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A DESCRIPTION AND COMPUTATIONAL ASSESSMENT OF THE SIGMET LNG VAPOR DISPERSION MODEL

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Summary

The SIGMET vapor dispersion model which has been used to predict dispersion of vapor clouds from catastrophic LNG spills on water is described. A summary of SIGMET predictions of LNG vapor dispersion from instantaneous spills of 10 m^3 to 25,000 m^3 LNG with different wind and atmospheric stability conditions is presented. SIGMET predictions made to test the sensitivity of the model to uncertainty in specification of turbulent dispersion coefficients and cloud-to-water energy and momentum transfer are shown. Comparisons are made between the SIGMET predictions for dispersion of neutrally buoyant and denser-than-air gases. Predictions of the model which differ significantly from those of classical air pollutant dispersion models and other currently used dense gas models are presented and discussed.

Introduction

In an earlier report prepared for the U.S. Coast Guard [1,2,3] on the prediction of LNG vapor dispersion following accidental spillage, the author recommended a more detailed evaluation of the SIGMET vapor dispersion model developed by Science Applications, Inc. (SAI) of La Jolla, California. The Cargo and Hazardous Materials Division of the U.S. Coast Guard contracted with the author to provide a description of SIGMET including a computational evaluation of:

(1) The methodology for describing turbulent mass, momentum and energy transfers and, by comparison with independent correlations available in the open literature, an estimate of the confidence level of the turbulent transfer coefficients used.

(2) The sensitivity of SIGMET results to uncertainties in the turbulent transfer coefficients.

(3) The sensitivity of SIGMET results to uncertainties in the specification of heat and mass transfer boundary conditions, particularly the sea-to-cloud momentum and heat transfer boundary conditions used for predicting vapor dispersion from catastrophic LNG releases onto water.

(4) The numerical stability and accuracy of the computer algorithm used

for solving the mass, momentum and energy balance partial differential equations.

(5) The effect of spill size on predicted flammable cloud travel distance for instantaneous LNG spills from 10 cubic meters to 25,000 cubic meters volume, and comparison with a similarly prepared relationship between flammable cloud travel distance and spill size predicted by the Germeles and Drake Model [1,4]. The SIGMET computer program was made available to the author, and it was agreed that a complete technical description of the model which respected the proprietary nature of the computer program code could be developed and provided as a part of the final report to the U.S. Coast Guard.

The final report [5] of this work contains a technical description of the SIGMET model in sufficient detail to allow independent judgment of the model, including a complete derivation of the model equations, transformation of the equations into a form suitable for machine solution, and a description of the computer algorithm. The report also contains the results of an extensive computational evaluation of the model directed to the question areas listed above. This paper presents a brief summary of the modelling methods used in SIGMET and outlines the principal results of the computational evaluation of the model for predicting vapor dispersion from catastrophic LNG spills onto water.

Description of SIGMET

Mass, momentum and energy balances are written for an arbitrary point in a segment of the atmosphere containing the dispersing LNG vapor. The hydrostatic approximation is invoked in the vertical momentum balance (neglecting acceleration in the vertical direction). Turbulent transport of mass, momentum, and energy is modelled using the first order, eddy diffusivity approach. The resulting balance equations for total mass, methane, momentum and energy, which are transformed to a co-ordinate system with dimensionless pressure as the vertical height co-ordinate and written in conservative form [5,6], are:

$$\frac{\partial \pi}{\partial t} = -\frac{\partial \pi u}{\partial x} - \frac{\partial \pi v}{\partial y} - \frac{\partial \pi \dot{\sigma}}{\partial \sigma} \tag{1}$$

$$\frac{\partial \pi C_f}{\partial t} = -\frac{\partial \pi u C_f}{\partial x} - \frac{\partial \pi v C_f}{\partial y} - \frac{\partial \pi \dot{\sigma} C_f}{\partial \sigma} + \frac{\pi}{\rho}\frac{\partial}{\partial x}\rho K_H \frac{\partial C_f}{\partial x} + \frac{\pi}{\rho}\frac{\partial}{\partial y}\rho K_H \frac{\partial C_f}{\partial y} + \frac{\rho g^2}{\pi^2}\frac{\partial}{\partial \sigma}\left[\rho K_V \frac{\partial \pi C_f}{\partial \sigma}\right] \tag{2}$$

