 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 ±0.25 cm. Minimum pertinent 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.[12]

The four operational limitations listed above have been incorporated into the performance envelopes shown in Figures 1 and 2. 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. Assuming land based spills comparable to those examined by Neff et al. (1976) or Meroney et al. (1977) it is expected that a spill at 200 m^3/min on the floor of an uninsulated dike may be scaled at 1:400 satisfactorily in the Meteorological Wind Tunnel at Colorado State University.[6,7] Performance envelopes have not been presented here for the finite spill case on land because the boiloff rate tends to vary irregularly with time depending on specific characteristics of the dike or bund shape and its material.

5. PERFORMANCE ENVELOPES: WATER BASED SPILLS

Water spill boiloff and dispersion differ from their land counterpart because they

1) Boiloff at a maximum rate (0.1 $m^3/sec/m^2$) as long as LNG remains,
2) Generally involve larger volumes (~25,000 m^3), and
3) The spill source has a variable area in time.

Since it is desirable to contain the 5% lateral contour within a test region unaffected by wall reflections, a second set of calculations were prepared assuming a transient spill configuration. One may employ the equations of Raj and Kalelkar to predict maximum liquid pool radius after an instantaneous spill.[13] Again following a modified version of calculations suggested by Van Ulden (1974) it is possible to calculate the gravity spread radius.[12] The gravity spread is assumed to occur until the frontal velocity equals the mena flow velocity. Subsequently one may emperically allow a 1.5 factor growth in radius before the 5% condition is reached. Since no entrainment is allowed during the gravity spread regime, this calculation is probably reasonable at low wind speeds and conservative at high wind speeds. Figure 3 constructed for a facility similar to the Environmental Wind Tunnel at Colorado State University suggests than a 20,000 m^3 spill must be modeled at 1:800 to achieve even a 4 m/sec prototype wind speed. A 5000 m^3 spill would be fairly comfortably structured at 1:600; however wind velocities under 3.0 m/sec would be difficult to control.

Hence a 20,000 m^3 spill could be modeled at 7 or 15 m/sec in a facility like the Environmental Wind Tunnel without too much trouble; however a 2.0 m/sec speed would be difficult to achieve. Since the initial cylinder depth of cold natural gas resulting from an LNG spill is $\leq$ 10 m then any length scale ratio less than 1/500 has a modeled depth less than 0.02 meters (2 cm). To gain good resolution with some hypothetical probe system it would be preferable not to go to larger length scale ratios.

6. LABORATORY METHODOLOGY

Simulation of the atmospheric surface layer in Boundary Layer Wind Tunnels has been considered in some detail by previous authors. Special procedures required to inject cold gas plumes are considered by Meroney et al. (1978).[11]

Representation of transient LNG spills on land or water require additional tools recommended below.

Variable-Boiloff Rate Simulation

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 Capistrano Test 044 are presented in Figure 4.[7,14] These gas flow rate curves were obtained by use of a programmed cam to close a micrometer needle valve controlling the flow of simulation set at a predetermined rate. Figure 5 shows a schematic of this valve arrangement and the location of the mass flow transducer used to measure the resultant flow rate versus time.

Transient-Concentration Instrumentation

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 6, 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 or Argon and an upper frequency response of 1000 Hz.[7]

Variable-Area-Source Release

When LNG spills on water, density causes the liquid to grow radially outward until all methane is vaporized. Generally this growth is thought to be linear with time. Since no cryogenic fluid will be used in the model tests, the resultant variable area nature of the release must be simulated by means of auxiliary equipment installed beneath the wind tunnel floor. For LNG spills on water the spill radius when all methane is vapor will be ~ 352, 271, or 209 m for 20,000, 10,000, and 5,000 m^3/spills respectively. At a scale of 1:600 one requires a source approximately 1 to 1.5 m diameter.

A variable area source devise has been constructed for the current China Lake spill series. As shown in Figure 7 it consists of a contoured honeycomb surface together with a mercury filled bladder. The device has been constructed at a diameter of 0.25 meters; however a larger version may be possible. A simple alternative for the larger size releases is a set of concentric anuluses metered by flowraters and monitored by cam operated solenoid valves.

