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DISPERSION OF VAPOR FROM LNG SPILLS -
SIMULATION IN A METEOROLOGICAL WIND TUNNEL

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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. 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 percent 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). 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. (Harsha, 1976).

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 et al., 1968; Chaudhry and Meroney, 1969; Cermak, 1975). 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 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

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

$\frac{g(T_H - T_o)H}{T\, U_H^2}$ - Bulk Richardson number or 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 diameter, 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 1:200. 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 and volume dilution rates so this is not proposed herein.

Previous experiments by Hoot and Meroney (1974), Bodurtha (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 consider the case of adiabatic mixing of the subject gas with ambient gases together with a fractional transport of thermal energy to a plume. A one-dimensional mixing model including considerations of conservation of energy and mass plus thermodynamic definitions of mixture properties produces

$$S.G._{mixture} = \{x \frac{M_o}{M_a} + (1-x)(1+\omega)/(1+\omega \frac{M_a}{M_{wv}})\}$$

$$\cdot \{x \frac{c_{p_o}^*}{c_{p_a}} + (1-x)(1+\omega \frac{M_a}{M_{wv}} \frac{c_{p_{wv}}^*}{c_{p_a}^*})/(1+\omega \frac{M_a}{M_{wv}})\}$$

$$\div \{x \frac{c_{p_o}^* T_o}{c_{p_a}^* T_a} + (1-x)(1+\omega \frac{M_a}{M_{wv}} (\frac{c_{p_{wv}}^*}{c_{p_a}^*} + \frac{h_{wv}^*}{c_{p_a}^* T_a}))/$$

$$(1+\omega \frac{M_a}{M_{wv}}) + \frac{Q}{n_a c_{p_a}^* T_a}\}$$

where S.G. is the specific gravity of the mixture, x is mole fraction of spilled gas, M is molecular weight, c_p^* is the molar specific heat capacity, n is moles, ω is specific humidity, and subscripts o, a and wv are spilled gas, air, and water vapor respectively. If one in addition assumes a linear decrease in plume temperature with mole fraction, a constant heat transfer coefficient, and a total thermal deficit equal to $n_o c_{p_o}^* (T_a - T_o)$, then

$$\frac{Q}{n_a c_{p_a}^* T_a} = A(\frac{c_{p_o}^*}{c_{p_a}^*})(1 - \frac{T_o}{T_a})(1-x)(x)$$

where A is a fraction between 0 and 1.0. Finally if one may assume ω, $\omega\, M_a/M_{wv}$, and $\omega\, M_a/M_{wv}\; c_{p_{wv}}^*/c_{p_a}^*$ are small with respect to $\omega\, M_a/M_{wv}\; h_{wv}^*/c_{p_a}^* T_a$, then

$$S.G._{mixt} \cong \{x(\frac{M_o}{M_a} - 1)+1\} \cdot \{x(\frac{c_{p_o}^*}{c_{p_a}^*} - 1)+1\}$$

$$\div \{x(\frac{c_{p_o}^* T_o}{c_{p_a}^* T_a} - \omega \frac{h_{wv}^* M_a}{c_{p_a}^* T_a M_{wv}} - 1) + \omega \frac{M_a}{M_{wv}} \frac{h_{wv}^*}{c_{p_a}^* T_a}$$

$$+ 1 + A \frac{c_{p_o}^*}{c_{p_a}^*} (1 - \frac{T_o}{T_a})(1-x)x\}$$

This simple model assumes all water vapor entrained is condensed and ignores the heat of solidification as a mean heat addition. Liquid water should reevaporate only after $T/T_a > .93$.

Sample computations for methane spills suggest qualitative behavior as shown in Figs. 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. Thus 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 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 Fig. 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

$$BFM = \left(\frac{\bar{h}}{k_s}\right)^2 a_s \theta = \frac{\text{Plume time over surface}}{\text{Time constant to change surface temperature}}$$

$\bar{h}$ = surface heat transfer coefficient
k_s = surface conductivity
a_s = surface diffusivity
θ = time of plume trajectory = x/u.

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 in the laboratory 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, ie., $St_m = St_p$, and heat transfer rates in the two cases should be in proper relation to plume entrainment rates.

3. WIND TUNNEL EXPERIMENT

A 1:100 scale model 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). In addition a point source spill without surrounding structures has been studied for various dense gas release conditions. All results presented herein are modeled with air-Freon-12 mixtures adjusted to simulate boiloff densities of methane. The assumption is thus made that $A \sim 0$ and all mixing is adiabatic with dry air.

