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# DISPERSION OF VAPOR FROM LIQUID NATURAL GAS SPILLS — EVALUATION OF SIMULATION IN A METEOROLOGICAL WIND TUNNEL: FIVE-CUBIC-METER CHINA LAKE SPILL SERIES

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## Summary

A series of six-cubic-meter liquid natural gas (LNG) spills were performed in 1978 at the China Lake Naval Weapons Center, CA. A parallel set of modeled spills were simulated in meteorological wind-tunnel facilities to provide field-test planning information, to extend the value of the limited set of field measurements carried out, and to evaluate the concept of physical modeling of LNG plume dispersion as a predictive hazard analysis tool.

## Nomenclature

| | |
|---|---|
| $M$ | mass ratio, $\rho_s Q/\rho_a U_a L^2$ |
| $MR$ | momentum ratio, $\rho_s Q^2/\rho_a U_a L^4$ |
| $R$ | volume flux ratio, $Q/U_a L^2$ |
| $Fr$ | densimetric Froude number, $U_a{}^2/g[(\rho_s - \rho_a)/\rho_a]L$ |
| $Fr_f$ | flux Froude number, $U_a{}^3 L/g[(\rho_s - \rho_a)/\rho_a]Q$ |
| $SG$ | specific gravity, $\rho_s/\rho_a$ |
| $Re$ | Reynolds number, $Q/\nu L^2$ |

## Introduction

Recent efforts to expand the world's natural gas supply include the transport of natural gas in a liquid state from distant gas fields. Unfortunately, storage and transport of liquid natural gas may involve a relatively large environmental risk. To transport liquid natural gas (LNG), it is maintained in the liquid state at −162°C. At this temperature, if a storage tank on a ship or on land were to rupture and the contents spill out onto the earth's surface, rapid boiling of the LNG would ensue, and the liberation of a potentially flammable vapor would result. Past studies have demonstrated that a cold LNG vapor plume remains negatively buoyant for most of its lifetime [1, 2]. A hazardous mixture will therefore extend downwind at ground level until the atmosphere has diluted the LNG vapor below the lower flammability

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limit (a local concentration of methane less than 5% by volume).

Liquid natural gas was spilled in small amounts onto a pond at the China Lake Naval Weapons Center, CA, during 1978, to examine the physics of LNG plume dispersion behavior. A parallel wind-tunnel model program was performed in the meteorological wind tunnel of Colorado State University to provide field-test planning information, to extend the value of the limited set of field measurements, and to evaluate the concept of physical modeling of LNG plume dispersion as a predictive hazard analysis tool. The measurement results described herein provided a foundation for the interpretation of terrain effects in the field experiments and an explanation for concentration vagaries noticed in the field data during wind direction variation. Wind-tunnel laboratory measurements permit a degree of control of safety and of meteorological, source and site variables not often feasible or economic at full scale. Nonetheless, satisfactory simulation of the behavior of dense plumes is not straightforward; a discussion of some of the problems associated with this approach follows.

## Laboratory simulation of dense plumes resulting from cryogenic spills

Physical modeling in wind tunnels requires consideration of the physics of the atmospheric surface layer as well as the dynamics of plume motion. Reliable criteria for simulating the pertinent physical properties of the atmospheric boundary layer have been demonstrated by several investigators [3, 4]. Frequently, partial simulation suffices when the test domain is limited in time and space. Specific problems associated with the dispersion of cold natural gas plumes have been previously discussed by Meroney et al. [5, 6].

*Prior experience: dense gas-plume simulation*

A number of controlled laboratory experiments have been conducted previously to evaluate the significance of density for dispersion of gaseous plumes. Sakagami and Kato [7] measured diffusion and vapor rise from a small ($5 \times 10$ cm) LNG well in the floor of a wind tunnel of cross-section $50 \times 50$ cm and length 200 cm. They confirmed a tendency for the gas to remain concentrated at ground level. Boyle and Kneebone [8] released LNG on water, pre-cooled methane, and propane in a specially built asbestos-wall wind tunnel of cross-section $1.5 \times 1.2$ m and length 5 m. No attempt was made to scale the atmospheric surface-layer velocity profile or turbulence. It was concluded that release of propane at room temperature simulated an LNG spill quite well, but the pre-cooled methane releases lofted, suggesting to the authors incorrect release temperature or exaggerated heat transfer from the ground surface. Hoot and Meroney [9] and Hall et al. [10] considered ground-level, point-source releases of heavy gases in wind tunnels. Hoot and Meroney found that releasing gases with specific gravities as great as 3.0 only slightly shifted the decay of maximum concentration with distance, despite significantly different plume cross-sections. Hall et al. considered transient and continuous releases on a rough surface (plume height as a function of roughness height) and on uphill 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. [11] 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 directions and constant boil-off rates, under both neutral and stable atmospheric stratifications. Subsequent measurements by Meroney et al. [12] examined transient releases in similar configurations as well as dense plumes on uphill slopes, and buoyant plume lift-off 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 $N_2$).

These latter measurements suggested that heat transfer effects may be small over the significant time scales; hence, gas density should be adequately simulated by using isothermal high-molecular-weight gas mixtures, during moderate winds. Visualization of similar tests for the range of model scales used (1 : 130 to 1 : 666) indicated similar plume geometries. The concentration results for the different model scales agreed to within the experimental accuracy of ±20%. Similarly, repeated identical tests also showed good agreement; hence, the Reynolds number must play a minor part in the dense-gas dispersion situations considered.