7. TEST PROGRAM VERIFICATION

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 Colorado State University have been prepared by Neff et al. (1976), Meroney et al. (1977), Meroney and Neff (1977), R & D Associates et al. (1978), and Harsha (1976).[6,7,8,15] 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. We are now in a position to compare the current wind tunnel data with both additional wind tunnel data taken at the Warren Springs Laboratory and Colorado State University and with field test data taken during the American Gas Association Phase II Program.[4,6,7,14]

The Battelle Columbus Laboratories correlation, which represents an upper bound of all concentration resulting from confined LNG land spills during the AGA Phase II program can be arranged as

$$\frac{\bar{u}\chi \ell_b^{\,2}}{Q} \doteq 130 \left(\frac{x}{\ell_b}\right)^{-2} .$$

where the buoyancy length scale, $\ell_b = \frac{g(\rho_g - \rho_a)\, Q}{\rho_a\, \bar{u}^{3}}$.[13,16]

Figure 8 presents the Colorado State University CO_2 release gas data, the CSU Freon-N_2 release, the CSU neutral stability data, the Battelle Columbus Laboratory correlation, and the Warren Springs data. The data taken under "stable" conditions and with He-N_2 releases in Reference 6 have not been included for the reasons cited there. Thus the data presented in Figure 8 do not reflect the effects of nonadiabatic heat transfer or the effects of atmospheric humidity, both of which would tend to reduce the gravitational forces that are responsible for the initial spreading and mixing of the vapor cloud. With regard to the Warren Springs data, a factor of two reduction in the "advertised" velocity was used to obtain a velocity more typical of that which the vapor plume was actually exposed to. A few Warren Springs and several CSU data points were eliminated because of plume blockage by the wind tunnel walls. In addition, the Warren Springs experiments employed a heavier simulation gas than CSU to allow the wind tunnel to operate at higher speeds. Although the Froude number was scaled properly, the turbulent mixing processes were probably reduced by the use of the heavy gas. Thus, we would expect the Warren Springs data to exhibit somewhat higher concentration values at a given scaled range. It should also be noted that the Battelle Columbus Laboratory correlation was generated from data occupying a limited region of x/ℓ_b (note for example, the Capistrano 044 data). Thus, the Battelle Columbus Laboratory curve in Figure 8 should be regarded as an extension of the original Battelle Columbus Laboratory correlation. A significant observation from Figure 8 is that the Battelle Columbus Laboratory correlation bounds the current and previous CSU data (with room temperature gas releases) in addition to the available field test data.

8. CONCLUSIONS

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 land 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 beyond 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 land spills has been reproduced for selected cases of the 1974 AGA landspill program. Water spills may be reproduced if additional consideration is given the characteristics of variable boiloff area. 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 Department of Energy to guide LNG hazard analysis.

