BEHAVIOR OF NEGATIVELY BUOYANT GAS PLUMES RESULTING FROM AN LNG SPILL

by

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ABSTRACT: Tests were conducted in the Meteorological Wind Tunnel Facilities at Colorado State University, U.S.A. to evaluate the rate of dispersion and extent of downwind hazards associated with the rupture of large liquid natural gas cryogenic storage tanks. These tests were conducted on two different dike storage areas, varying in scale from 1:666 to 1:130. Two different model release gases were used to simulate the behavior of the cold methane plume. One was a gas of molecular weight 40.6 at 294°K and the other was a gas of molecular weight 16 at 112°K. Concentration and temperature measurements, and photographic records were obtained for different wind speeds, wind directions, and boiloff rates under both neutral and stable density stratification. On the basis of the experimental measurements reported herein, the following comments may be made:

1) The dimensionless concentration coefficient $\chi \bar{U} H_T^2/Q$ is a function of non-dimensional downwind distance x/H_T. This function suggests an initial decay rate in the region $x/H_T < 10$ less than the decay rate in the region of $x/H_T > 10$ and perhaps data should be evaluated in terms of a different length scale related to buoyancy parameters.

2) The dimensionless concentration coefficient curves assymptotically approach the slope of those given by the appropriate Pasquill diffusion category for both neutral and stable flow.

3) 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 agree to within the experimental accuracy of approximately ± 20%. Similarly identical tests also show good agreement.

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SUMMARY Results are presented from wind-tunnel simulation of the dispersion of cold natural gas plumes resulting from the rupture of large cryogenic LNG storage tanks.

1 INTRODUCTION

The objective of this study was to evaluate the rate of dispersion and extent of downwind hazards associated with the rupture of large liquid natural gas (LNG) cryogenic storage tanks. In particular the use of diked storage areas to ameliorate the extent of potential damage was examined. It is estimated that in the 1980 time period 0.04 trillion cubic meters per year of natural gas will be supplied in the form of LNG. In the Australasian area alone there are nine gas liquification projects under consideration (Lom, 1974). Thus safety at LNG facilities is of utmost importance to the gas industry and the public. The hazards associated with LNG release are fire and thermal radiation from such fires. If ignition does not occur immediately during an accidental LNG release, the boiling LNG produces vapors which are mixed with ambient air and transported downwind. This cloud is potentially flammable until the atmosphere dilutes the gas mixture below the lower flammable limit (LFL) (a local concentration for methane below 5 per cent by volume). If the flow from a rupture in a full LNG storage tank could not be stopped for some reason it is conceivable 28 million cubic meters (1BSCF) of LNG would be released in 80 minutes (AGA, 1974b).

As a result of concern over such problems associated with the transportation and storage of LNG, the gas and petroleum industries have sponsored a series of previous studies on cryogenic spills of LNG and other liquids such as liquid oxygen and liquid ammonia on both land (AGA, 1974a) and water (Feldbauer, et al., 1972; Burgess, et al., 1972; etc.). Measurements of plume dispersion downwind of large and small spills have been incorporated into a variety of prediction models (AGA, 1974a; 1974b; Van Ulden, 1974; Germeles and Drake, 1975; Cox and Roe, 1977). Unfortunately it appears authors of these models interpreted available measurements quite differently (Ecosystems, 1973; Murphy, 1974; Fay, 1973). In addition predictions are very sensitive to source type, boiloff rate, dispersion coefficient data, weather conditions, and expected peak to mean concentration ratio.

In the event of a 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 source. The negatively 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. 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 an LNG spill quite well, but the precooled methane runs lofted suggesting to the authors incorrect release temperature or exaggerated heat transfer rates 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 $\simeq$ roughness height) and on up and downhill slopes. Hall reported shallow, wide plumes whose shapes were considerably altered by 1 in 12 ground slopes.

Further tests to illuminate the missing physics of LNG spill behavior would be appropriate. The purpose of this study is to provide guidance on 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.

2 LABORATORY SIMULATION OF CRYOGENIC SPILLS

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). Experiments by Hoot and Meroney (1974), Bodurtha (1961), Val 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. Thus it is important to model not only the initial Froude number of a plume but its characteristic variation with dilution also. Room temperature releases of air-Freon-12 mixtures will behave like a cold methane plume undergoing adiabatic entrainment of dry air. 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.

3 WIND TUNNEL EXPERIMENT

Scale models of two typical LNG storage tanks have been studied in a meteorological wind tunnel for a neutral and a 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 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). All results presented herein are modeled with air-Freon-12 mixtures or pre-cooled Helium-Nitrogen mixtures adjusted to simulate boiloff densities of methane. The gases were tagged with small quantities of propane or Krypton-85 to permit concentration measurements. The 1/200 scale models shown in Figure 1 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 remarked upon by Boyle and Kneebone (1973). A schematic of the model configuration and the associated concentration measurement equipment is shown in Figure 2.