$$\frac{\partial \pi u}{\partial t} = -\frac{\partial \pi u u}{\partial x} - \frac{\partial \pi u v}{\partial y} - \frac{\partial \pi u \dot{\sigma}}{\partial \sigma} - \pi\frac{\partial \phi}{\partial x} - \frac{\pi \sigma}{\rho}\frac{\partial \pi}{\partial x} + \frac{\pi}{\rho}\frac{\partial}{\partial x}\rho K_H \frac{\partial u}{\partial x} + \frac{\pi}{\rho}\frac{\partial}{\partial y}\rho K_H \frac{\partial v}{\partial y} + \frac{\rho g^2}{\pi^2}\frac{\partial}{\partial \sigma}\left[\rho K_V \frac{\partial \pi u}{\partial \sigma}\right] \tag{3}$$

$$\frac{\partial \pi v}{\partial t} = -\frac{\partial \pi uv}{\partial x} - \frac{\partial \pi vv}{\partial y} - \frac{\partial \pi v\dot{\sigma}}{\partial \sigma} - \pi \frac{\partial \phi}{\partial y} - \frac{\pi \sigma}{\rho} \frac{\partial \pi}{\partial y} + \frac{\pi}{\rho} \frac{\partial}{\partial x} \rho K_{\mathrm{H}} \frac{\partial v}{\partial x}$$
$$+ \frac{\pi}{\rho} \frac{\partial}{\partial y} \rho K_{\mathrm{H}} \frac{\partial v}{\partial y} + \frac{\rho g^2}{\pi^2} \frac{\partial}{\partial \sigma} \left[\rho K_{\mathrm{V}} \frac{\partial \pi v}{\partial \sigma}\right] \tag{4}$$

$$\frac{\partial \pi H}{\partial t} = -\frac{\partial \pi uH}{\partial x} - \frac{\partial \pi vH}{\partial y} - \frac{\partial \pi \dot{\sigma} H}{\partial \sigma} + \frac{\pi}{\rho} \frac{\mathrm{DP}}{\mathrm{Dt}} + \frac{\pi}{\rho} \frac{\partial}{\partial x} \rho K_{\mathrm{H}} \frac{\partial H}{\partial x}$$
$$+ \frac{\pi}{\rho} \frac{\partial}{\partial y} \rho K_{\mathrm{H}} \frac{\partial H}{\partial y} + \frac{\rho g^2}{\pi^2} \frac{\partial}{\partial \sigma} \left[\rho K_{\mathrm{V}} \frac{\partial \pi H}{\partial \sigma}\right] \tag{5}$$

In eqns. (1)—(5) the dependent variables are time averages, and the eddy diffusivities for mass, momentum and energy transfer, as well as the components of the horizontal coefficient matrix, have all been assumed equal. These assumptions result in a requirement for specification of only the "horizontal" (K_{H}) and "vertical" (K_{V}) diffusivities. The system of equations is closed using the ideal gas equation of state to relate local density, pressure, and temperature and the following approximate linear relation between local enthalpy and temperature.

$$H = \left[C_{\mathrm{P_{air}}}(1 - C_{\mathrm{f}}) + C_{\mathrm{P_{CH_4}}} C_{\mathrm{f}}\right] T + W L_0 (1 - C_{\mathrm{f}}) f(T) \tag{6}$$

where $f(T)$ = 0 for $T \leqslant 263$ K
= $(T - 263)/20$ for $263 < T < 283$
= 1 for $T > 283$

Equations (1)—(5) are written in finite difference form for subsequent computation of the dependent variables at the nodes of a spatial grid representing a segment of the atmospheric boundary layer containing the dispersing LNG vapor. The initial conditions (prespill) of local velocity (wind), temperature, pressure, relative humidity and LNG vapor concentration (normally zero initially) are specified at each grid point, and the system of finite difference equations is solved subject to the boundary conditions imposed on the atmospheric grid shown in Fig. 1. The method of assigning the velocity and thermodynamic variables on the boundary is described in detail in the final report to the U.S. Coast Guard [5].

The following sections summarize the treatment of the vapor source description (LNG liquid spread and evaporation), water-to-cloud heat and momentum transfer, and specification of turbulent eddy diffusivities.