9. ACKNOWLEDGEMENTS

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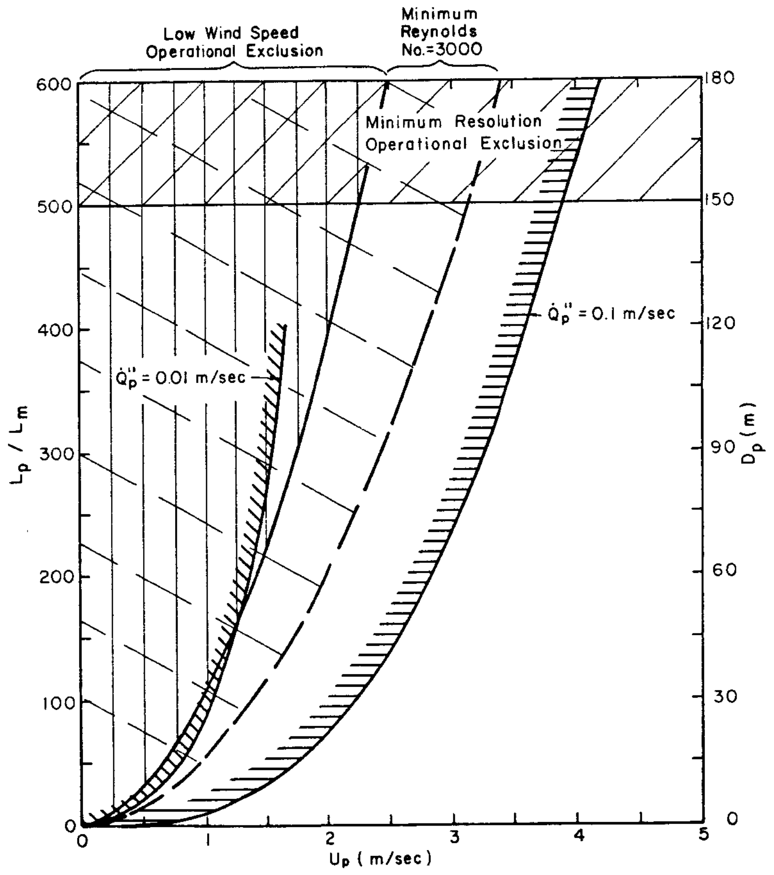

Figure 1. *Performance Envelope to Simulate LNG Spills - Constant Boiloff Conditions*

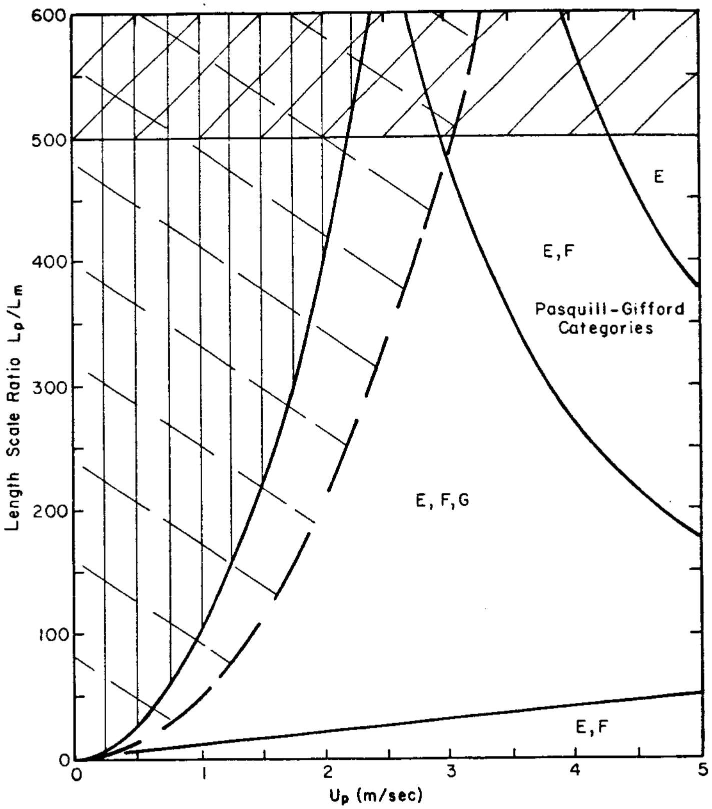

Figure 2. *Performance Envelope - Atmospheric Stable Stratification on Envelope for D_m = 0.3 m*