The major practical limitations to accurate wind-tunnel simulation of LNG dispersion are operational constraints, particularly the inability to obtain a steady wind profile or to simulate accurately 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 side-walls, these considerations permit the development of a performance envelope for a particular wind-tunnel facility; examples of such envelopes have been given by Meroney et al. [5].

*Partial simulation criteria: dense gas plumes*

Considering the dynamics of gaseous plume behavior, exact similitude requires the simultaneous equivalence of mass, momentum flux and volume flux ratios, densimetric Froude number, Reynolds number, and specific gravity (see Nomenclature). Consideration of variable-property, non-ideal gases and the thermal behavior of the plume mixture introduces additional constraints on variations in the specific heat capacity [13].

For a plume whose temperature, molecular weight, and specific heat are all different from that of the ambient air, which is the case for a cold natural gas plume, the constraint of equivalence in the variation of the specific gravity upon mixing must be relaxed slightly if a gas different from that of the prototype is to be used for modeling. Calculations for equivalent cold or isothermal dense plumes using a single-box model, such as those used by Fay [14] and Meroney and co-workers [15], reveal only small perturbations in the predicted concentrations.

A reasonably complete simulation may be obtained in some situations even when a modified initial specific gas ratio is stipulated. By increasing the specific gravity of the model gas compared to the prototype gas, the reference velocity over the model is increased. It is difficult to generate a flow similar to that of the atmospheric boundary layer in a wind tunnel operated at very low wind speeds. Thus the effect of modifying the model's specific gravity extends the range of flow situations which can be modeled accurately. Meroney et al. [16] and Isyumov and Tanaka [17] found that Froude number and volume flux equality provided conservative ground-level concentrations for buoyant plumes. Skinner and Ludwig [18] obtained similar, elevated plume trajectories when flux Froude number and momentum ratio equivalences were required.

Scaling of the effects of heat transfer by conduction, convection, radiation, or latent heat release from entrained water vapor cannot be reproduced when the model source gas and environment are isothermal. Fortunately, for LNG plumes dispersing in a noncalm environment, the effects of heat transfer by conduction, convection, and radiation from the surroundings are sufficiently small that the plume buoyancy remains essentially unchanged [12]. The influence of latent heat release by moisture upon the plume's buoyancy is a function of the quantity of water vapor present in the plume and of the humidity of the ambient atmosphere. Such phase-change effects on plume buoyancy can be very pronounced in some prototype situations where large amounts of water vapor are entrained. Fortunately the China Lake site has very low humidity.

The modeling of the plume Reynolds number is relaxed in all physical model studies. This parameter is thought to be of small importance, since the plume's character will be dominated by background atmospheric turbulence soon after its emission. But, if one were interested in plume behavior near the source, then steps would have be taken to insure that the model's plume was fully turbulent.

*Simulation of the China Lake LNG spill plume*

The buoyancy of a plume from an LNG spill is a function of both the mole fraction of methane and temperature. If the plume entrains air adiabatically, then it will remain negatively buoyant for its entire lifetime. A release of an isothermal high-molecular-weight gas will behave in a similar manner to a cold plume entraining air adiabatically, within small variations due to differences between the specific heat capacities of the source gas and air (see discussion in preceding section). Hence, to simplify laboratory procedures, the equality of model and prototype specific gravities was relaxed so that pure argon could be used as the source gas. Other high-molecular-weight gas mixtures are possible; however, argon produces a favorable signal-to-noise ratio for the concentration probes used (see below). The equivalence of momentum flux ratios is not physically significant for a ground source released at low flow rates over a large area (as was the case for LNG released on the China Lake test pond); hence, model conditions were stipulated on the basis of equivalence between densimetric Froude numbers and volume flux ratios. Undistorted scaling of the velocity components was maintained, which implies undistorted scaling of source strength.

Since the thermally variable prototype gas was simulated by an isothermal simulation gas, the concentration measurements obtained in the model must be adjusted to the equivalent concentrations that would be measured in the field. This scaling is necessary because the number of moles released in a cold methane plume is larger than the number of moles released in an isothermal plume of equivalent volume source strength. Ideal-gas law behavior leads to the relationship which is derived in [13]:

$$\chi_p = \chi_m/[\chi_m + (1-\chi_m)T_s/T_a]$$

where $\chi_m$ is the volume (or mole fraction) measured during the model tests, $T_s$ is the temperature of the LNG source under field conditions, and $T_a$ is the ambient air temperature under field conditions.