LNG liquid spread-vapor generation sub-model

The LNG spill pool boundary location is computed using a density intrusion model previously used by most other investigators in the field [4,7, 8,9].

$$\frac{\mathrm{d}R}{\mathrm{d}t} = \left[1.4\, g \left(\frac{\rho_{\ell} - \rho_{\mathrm{w}}}{\rho_{\mathrm{w}}}\right) H\right]^{1/2} \tag{7}$$

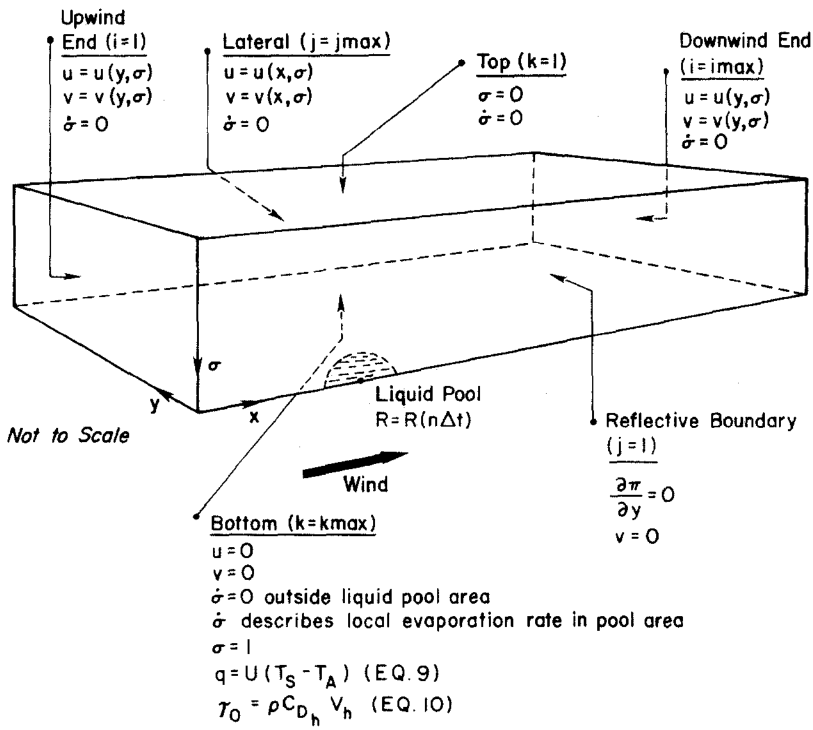

Fig. 1. Boundary conditions for SIGMET finite difference equations.

The spreading liquid is assumed to remain cylindrical, with decreasing height, and the pool radius is computed using eqn. (7) until a minimum pool thickness is reached, at which time the liquid pool is assumed to break up. After pool breakup, the pool evaporation rate is assumed to decrease according to an empirical relation proposed by Feldbauer et al. [10].

$$\dot{M} = \dot{M}_{\max} \exp\left[\frac{-0.04}{\rho H_{\mathrm{mw}}}(t - t_{\max})\right] \tag{8}$$

In the computations reported here, SAI assumed a constant LNG evaporation rate of 0.196 kg/m^2 sec. The resulting LNG pool radius and evaporation rate for a 25,000 m^3 LNG spill onto water is shown in Fig. 2. The predicted evaporation rate is compared with extrapolations of the limited small scale liquid spreading test data of ESSO [10] (~ 1 m^3 spills) and the U.S. Bureau of Mines [11] (~ 0.5 m^3 spills), where the liquid pool radius was found to be proportional to time.

Surface-to-cloud energy and momentum transfer sub-models

Energy transfer to the cloud from the surface occurs in association with the LNG vapor flux from the spreading pool; it is assumed that the enthalpy

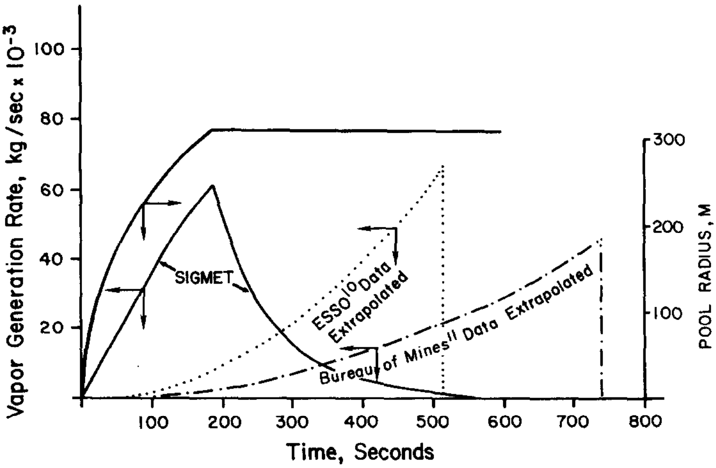

Fig. 2. LNG pool size and evaporation rate; 25000 m³ instantaneous spill on water.

of the LNG vapor transported across the pool surface—atmosphere boundary is that of saturated methane vapor at the atmospheric boiling point.