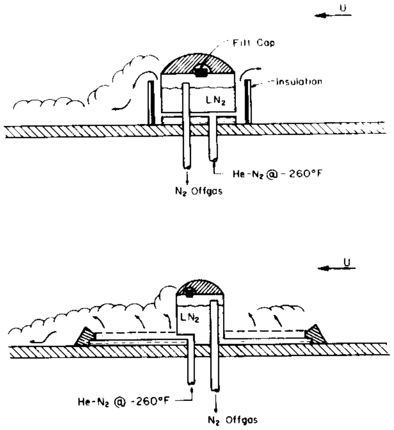

Figure 1 High and Low Dike Models for Simulation With Helium-Nitrogen Gas Mixture

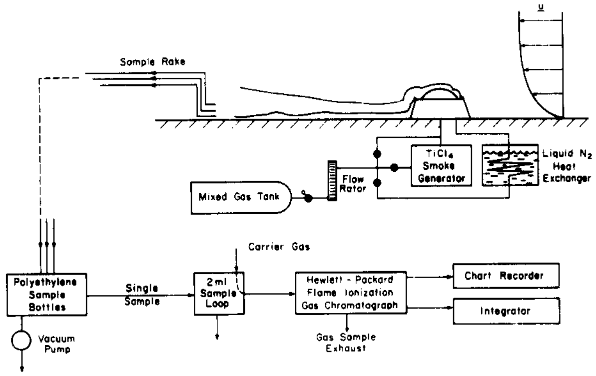

Figure 2 Block Diagram of Gas-Mixture Release System and Mean Concentration Sampling System

Concentration measurements were performed in the Colorado State University Meteorological Wind Tunnel (MWT). 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. Additional details concerning the test configuration are contained in Neff (1977).

4 TEST PROGRAM RESULTS

For the neutral approach flow situation simulated herein the velocity profiles power law coefficient was between 0.23 to 0.34. These coefficients are characteristic of flow ranging from tall grassland crops to suburban roughness. A stable approach flow appropriate to Pasquill F Diffusion category and associated with a 0.72 power law exponent was also examined.

4.1 Flow Visualization

Flow visualization indicates that the initial movement of both the plume simulated by a Freon 12-N$_2$ gas mixture at 294°K and the plume simulated by a He-N$_2$ gas mixture at 112°K displayed a similar buoyancy dominated character. The plume fell rapidly down over the dike walls to the ground and then proceeded slowly downwind in an undulating wavelike motion until the atmospheric turbulence started to penetrate this seemingly layered flow and thus give way to increased vertical dispersion with distance downwind. For the Freon 12-N$_2$ simulation gas this layering effect was strongly dependent upon the stability, boiloff rate, and distance downwind. With neutral stratification the largest boiloff rates simulated (1800 and 1000 kg sec^{-1} for the High Dike and 1000 kg sec^{-1} for the Low Dike) gave this layered appearance for upwards to a prototype equivalent distance of 450 meters downwind. Figures 3 and 4 give an artist representation of this type of plume geometry for the High Dike and Low Dike at 45° respectively. For the lower boiloff rates this layered appearance was broken up within 60 meters of the plume's leading edge. With stable stratification similar observations were made but instead of the layered appearance giving way to vertical plume growth, the layered appearance dissipated into a wispy, ill-defined upper plume boundary that did not grow significantly with height as it moved downwind.

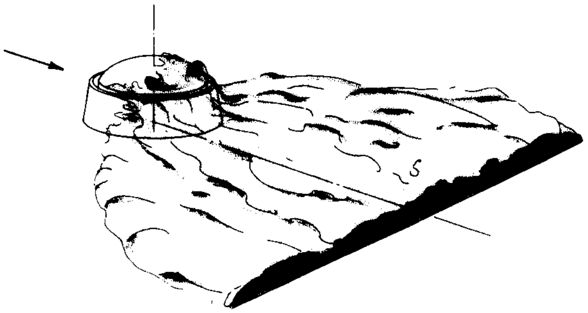

Figure 3 Visualization of Plume From High Dike Model - Wind Direction 0°

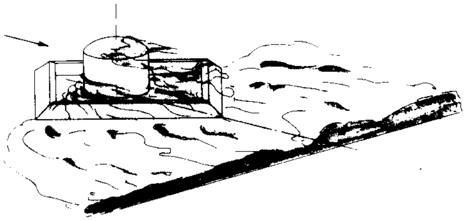

Figure 4 Visualization of Plume From Low Dike Model - Wind Direction 45°

For the same dike geometry the rate of initial plume spread in the lateral directions varied directly with boiloff rate and inversely with wind speed. That is, to maintain approximately the same rate of spread with an increased boiloff, the wind speed would have to be increased and vice versa. At low wind speeds and high boiloff rates the gravity spread rate increases to a point where the plume would spread out to the walls of the tunnel and then crawl upwind of the dike complex in a front perpendicular to the wind direction. With stable stratification the plume would spread out on the ground and migrate quite far upwind (300 meters) for the higher boiloff rates and low wind speeds. This upwind movement was present to some extent for the lower boiloffs and higher wind speeds.