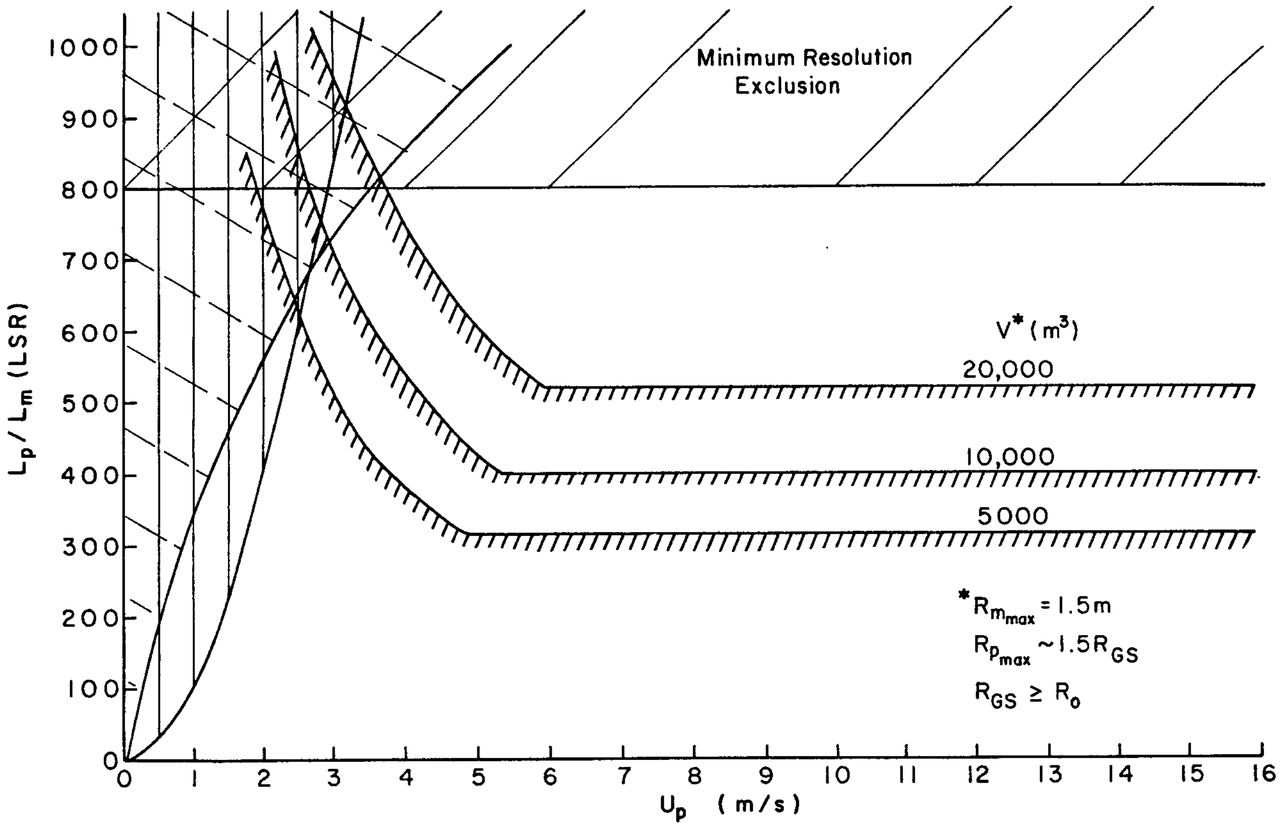

Figure 3. Performance Envelope Environmental Wind Tunnel Water Spills LNG Limit to Gravity Spread When $U_\delta = \overline{U}$