The full-scale source boil-off rate per unit area over the time duration of a spill of LNG on water is highly unpredictable. As there were no data on the variable areas and volumes used in the different LNG tests conducted at

TABLE 1

Prototype conditions[a]

| Characteristic | Test No. | | | |
|---|---|---|---|---|
| | 18 | 19 | 20 | 21 |
| Release diameter, $D$ (m) | 20 | 20 | 20 | 20 |
| Total release volume, $V_{LNG}$ ($m^3$) | 4.39 | 5.2 | 4.5 | 4.2 |
| $V_{LNG}$ (at boil-off temperature) ($m^3$) | 1000 | 1184.5 | 1025 | 956.7 |
| Spill duration, $\Delta t$ (s) | 67 | 59 | 77 | 53 |
| Boil-off rates, $\dot{m}$ (kg $s^{-1}$) | 27.7 | 37.4 | 24.8 | 33.6 |
| $Q$ (at boil-off temperature) ($m^3$ $s^{-1}$) | 14.9 | 20.1 | 13.3 | 18.0 |
| Wind speed, $U$, at a height of 2 m (m $s^{-1}$) | 6.7 | 5.1 | 12.4 | 4.9 |
| Wind direction | 214° | 260° | 256° | 224° |
| Stability (Pasquill—Gifford category) | C | C—D | C | C |
| Humidity (%) | 16 | 29 | 15 | 21 |
| Reynolds number, $UD/\nu$, at a height of 2 m | $8.8 \times 10^6$ | $6.7 \times 10^6$ | $1.6 \times 10^7$ | $6.4 \times 10^6$ |
| Froude number, $U^2/g(\Delta\rho/\rho)D$, at a height of 2 m | 0.42 | 0.24 | 1.42 | 0.22 |

[a] $T_{b.o.}$ = 111.63 K; $\rho_{LNG}$ = 422.63 kg $m^{-3}$; $\rho_{NG}$ (at boil-off temperature) = 1.86 kg $m^{-3}$; $\nu_a$ = 1.526 × $10^{-5}$ $m^2s^{-1}$; $\rho_a$ = 1.186 kg $m^{-3}$.

China Lake, the source conditions were approximated by assuming a steady boil-off rate for the duration of the spill over a constant area. Prototype and model conditions are specified in Tables 1 and 2.

TABLE 2

Model conditions[a]

| Characteristic | Test No. | | | |
|---|---|---|---|---|
| | 18 | 19 | 20 | 21 |
| Release diameter, $D$(cm) | 23.5 | 23.5 | 23.5 | 23.5 |
| Total release volume, $V$ (cm$^3$) | 1625 | 1929 | 1669 | 1558 |
| Boil-off duration, $\Delta t$ (s) | 8.7 | 7.7 | 10.8 | 6.9 |
| Boil-off rate, $Q$ (cm$^3$ s$^{-1}$) | 186 | 251 | 166 | 225 |
| Specific gravity | 1.38 | 1.38 | 1.38 | 1.38 |
| Wind speed, $\overline{U}$, at a height of 1.3 cm (cm s$^{-1}$) | 60 | 46 | 112 | 44 |
| Wind direction | 214° | 260° | 256° | 224° |
| Stability (Pasquill—Gifford category) | D | D | D | D |
| Reynolds number, $\overline{U}D/\nu$, at a height of 2.4 cm | 9,400 | 7,100 | 17,200 | 6,900 |
| Froude number, $U^2/g(\Delta\rho/\rho)D$, at a height of 2.4 cm | 0.42 | 0.24 | 1.43 | 0.23 |

[a] $\rho_{Ar}$ = 1.65 kg m$^{-3}$; length scale ratio (LS) = 85; $(U_a)_m = [(SG_m - 1)/(SG_p - 1)]^{1/2}(1/LS)^{1/2}(U_a)_p$; $t_m = [(SG_p - 1)/(SG_m - 1)]^{1/2}(1/LS)^{1/2} t_p$; $Q_m = [(SG_m - 1)/(SG_p - 1)]^{1/2}(1/LS)^{1/2} Q_p$; $L_m = (1/LS)L_p$.

## Laboratory methodology

Simulation methods required to produce a model atmospheric boundary layer have been described in some detail by Cermak [3]. Special procedures and equipment required for measurements of dense plumes are described in Meroney et al. [5, 6].

*Wind-tunnel facility*

The environmental wind tunnel (EWT) at Colorado State University was used for the LNG-spill test series. This wind tunnel, designed especially to study atmospheric flow phenomena, incorporates special features such as an adjustable ceiling, rotating turntables, transparent boundary walls, and a long test-section (3.6 m wide × 2.1 m tall × 17.4 m long) to permit reproduction of micrometeorological behavior at larger scales. Mean wind speeds of 0.15—12 m s$^{-1}$ can be obtained in the EWT. Boundary-layer depths 1 m thick over the downstream 6 m can be obtained by using vortex generators at the test-section entrance and surface roughness on the floor. The flexible test-section roof of the EWT is adjustable in height to permit the longitudinal pressure gradient to be set at zero. For the present tests, the vortex generators at the tunnel's entrance were followed by 10 m of smooth floor, and a 3 m approach ramp to a model of the topography at the China Lake site.

*Models*

1 : 85 and 1 : 170 scale models of the China Lake topography were constructed for use in the EWT. The topographic relief of the China Lake site is shown in Fig. 1. A cylindrical plenum manufactured with a perforated upper plate was centered in the middle of the test-site pond. The source gas, argon, stored in a high-pressure cylinder, was directed through a solenoid valve, a flowmeter, and onto the circular-area source mounted in the model pond. All source release conditions were step functions; thus, their profiles can be recreated from the data in Table 1.