Conduction—convection heat transfer between the sea surface and the atmosphere—gas cloud is computed from the relation

$$q = U(T_S - T_A) \tag{9}$$

with a constant value of U, the overall heat transfer coefficient, of 20.4 Joules/m^2 sec K.

Momentum transfer to the cloud from the surface also occurs due to the LNG vapor flux from the spreading pool and is simulated with a boundary condition specifying the rate of local surface pressure increase in the grid [5]. Momentum transfer due to interfacial shear at the sea surface—atmosphere boundary is computed from the relation

$$\tau_0 = \rho \, C_{d_h} \, V_h^2 \tag{10}$$

with a constant value of C_{d_h}, the drag coefficient, of 0.001. The velocity reference height, h, in eqn. (10) was about 1 meter in the calculations reported here.

Turbulent mass, momentum, and energy transfer sub-model

The SIGMET LNG vapor dispersion model incorporates the eddy diffusivity model for describing turbulent momentum, mass and energy transfer. The Reynolds analogy is assumed, and all components of the horizontal coefficient matrix are assumed equal and denoted by K_H. Similarly, the two components of the vertical diffusivity matrix are assumed equal and are denoted by K_V.

Specification of vertical eddy kinematic viscosity coefficients by K_V in SIGMET is based on methodology proposed by Smith and Howard [5,12]. The following relation is used to compute the vertical diffusivities.

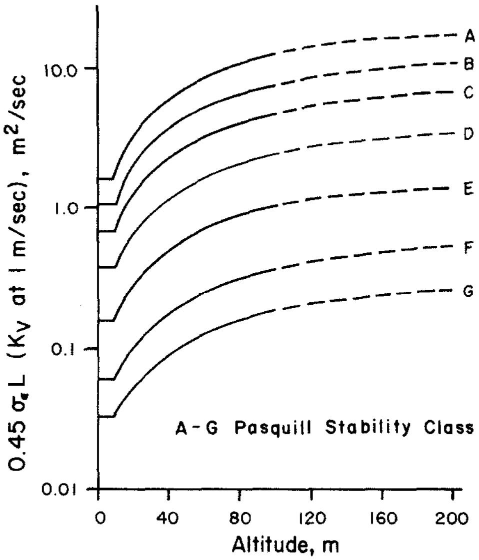

Fig. 3. ($0.45\ \sigma_\epsilon L$), or K_V at 1 m/s, used in SIGMET.

$$K_V = 0.45\ \sigma_\epsilon\ L\ V \qquad (11)$$

Correlations for σ_ϵ, the standard deviation of wind direction, and L, the turbulence scale length, with height and atmospheric stability are taken from Smith and Niemann [13] and Taylor [14] respectively. The values of $0.45\ \sigma_\epsilon\ L$, which can be interpreted as the value of K_V at 1 m/sec velocity, used in SIGMET are shown in Fig. 3 as a function of locally specified Pasquill stability class. Pasquill atmospheric stability classes are correlated with the local vertical temperature gradient as shown in Table 1.

Values of the vertical diffusion coefficient are calculated at each grid location and at each time step, as follows:

(1) The local vertical temperature gradient $\Delta T/\Delta Z$ is computed at the grid nodes.

TABLE 1

Correlation of Pasquill stability categories with vertical temperature gradient

$\Delta T/\Delta Z$ (K/100 m)	Stability class
< -1.9	A
-1.9 to -1.7	B
-1.7 to -1.5	C
-1.5 to -0.5	D
-0.5 to 1.5	E
1.5 to 4.0	F
> 4.0	G

(2) Interpolation of data shown in Table 1 gives the "local" stability classification, and the value of $0.45\ \sigma_\epsilon\ L$ is selected for the appropriate elevation from data shown in Fig. 3.

(3) The local horizontal velocity, V, is calculated as the vector sum of u and v.

(4) K_V is then calculated as

$$K_V = 0.45\ \sigma_\epsilon\ L\ V$$

unless $V < 1.0$ m/sec, in which case

$$K_V = 0.45\ \sigma_\epsilon\ L\ .$$

Minimum limits on the vertical diffusivity are imposed by holding the value of $0.45\ \sigma_\epsilon\ L$ constant with elevation below 10 meters and by setting a lower limit of 1 m/sec for V in eqn. (11). These restrictions may be questionable for shallow clouds and at low wind or cloud spreading velocities.