Final Radius ≅ $1.5\ R_{GS} > 1.5\ R_o$

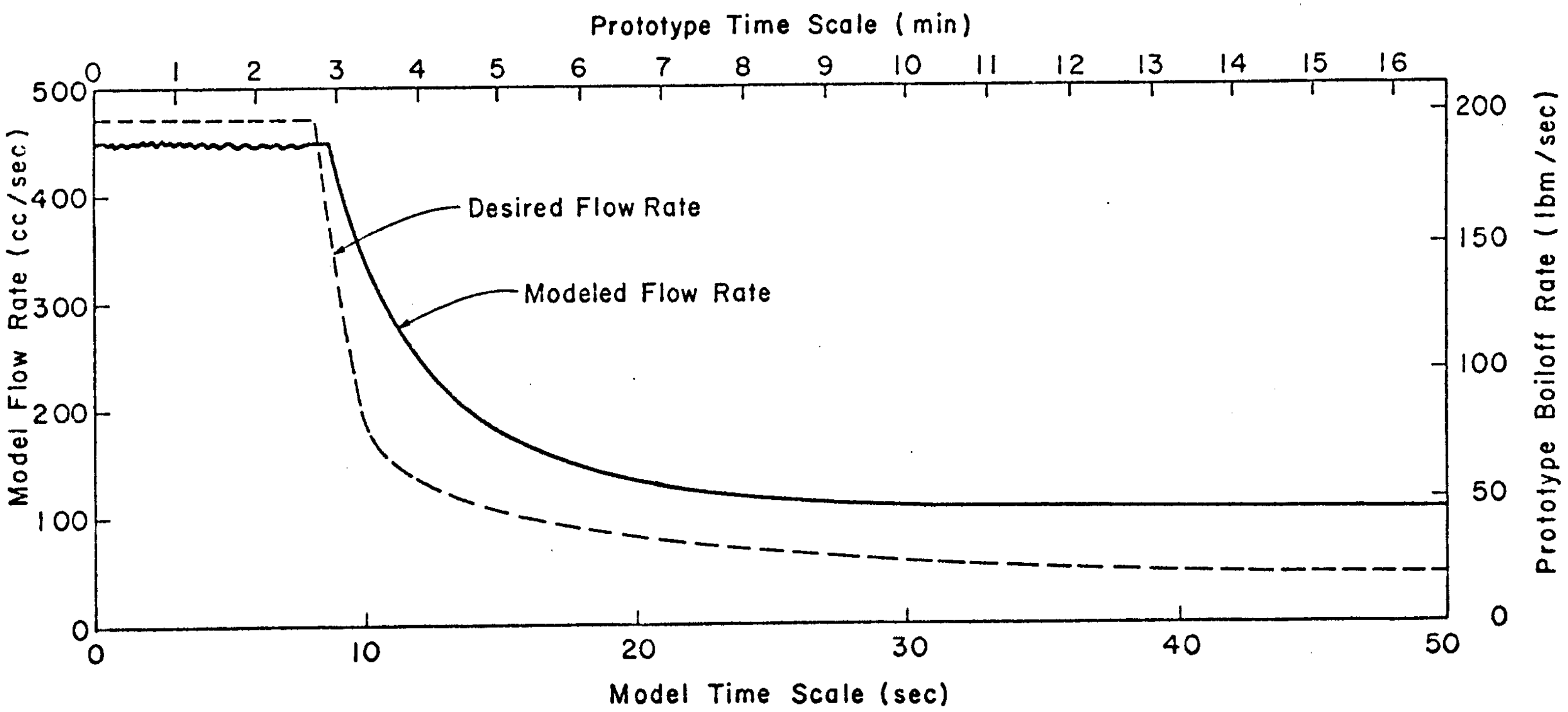

Figure 4. Capistrano 044 Gas Release Rates for Model and Prototype