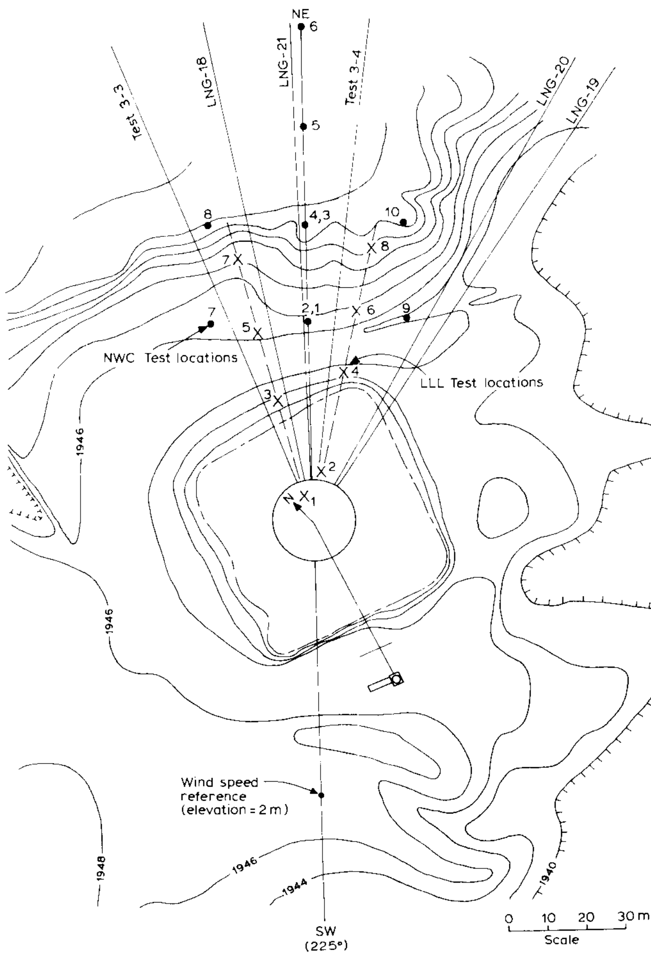


Fig. 1. Topography of China Lake test site.

*Wind profiles and turbulence measurements*

Velocity profile measurements and reference wind speed conditions were obtained using a Thermo-Systems Inc. (TSI) Model 1050 anemometer and a TSI Model 1210 hot-film probe. Turbulence measurements were made with this sytem for the longitudinal velocity component and with a TSI split-film probe connected to two TSI 1050 anemometers for both longitudinal and vertical component measurements. Since the voltage responses of these anemometers are nonlinear with respect to velocity, a multipoint calibration of system-response versus velocity was utilized for data reduction.

*Concentration measurements*

The concentrations of methane produced during an LNG spill are inherently time dependent. It is necessary to have a frequency response to concentration fluctuations of at least 50 Hz to isolate peaks of methane concentration greater than 5% by volume (the lower flammability limit (LFL) of methane in air); hence, an aspirating hot-film probe was used for this study (see Fig. 2).

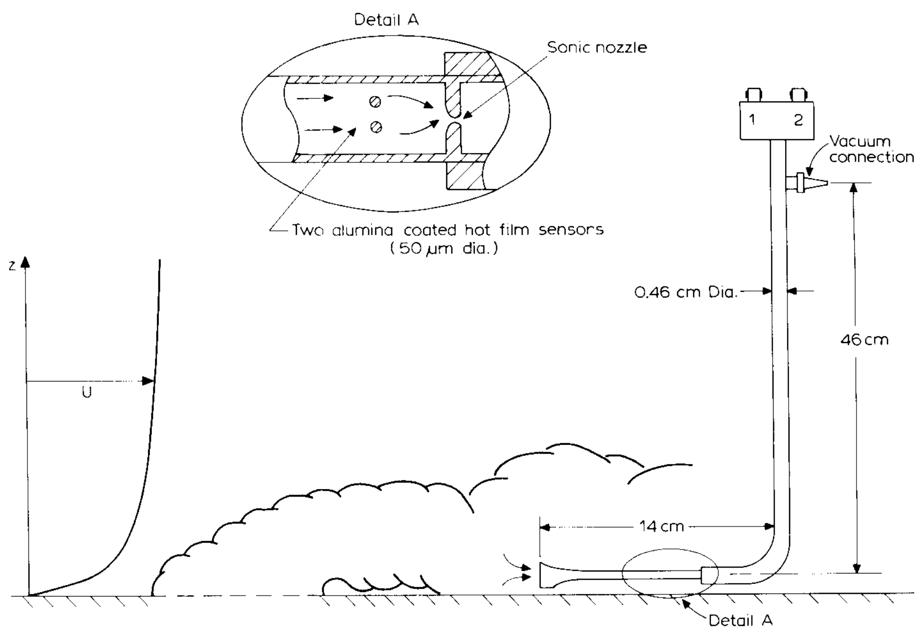


Fig. 2. Hot-film aspirating concentration-probe.

The basic principles governing the behavior of such a probe have been discussed by Blackshear and Fingerson [19], Brown and Rebollo [20], Kuretsky [21], and Jones and Wilson [22]. A vacuum source sufficient to choke the flow through the small orifice just downwind of the sensing elements was applied. Only one of the two films in this special probe was an active element for the measurements of concentration in the present study.

This film was operated in constant-temperature mode at a temperature above that of the ambient air. A feedback amplifier maintained a constant-overheat resistance through adjustment of the heating current. A change in output voltage from this sensor circuit corresponds to a change in heat transfer between the hot wire and the sampling environment.