Values of the horizontal diffusivities, K_H, are determined by multiplying the local values of K_V by a factor dependent on the local stability classification as shown in Table 2 [15,16].

Computational assessment of SIGMET

Computer runs simulating the liquid spread, vapor generation and vapor dispersion of LNG spilled on water were supplied by SAI, at the author's request, for evaluation of the following:

(1) Sensitivity of the dispersion prediction to:
  (a) changes in turbulent transfer coefficients,
  (b) changes in sea surface-to-atmosphere heat and momentum transfer coefficients.

(2) Effect on dispersion prediction of:
  (a) wind speed,
  (b) atmospheric stability,
  (c) instantaneous spill size.

(3) Comparison with Gaussian model predictions for dispersion of neutrally buoyant gas releases.

The "standard" SIGMET computer run which was critically evaluated and used as a basis for subsequent run comparisons was the simulation of a

TABLE 2

Ratio of horizontal and vertical diffusivities

Stability class	K_H/K_V
D	1.0
E	10.0
F	25.0

25,000 m^3 LNG instantaneous spill onto water in a neutral (Pasquill D) atmosphere. Specifications for the standard run are given in Table 3. Ground level methane LFL (5%) contours at selected times are shown for the standard run in Fig. 4. The maximum downwind time average LFL travel is about 2600 meters, occurring at 950 seconds past spill time. The maximum width is about 2000 meters. This result is used as a basis for comparison runs designed to evaluate the following factors.

Turbulent transfer coefficient sensitivity

A literature search indicated that suggested correlations of height-dependent vertical momentum diffusivity in the atmospheric boundary layer differed by several hundred percent for any stability condition. There are no data available to check directly the applicability of these diffusivity specification methods (including the SIGMET method), which are based on atmospheric turbulence measurements under relatively stationary conditions, to the modelling of turbulence in a highly non-stationary process with vertical temperature gradients much larger than those which are the basis of the stability characterization shown in Table 1. It therefore appeared appropriate to test the sensitivity of the SIGMET model to changes in vertical diffusivity one order of magnitude lesser and greater than specified in SIGMET. Figure 5 shows maximum downwind distance to methane LFL for computer runs with the SIGMET-specified vertical diffusivities and for runs in which the vertical diffusivities were reduced by factors of 2 and 10 and increased by a factor of 10. The predicted down-

TABLE 3

Specifications for SIGMET 25,000 m^3 instantaneous spill "standard run"

Atmosphere and water conditions	
Atmospheric stability	Pasquill D (—1.0 K/100 m)
Wind velocity	2.24 m/s
Air temperature	68°F (293 K)
Water temperature	58°F (288 K)
Relative humidity	68% (0.001 kg H_2O/kg dry air)
Pressure	
Top of grid	980 mbar (constant)
Sea surface	1000 mbar (initially, varies)
Finite difference equation specifications	
Mesh size (total 10,000 m long; 2400 m wide (half width); 200 m depth)	
Horizontal	$\Delta x = \Delta y = 200$ m (uniform)
Vertical	Δz varying, about 1 m at sea surface to about 20 m at grid top
Time step	2 s (uniform)

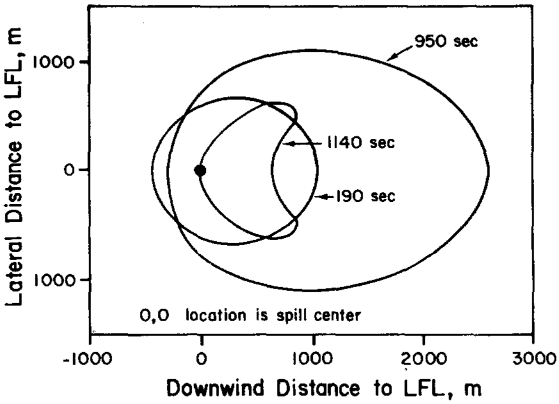

Fig. 4. Ground level LFL contours; 25000 m³ "standard" run.

wind travel is changed by a factor of about 2 for a corresponding change by a factor of 10 in the vertical diffusivity. This dependence on K_V is less than would be expected in the absence of gravity spread effects. It was noted that the maximum horizontal area of the LFL cloud boundary is of the order of 10 times greater when the diffusivities are reduced by a factor of 10. It appears that with markedly lower vertical diffusion rates, the cloud spreads further laterally due to density effects and therefore has a larger area through which vertical diffusion can occur. Since the area for vertical diffusion increases when the vertical diffusivity is decreased, the resulting predicted downwind travel is not increased as markedly as would be expected if gravity spreading were not important.