The observed effects of the wake and cavity regions generated by the aerodynamics of the tank and dike structure varied with tank and dike geometry, wind speed, and stratification. For the Low Dike and Tank complex the effect of increased plume dispersion due to turbulence in its wake was insignificant. The only aerodynamic effect noticeable for this structure was that of a standing plume in the cavity regions of the tank and dike. For the High Dike and Tank the effect of increased plume dispersion due to turbulence in its wake was most significant. Strong vortices which formed near the ground on each side of dike structure would entrain a large amount of the plume and transport it downwind. This effect would give the plume a bifurcated form on the ground with what appears to be maximum concentrations traveling downwind at a separation distance slightly greater than that of the dike diameter. Another vortex was generated on the tank top and traveled slightly upward in the downwind direction. This vortex appeared to act as a vent to the standing plume in the cavity region. A similar aerodynamic structure as this has been reported for flow over a hemisphere. The strength of these vorticies was enhanced by an increase in wind speed but seemed to disappear almost completely in a stable atmosphere.

4.2 Concentration Measurements

Concentration measurements were obtained for as many as 50 different sample points distributed over an equivalent ground zone of 100 to 2000 meters long by 250 meters wide and in the vertical over a height of 0 to 120 meters. A series of vertical profiles revealed the shallow layer character of a dense gas plume. Ground level contour plots of per cent methane confirmed the presence of a bifurcated plume as suggested by the visualization photographs.

The Pasquill-Gifford calculation technique is the most familiar methodology utilized today for atmospheric dispersion; hence the model LNG vapor plume measurements have been grouped on the basis of the variation of maximum ground level concentration versus downwind distance. Figure 5 displays concentration results as

$$K = \chi \bar{U} H^2 / Q \text{ vs } x/H$$

where χ = maximum ground level concentration at a given downwind distance,
$\bar{U}$ = reference velocity at height H,
H = reference tank height, and
Q = source strength
for a typical set of Low Dike release data.

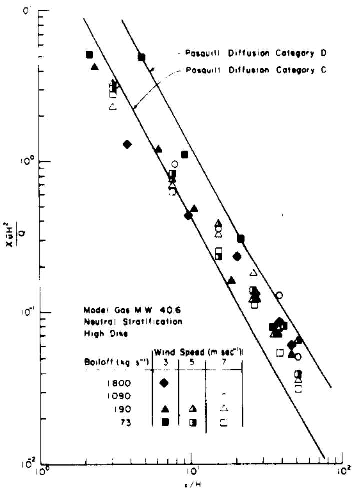

Figure 5 Dimensionless Concentration Coefficient vs Downwind Distance, K vs x/H

Even in the presence of the tank/dike wake most data vary approximately as $K \sim (x/H)^{-2}$ which agrees with earlier measurements made by Hoot and Meroney (1974) and Hall, et al. (1975) especially for x/H > 10. In the immediate vicinity of the tank and dike plume spread is dominated by buoyancy forces. Thus a buoyancy length scale such as

$$\ell_b = \frac{g(\rho_g - \rho_a)Q}{\pi \rho_a \bar{U}^3} ,$$

where ρ_a and ρ_g are atmospheric and initial model gas density respectively, may be more appropriate than H to scale dispersion in this region. A plot (Figure 6) of

$$K_{\ell_b} = \frac{\chi \bar{U} \ell_b^{\ 2}}{Q} \text{ vs } \frac{x}{\ell_b} \text{ for } \frac{x}{H} < 10.0$$

collapses concentration data from the twelve equivalent sets of neutral Freon-12-N_2 model gas High Dike releases on to a single line. The classical correlation permits an order of magnitude variation in K at a given $x/H < 10$; whereas the buoyancy length scale parameter correlates data over two model scales, four wind speeds, and six boiloff rates within a factor of two.

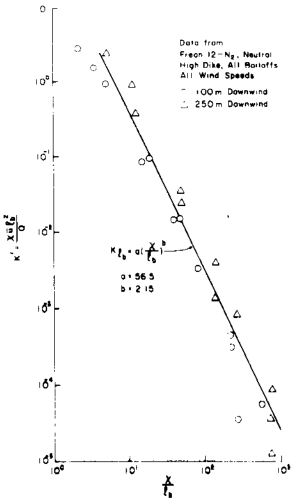

Figure 6 Dimensionless Concentration Coefficient vs Downwind Distance K_{ℓ_b} vs x/ℓ_b

Distances downwind to lower flammability limit (LFL) for various boiloff rates, wind speeds, and stratifications varied from less than 100 to greater than 2000 meters for the High Dike and similarly for the Low Dike. Distance to LFL decreased with increased wind speed, increased with increased boiloff rates, and increased with stable stratification of the approach wind. It is probable that more realistic variable boiloff rate conditions and the absence of plume reflection from tunnel side walls will reduce these distances. Nonetheless the values measured are similar to those noted by Humbert-Basset and Montet (1972) and AGA (1974a) for field releases of LNG vapor.

5 ACKNOWLEDGMENTS

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