The heat transfer rate from a hot cylindrical film to a gas flowing over it depends primarily upon the film diameter, the temperature difference between the film and the gas, the thermal conductivity and viscosity of the gas, and the gas velocity [22]. For a film in an aspirated probe with a sonic throat, the gas velocity can be expressed as a function of the ratio of the probe cross-sectional area at the film position to the area at the throat, the specific heat ratio, and the speed of sound in the gas. The latter two parameters, as well as the thermal conductivity and viscosity of the gas, mentioned earlier, are determined by the gas composition and temperature. Hence, for a fixed probe geometry and film temperature, the heat transfer rate, or the related voltage drop across the film, is a function only of the gas composition and temperature. Since all tests performed in this study were for an isothermal flow situation, the film's response was a function only of gas composition.

For probe calibration, argon—air mixtures of known compositions were passed through a heat exchanger to condition the gas to the tunnel temperature. These known compositions were produced from bottles of pure argon and pure air passed through a Matheson gas proportioner, or were drawn from a bottle of prepared gas composition provided by Matheson Laboratories. For an overheat ratio (temperature of film/ambient temperature) of 1.75, the voltage drop varies monotonically with argon concentration. Higher overheat ratios led to failure.

The effective sampling area of the probe inlet is a function of the probe aspiration rate and of the distribution of approach velocities of the gases to be sampled. A calculation of the effective sampling area during all tests suggested that this area was always less than the area of the probe inlet, 1.88 $cm^2$. Thus the resolution of the concentration measurements as applied to the China Lake site is $\sim 1.6$ $m^2$.

The travel time from the sensor to the sonic choke limits the upper frequency response of the probe. At high frequencies the correlation between concentration fluctuations and velocity fluctuations (velocity fluctuations are a result of the changes of sonic velocity with concentration) at the sensor begins to decline. Wilson and Netterville [24] examined the operating characteristics of similar, small, aspirated concentration-sensors. They calibrated their sensors dynamically and found a flat response to $\sim 200$ Hz. The CSU aspirated probe was expected to have an electronic upper frequency response of 1000 Hz, but, to improve signal-to-noise characteristics, the signal was filtered at 200 Hz. This is well above the expected frequencies of concentration fluctuations.

The errors caused by the assumption of piecewise linearity between calibration points in the reduction of the concentration data are approximately the component value (percent argon) ±75%. The errors caused by calibration changes due to temperature drift are ~0.1% of the component value per degree centigrade. Since the tunnel temperature varies at most by ± 5°C during a given test period, the maximum error due to temperature drift would be 0.5% of the component value. Final accumulated errors result in a confidence level of ±0.8% methane at measured levels near 2.5%.

**Test program results**

Summaries of the prototype and model test conditions for the LNG spill tests 18, 19, 20 and 21 performed during the fall of 1978 at the China Lake Naval Weapons Center are presented in Tables 1 and 2, respectively. All dimensions reported for the wind-tunnel results are in the equivalent full scale values. The coordinate origin for all figures is the LNG spill point (see Fig. 1). The positive $x$-axis is in the direction of the prevailing wind.

*Characteristics of the modeled boundary layer*

Measurements of the approach-flow characteristics were obtained for the model flow over the China Lake scale topography. These characteristic length and velocity scales should be comparable with those expected to occur over the China Lake site. Counihan [25] has summarized the values of aerodynamic roughness $z_0$, longitudinal-velocity integral length scale $\Lambda_x$, and the power-law index $1/n$ that may be expected to occur in the atmosphere. Table 3 compares values of these quantities as cited by Counihan and values scaled up from the model tests. Figures 3 and 4 show the profiles of mean velocity and local turbulence intensity, respectively. Profile measurements were not available for the field measurements.

TABLE 3

Summary of approach-flow characteristics

| Parameter | Field data[a] | Model values |
|---|---|---|
| $z_0$ (m) | 0.01 –0.15 | 0.017 |
| $1/n$ | 0.143–0.167 | 0.18 |
| $\Lambda_x$ (m) at a height of 2 m | 12.0 –30.0 | 14.5 |
| $\Lambda_z$ (m) at a height of 2 m | 1 –2 | 5.1 |

[a]See ref. 25.

*Test series results*

The China Lake boil-off rate, boil-off duration, and wind speed for the LNG tests 18 and 19 were simulated in the EWT using a smooth floor. The same tests were then repeated, but this time the topography of the China

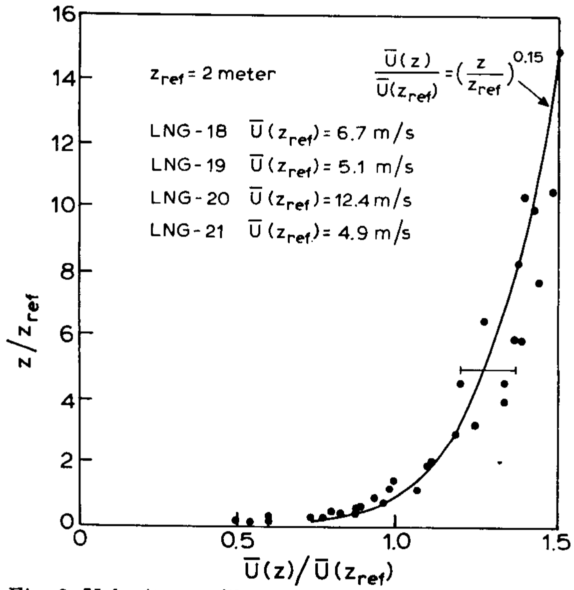


Fig. 3. Velocity profiles.