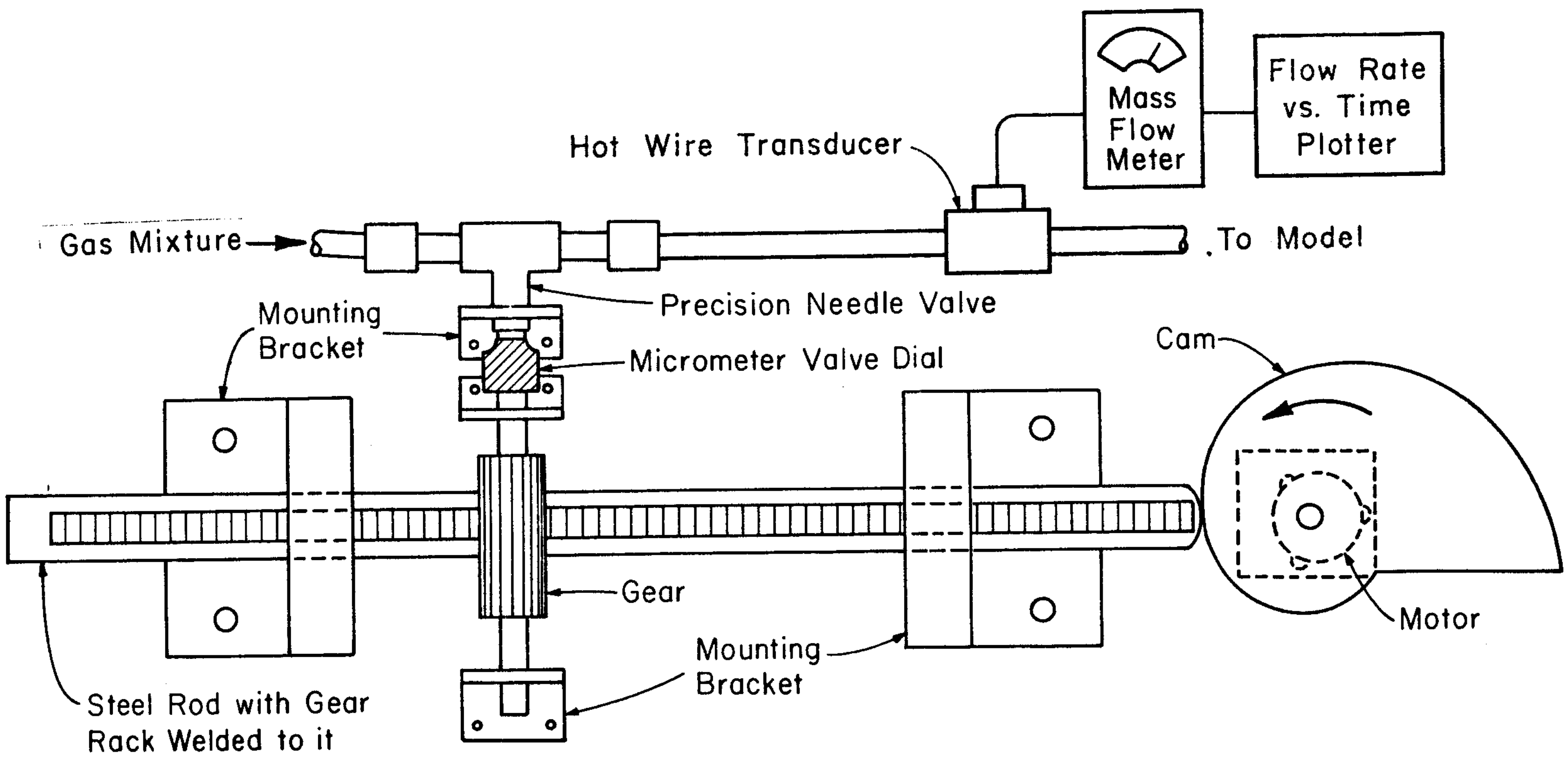

Figure 5. Variable Flow Rate Control Valve

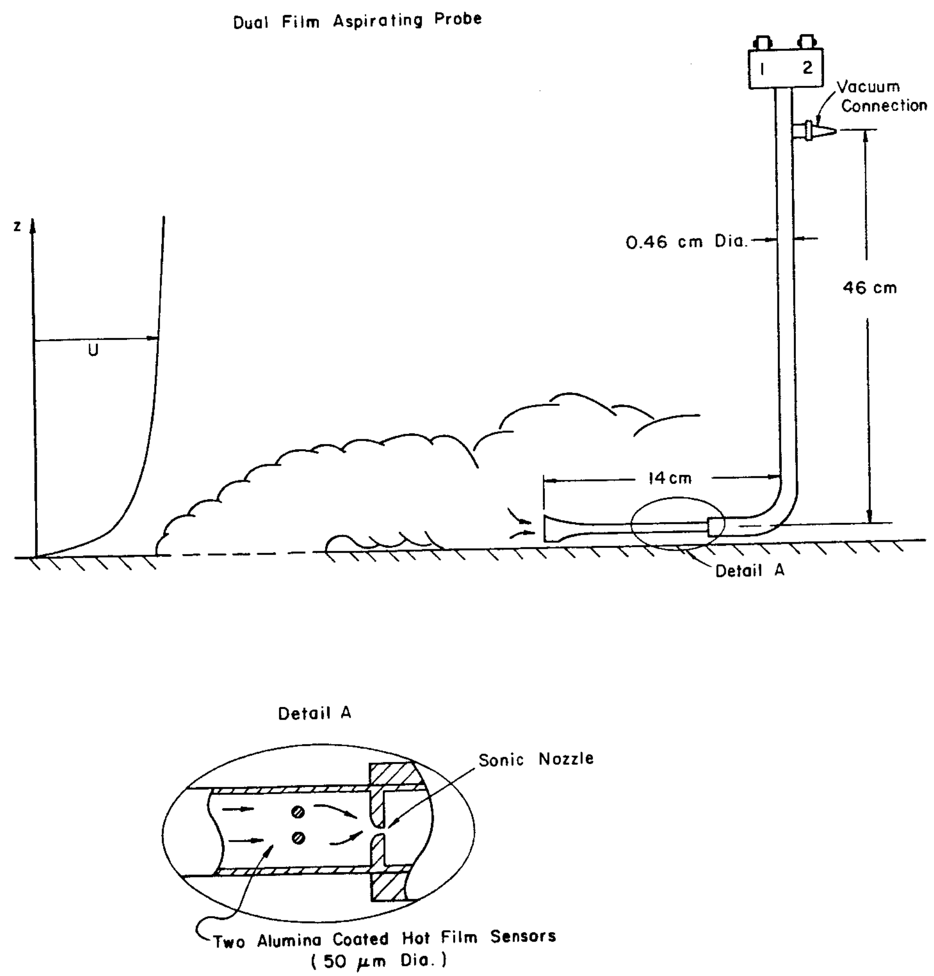