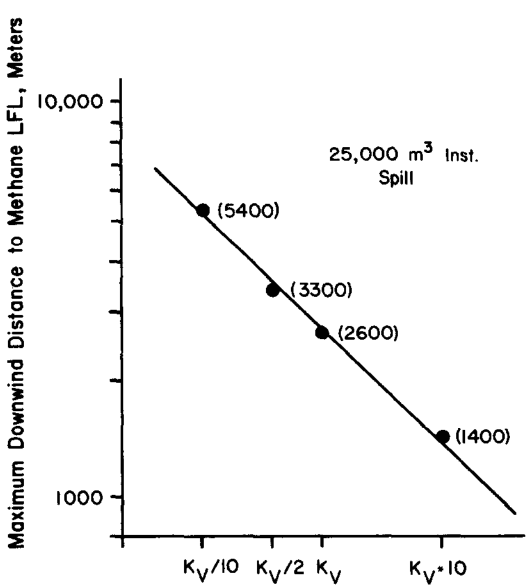

Fig. 5. Effect of vertical diffusivity; 25000 m³ instantaneous spill.

Water—atmosphere momentum and heat transfer sensitivity

A literature survey indicated that the overall heat transfer coefficient used in SIGMET to predict heat transfer between the sea surface and the cloud might be high by about one order of magnitude, and the drag coefficient applied at the water—atmosphere boundary might be high by as much as a factor of 5. When the sea surface-to-cloud overall heat transfer coefficient was decreased to 2.04 Joules/m^2 sec K (a factor of 10), the predicted downwind LFL travel increased by about 50% to approximately 3800 m. Although some anomalies were present in the result of a run with the drag coefficient reduced by a factor of 5, the results indicated that maximum downwind LFL travel was not increased.

Effect of wind velocity

Figure 6 shows predicted maximum downwind LFL travel distance as a function of wind speed. The point for 2.24 m/sec is from the "standard run", and the point for 4.48 m/sec is from a run made for this study in which all other parameters were the same as the standard run. The points for wind velocities of 2.57, 6.95, and 12.0 m/sec were taken from England et al. [17] and are for 30,000 m^3 spills. The differences in maximum downwind distances predicted by SIGMET for 25,000 m^3 and 30,000 m^3 spills at the same wind speed are small, justifying inclusion of all of the points shown in Fig. 6 to indicate cloud travel dependence on wind speed. The increased maximum downwind LFL distances with higher wind speeds are due to enhanced "bulk" movement of the cloud in the higher wind field. The increased diffusion rates (associated with increased velocity) are more than compensated for by the increased rate of advection downwind, and the cloud travels farther before dropping (by vertical diffusion) below LFL. This effect is associated with the

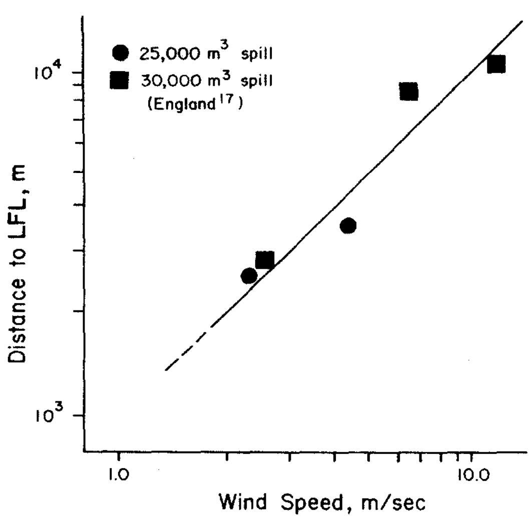

Fig. 6. Effect of wind speed.

finite time duration of the LNG evaporation process and the relative importance of vertical diffusion and x-direction advection. It is expected that for steady releases SIGMET would predict shorter downwind LFL travel distances with increased wind speed (consonant with plume model predictions).