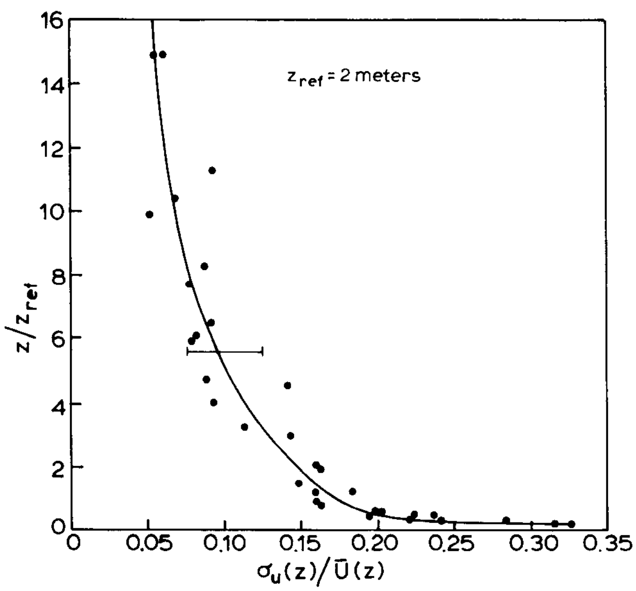


Fig. 4. Local longitudinal turbulence intensity profile.

Lake site was included*. Thorough concentration measurements downwind were obtained for these four tests. A summary of the test conditions for the four tests is presented in Table 2. Comparisons between the similar tests, one

*Unfortunately, the wind directions provided by the field investigators were in error. These two tests were re-run in a final test series.

performed with the model topography and one performed using a smooth floor, revealed that the dispersion at the China Lake site is greater than would be experienced if the spill occurred in a very smooth and flat area.

Finally, concentration measurements downwind were obtained for the simulated LNG field tests 18, 19, 20, and 21. A summary of the field conditions simulated is presented in Table 1. A summary of the model conditions for these tests is presented in Table 2. Ground-level peak concentration contours for each test are shown in Fig. 5—8. These contour lines were produced

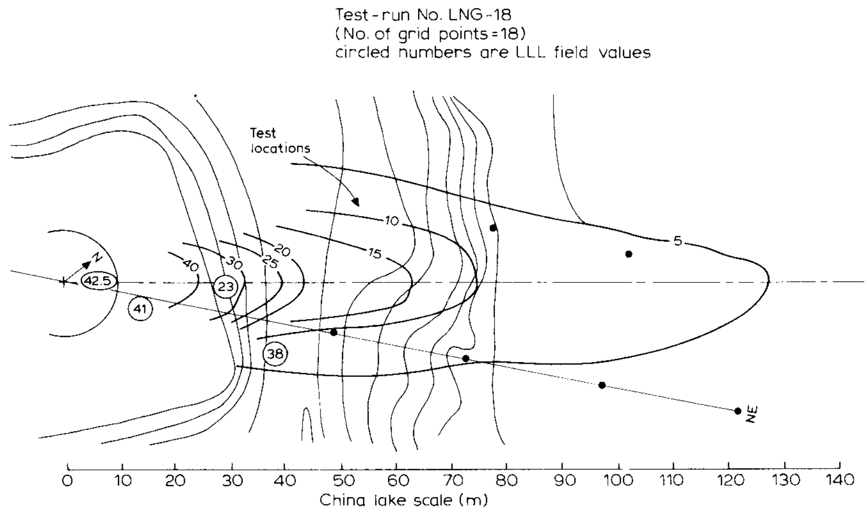


Fig. 5. Model test 18: ground contour plot of peak concentration.

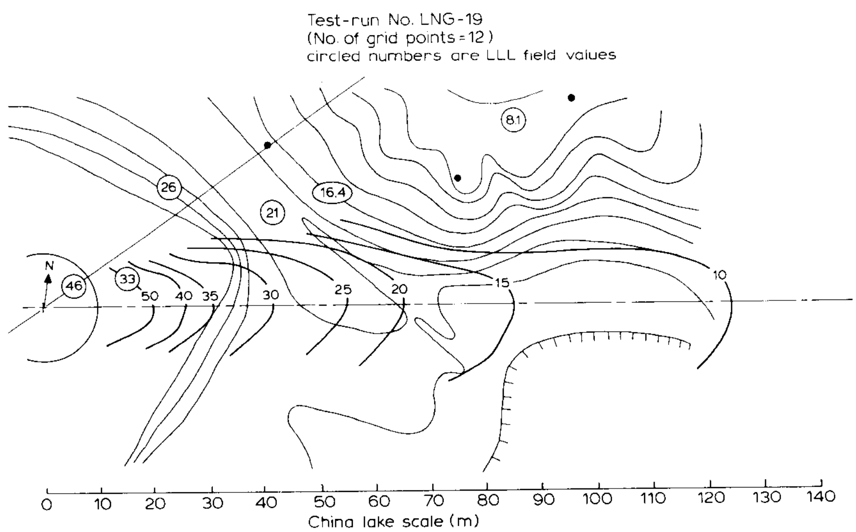


Fig. 6. Model test 19: ground contour plot of peak concentration.