Figure 6. Dual Film Aspirating Concentration Probe

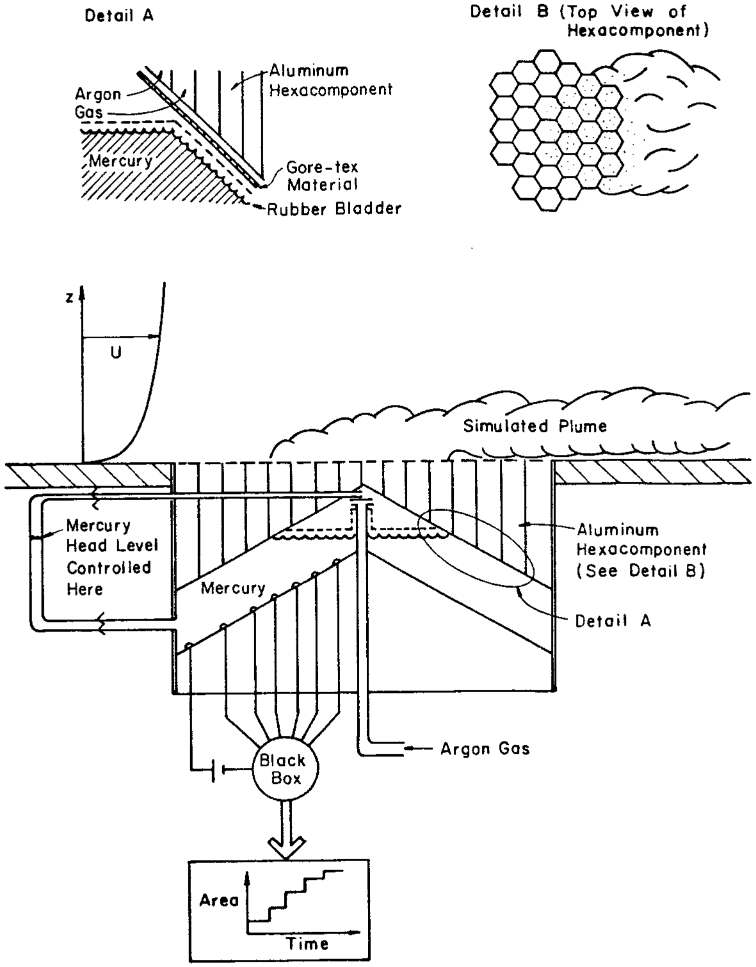

Figure 7. Variable Area Source Model