Effect of atmospheric stability

The effect of atmospheric stability was checked by comparing two computer runs, one with a neutral (D) atmosphere specification, and one with a stable (F) atmosphere specification, with all other parameters identical to the standard run except that the wind velocity was 10 m.p.h. The predicted LFL ground track for the F stability prediction was wider, and the maximum downwind travel was about 60% greater, than for D stability conditions.

Effect of spill size

Figures 7 and 8 show maximum downwind LFL distances for 5 m.p.h. and 10 m.p.h. wind speeds as a function of (instantaneous) spill volume. Excepting spill volume (and wind velocity) all other parameters input to the model were the same as for the standard run. For comparison, Figs. 7 and 8 also show maximum downwind LFL distances predicted by the Germeles and Drake model [4]. It would be expected that the predictions of these two models would differ more for stable atmosphere releases. However, the indicated agreement of predicted maximum downwind distance to LFL shown for spills up to about 1000 m^3 and the subsequent divergence of the predictions for larger spills indicates the potential difficulty in validation of models, which are to be used to model catastrophic spills, with field trials. The results shown in Figs. 7 and 8 suggest that some model-predicted measures of dispersion, such as maximum distance to LFL, may not be discriminated in field trials unless very large (perhaps prohibitively so) quantities are released.

Effect of neutral vs. negatively buoyant releases

The downwind LFL travel distances predicted by SIGMET for large (25,000 m^3) LNG spills are much shorter than would be predicted for neutrally buoyant releases of the same volumes using classical air pollutant dispersion models. The effect of atmospheric stability on downwind LFL travel is also predicted by SIGMET to be less than suggested by classical "Gaussian" models. These effects have been attributed to gravity spreading of the LNG vapors and to vertical temperature stratification associated with the cold LNG vapors, respectively. Analysis of the vertical diffusivity profiles utilized in SIGMET indicates that the vertical diffusivities reflect conditions caused by the presence of the cloud (through vertical temperature gradients) rather than the turbulence characteristics normally associated with the prevailing atmospheric conditions. The predicted turbulence inside the LNG cloud is generally characteristic of a stable atmosphere, since the vertical temperature gradients are positive. If the shorter distances predicted by SIGMET for LNG vapor dispersion are due mainly to effects associated with gravity spreading, much

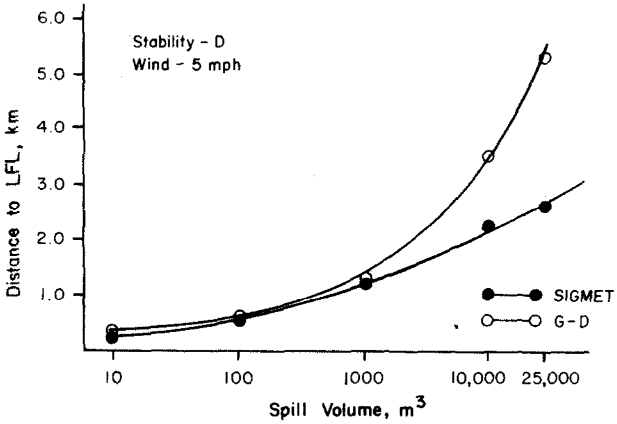

Fig. 7. *Maximum distance to LFL vs. spill size — 5 mph wind.*

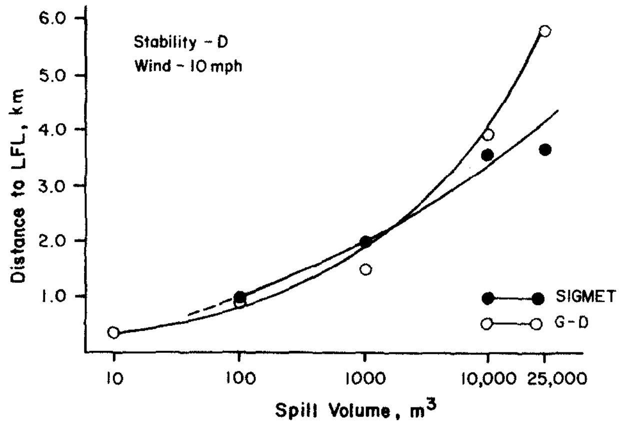

Fig. 8. Maximum distance to LFL vs. spill size — 10 mph wind.

longer distances should be predicted by SIGMET for dispersion of a neutrally buoyant release (of the same mass) with similar diffusivities. Furthermore, SIGMET predictions should show a much greater dependence of downwind travel distance on atmospheric stability for neutrally buoyant, ambient temperature gas releases.