4. RESULTS AND DISCUSSION

Density differences were observed to have significant effect on the downstream diffusion pattern of a ground source. Plumes exhibited an extremely large and rapid lateral spreading. Concentration profiles in the lateral direction were quite flat. The effect on mean centerline concentration was primarily multiplicative, retaining the same power-law decay with downstream distance as is normally observed with neutral plumes. As noted in Figs. 3 and 4 the maximum concentrations of the denser gases decay at similar rates but remain at slightly higher values.

As expected the presence of tank and dike storage structures increases local aerodynamic turbulence. At low boiloff rates gases are diluted quickly and visualization by titanium-tetrachloride marker smoke reveals neutral behaving plumes. For high boiloff rates, however, equivalent to near 1500 kg methane/sec in a 3 m/sec wind the density of the gas released dominates the plume dispersion pattern. High dike releases display gases spilling over the dike like water running over a spillway. Gases strike the floor and spread laterally with an included angle of nearly 120°.

Low dike high release situations also depict rapid lateral spreading. Orientation influences initial spreading somewhat but the general features of dispersion are unchanged.

The experimental sequence discussed suggests that plumes will initially spread rapidly laterally with little vertical mixing. The plume remains next to the ground only diffusing vertically as density gradients decrease. This scenario agrees with the bulk of field observations.

An alternative plume trajectory has been suggested by some investigations--Ecosystems (1973). They suggest the plume will travel unmixed meanwhile absorbing heat at its boundaries, then when it has passed from a negative to a positively buoyant condition it will lift off the ground and rise sharply into the atmosphere. This period of transport without mixing does not agree with previous field or laboratory experience (Murphy, 1974). Nonetheless if it occurs it reduces the extent of the hazard zone significantly; thus measurements are underway utilizing a helium-nitrogen laboratory gas cooled to 112°K. Early results suggest that the assumption $A \sim 0$ may be over-conservative, but simulation is closely tied to interpretation of the similarity of field to model heat transfer rates.

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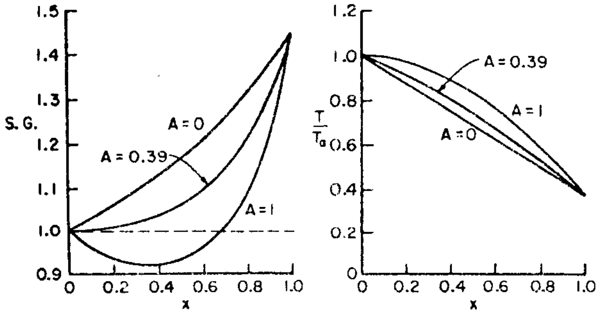


Figure 1. Methane - Dry Air Mixtures

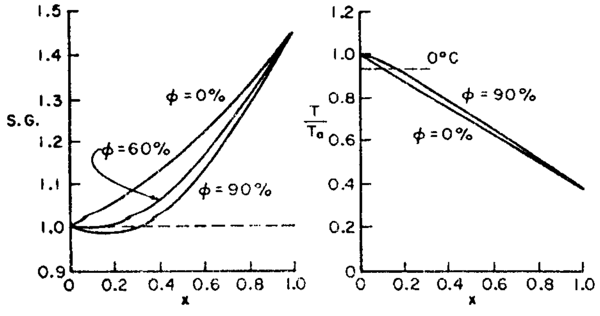
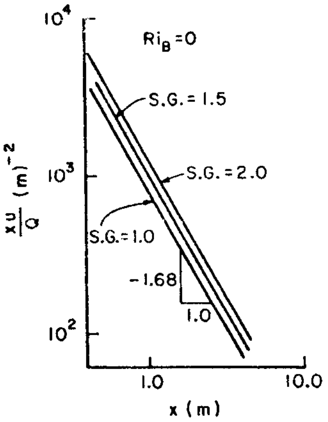


Figure 2. Methane - Moist Air Mixtures



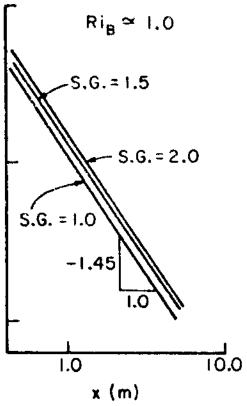


Figure 3. Figure 4.

Ground Level Centerline Concentrations - Dense Plumes - Point Source