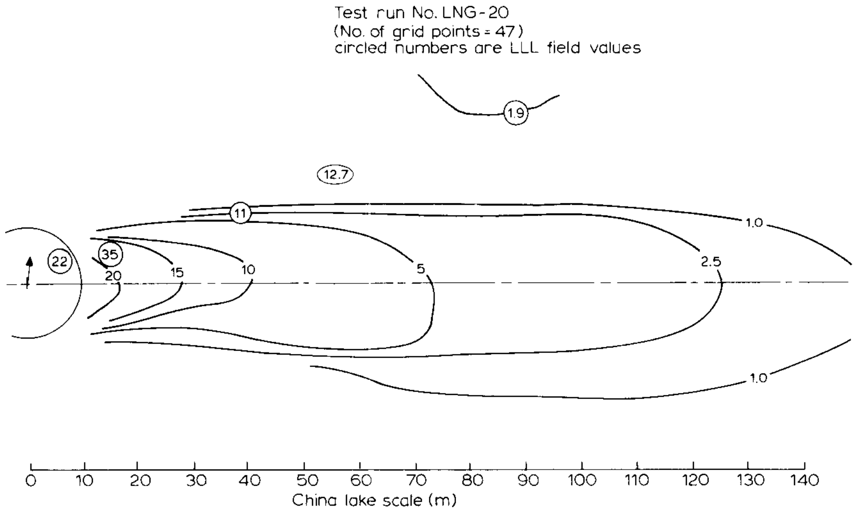


Fig. 7. Model test 20: ground contour plot of peak concentration.

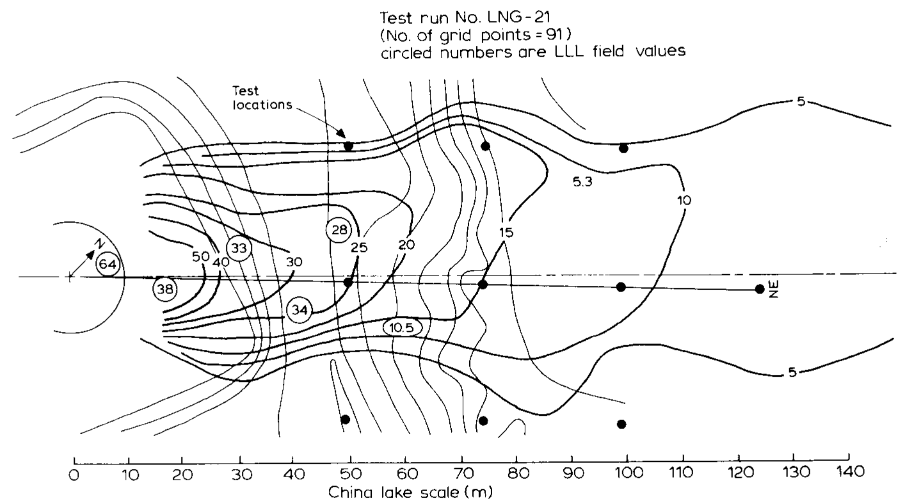


Fig. 8. Model test 21: ground contour plot of peak concentration.

by hand interpolation between 18 to 91 grid points over the model. The grid spacing was varied from experiment to experiment to reflect expected plume behavior. A summary of the times of arrival, peak concentrations and passage of the plume, and the maximum peak concentrations observed is tabulated in ref. 13.

## Comparison with field data

As part of the China Lake field-test series, field concentration measurements were obtained over two independent measurement grids. The Naval Weapons Test Center established a grid of ten different concentration-measurement stations, and the Lawrence Livermore Laboratory (LLL) provided eight towers with a variety of concentration sampling equipment [25]. The primary purpose of the LLL grid was sensor evaluation. Both these grids are indicated in Fig. 1.

The degree to which data modeled physically correlate with values obtained in the field is dependent upon the approximations assumed in the formulation of the model and upon the inherent randomness of atmospheric diffusion processes. The assumptions employed in the construction of the physical model of LNG vapor dispersion at the Naval Weapons Test Center were discussed above. The randomness of wind directions and velocities in the atmosphere is such that a single time-realization for a fixed point in space is insufficient to describe the complete probability distribution of peak concentrations that may be observed at that point. Without ensemble-averaging of similar tests in the field, the values found during a single realization may range over a limited portion of an unknown probability distribution. Pasquill [27] noted that in many circumstances of practical interest the uncertainty found between continuous releases of gaseous plumes may be at best 10—50% in the average and a factor of two or more for individual data [26]. In addition to the small-scale effects of local randomness, the atmosphere has large-scale variations which lead to meandering of the mean plume motion. These large-scale meanderings are not modeled in wind tunnels, and lead to the primary source of discrepancy between model and field concentration measurements.

The Naval Weapons Test Center grid consisted of ten different concentration sensors. These instruments were all of the catalytic combustion type. The principle of operation of these instruments is that a hot catalytic filament causes methane passing over it to oxidize, and the rise in temperature due to the reaction changes the electrical resistance of the filament. These detectors are accurate only for low (below 7%), slowly varying methane concentrations.