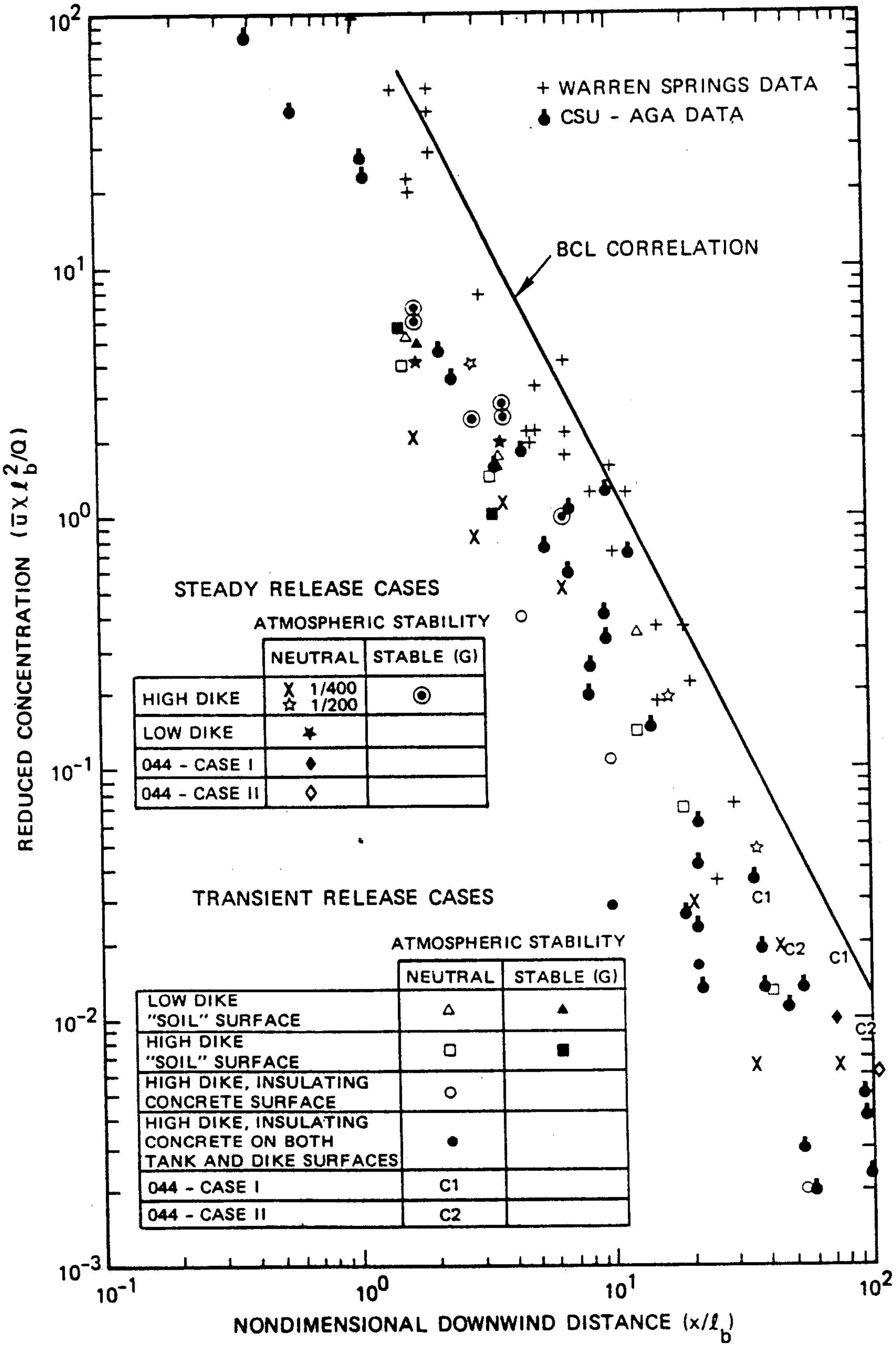

Figure 8. Comparison of Selected Wind Tunnel and Field Test Concentration Data