SIGMET simulations were made of the release and dispersion of a neutrally buoyant gas (mass equivalent to 25,000 m^3 LNG) with other parameters as specified for the standard run, into a 5 m.p.h. wind field with D and F stability. The F stability run indicated much larger downwind travel distances. Because of the desire to maintain the same grid step and time step size in all comparison runs, and the greatly increased computer storage and time requirements for the neutrally buoyant release simulation in an F stability atmosphere, SIGMET calculations were only carried out to 6000 meters downwind. However, extrapolation indicated the maximum downwind distance to the 5% concentration to be about 17,000 meters (10.6 miles). The maximum downwind travel for the neutrally buoyant release in a D stability atmosphere was about 2200 meters. This is only slightly less than the maximum distance predicted for the equivalent mass LNG cloud in which the vertical diffusivities are an order of magnitude smaller. The roughly equal downwind distances for the LNG dispersion and the neutrally buoyant cloud dispersion in a neutral atmosphere is explained by the large differences in width of the clouds and the associated large differences in area for vertical diffusion. These results for neutrally buoyant cloud dispersion provide strong evidence that the short distances predicted by SIGMET for LNG cloud dispersion are associated with the gravity spreading process. The long distance predicted for the dispersion of a neutrally buoyant cloud in an F stability atmosphere also provides strong, if indirect, evidence that the shorter distances predicted for LNG clouds are not a numerical artifact associated with artificial viscosity or numerical dispersion in the advection computation.

Conclusions and recommendations

The primary uncertainties in the SIGMET simulation of catastrophic LNG releases are probably associated with vertical turbulent transfer modelling and vertical advection of the cold vapors. Lesser uncertainties appear associated with boundary value specifications for momentum and energy transfer. It is the author's opinion that the SIGMET predictions described herein can be viewed as reasonably realistic estimates if the ranges in uncertainties in turbulent transfer and sea-surface-to-atmosphere heat transfer suggested are considered.

The "comparisons" discussed herein are largely based on predicted maximum downwind time average LFL travel distance. For risk assessment use, other factors such as horizontal and vertical extent of the cloud flammable limits and peak-to-average ratio must be considered.

The results described herein should be compared with results of hydrodynamic codes which do not incorporate the hydrostatic approximation.

Since an overriding uncertainty in predicting dispersion of dense gases is due to the lack of data with which to check turbulence models, future dense gas spill tests should address this need.

Acknowledgements

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Notation

C_{d_h} drag coefficient, dimensionless

C_f	mass fraction methane (kg/kg)
C_p	constant pressure heat capacity (Joules/kg K)
g	gravitational acceleration (m/sec^2)
H	enthalpy, Joules/kg, or LNG pool depth (m)
H_{mw}	minimum LNG pool thickness (m)
K_H	diffusivity for horizontal flux of mass, momentum or energy (m^2/sec)
K_V	diffusivity for vertical flux of mass, momentum or energy (m^2/sec)
L	atmospheric turbulence scale length (m)
L_0	latent heat of water (Joules/kg)
$\dot{M}$	LNG pool evaporation rate (kg/sec)
$\dot{M}_{max}$	maximum LNG pool evaporation rate (kg/sec)
P	pressure (N/m^2)
q	sea-to-atmosphere heat flux (Joules/m^2 sec)
R	liquid LNG pool radius (m)
T	temperature (K)
t	time (sec)
t_{max}	time of LNG liquid pool breakup (sec)
U	overall heat transfer coefficient (Joules/m^2 sec K)
u	magnitude of x-direction velocity (m/sec)
v	magnitude of y-direction velocity (m/sec)
V	local mean velocity (m/sec)
W	kg water vapor per kg air
x,y,z	Cartesian coordinates (m)

Greek symbols

π	$P_S - P_T$ (decibars)
ρ	density (kg/m^3)
σ	$\dfrac{P - P_T}{P_S - P_T}$, dimensionless pressure coordinate
$\dot{\sigma}$	$\dfrac{D'\sigma}{Dt}$, substantial derivative in x, y, σ, t coordinates
σ_ϵ	standard deviation of wind direction (radians)
τ_0	turbulent shear stress (drag) at water surface (N/m^2)
ϕ	geopotential height = gz

Subscripts

A	denotes atmosphere
h	denotes z = h
ℓ	denotes liquid methane (LNG assumed pure methane)
S	designates surface condition
T	denotes top of computational grid
w	denotes water

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