Table 4 compares peak concentrations observed in the field at the Naval Weapons test grid points with those obtained for the wind-tunnel model. This comparison is in general quite poor. There are several factors which may account for this scatter in comparable data over several orders of magnitude. They are: (1) the mean wind direction specified for each wind-tunnel test may have been in error, owing to the large shifts in wind direction during the field experiments; (2) the fluctuations in direction that occurred during the field tests were as large as $\pm 50^{\circ}$ (physical modeling of large wind-direction fluctuations is not possible in a wind tunnel); (3) the wind speed observed in the field changed by as much as $\pm 1.8$ m s$^{-1}$ during the tests (this amount of fluctuation can account for variation by $\sim \pm 50\%$ in measured concentration values); (4) the peak concentration fluctuations in the field tests were too rapid for the catalytic sensors to respond; (5) the field concentrations were

TABLE 4

Summary of peak concentration data at test-point locations for model and field experiments

| Location | Test No. 18 | | Test No. 19 | | Test No. 20 | | Test No. 21 | |
|---|---|---|---|---|---|---|---|---|
| | Field | Model | Field | Model | Field | Model | Field | Model |
| *China Lake Naval Weapons Grid* | | | | | | | | |
| 1 | >5% | 5.9 | >5% | 0 | 1.6% | 0 | 1.6% | 19 |
| 2 | >5% | 5.3 | >5% | 0 | 1.0 | 0 | 1.6% | 24.7 |
| 3 | >5% | 4.1 | 0.75 | 0 | 0 | 0 | 0.7 | 10.6 |
| 4 | >5% | 4.0 | >5% | 0 | 0 | 0 | 1.6% | 17.7 |
| 5 | 0.7 | 3.6 | 0 | 0 | 0 | 0 | 0.6 | 12.3 |
| 6 | 0 | 1.7 | 0 | 0 | 0 | 0 | 0.3 | 6.1 |
| 7 | 4.0 | 7.6 | 0 | 0 | 0 | 0 | 2.1 | 4.3 |
| 8 | 0 | 6.4 | 0 | 0 | 0 | 0 | 0 | 10.8 |
| 9 | 0 | 0 | >5% | 20.8 | 2.4% | 8.8 | 0 | 4.0 |
| 10 | 0.3 | 0 | >5% | 0 | 1.8% | 2.5 | 0 | 1.5 |
| *Lawrence Livermore Lab. Grid* | | | | | | | | |
| 1 | 42.5 | >40.0[a] | 46.0 | >50.0[a] | 22.0 | >20.0[a] | 64.0 | >50.0[a] |
| 2 | 41.0 | >40.0 | 33.0 | ~50.0 | 35.0 | ~19.0 | 36.0 | >50.0 |
| 3 | 23.0 | ~32.0 | 26.0 | ~10.0 | — | ~ 0 | 33.0 | ~35.0 |
| 4 | 38.0 | ~ 7.0 | 21.0 | ~15.0 | 11.0 | ~ 2.5 | 34.0 | ~25.0 |
| 5 | — | | — | ~ 0 | — | ~ 0 | 28.0 | ~27.0 |
| 6 | — | | 16.4 | ~ 8 | 12.75 | ~ 0.8 | 10.5 | ~10.0 |
| 7 | — | | 0.0 | ~ 0 | 0.6 | ~ 0 | 5.3 | ~12.0 |
| 8 | — | | 8.1 | ~ 0 | 1.9 | ~ 0 | — | ~ 5.0 |

[a]Approximate values only; model data were not obtained at the equivalent Lawrence Livermore grid sites.

too large for the catalytic sensors to respond; and (6) the approximations used in simulating the LNG field-test series were too weak to achieve proper simulation.

The Lawrence Livermore Laboratory obtained concentration time histories at a variety of different heights on their eight towers equipped with concentration sensors [26]. Several different types of sensors were employed. Each of these detector responses was verified by simultaneous grab-bag sampling of the gases flowing over the sensor. This technique provides an accurate method of verifying that the different sensors' responses were correct. The peak field concentrations obtained from the lowest sensor elevation at each of the eight towers are summarized together with approximate model values in Table 4. Since the response times of the various instruments utilized by Lawrence Livermore Laboratory (grab samplers, thermocoupling aspirated batherometers, infrared analyzers, etc.) were only several seconds, concentrations were essentially measured instantaneously. A peak concentration is defined as the maximum value detected during the nonstationary variation of the plume concentration as it passes a given sampler. Nonstationary wind conditions made any analysis of arrival time, departure time, or mean concentration meaningless.

Multiple plume-release replications over the China Lake model revealed that peak concentrations were reproducible to within a small range (±5%); hence this property was chosen for the model/field comparisons despite the uncertainties outlined early in this section [27]. Since flammability depends upon instantaneous stochiometric composition, peak concentrations were also of maximum interest to the sponsor. As concentrations over the model were not obtained at the Lawrence Livermore grid sites, the values noted for model equivalents are only approximate. These values were obtained by interpolation of the hand-drawn ground-level peak concentration contours in Figs. 5—8. On these figures the circled numbers are the peak concentrations observed in the field on the Lawrence Livermore grid.

The correlation between the Lawrence Livermore data and the model data is generally superior to that between the Naval Weapons Test Center data and the model data. There remain, however, a number of sampling points where poor agreement exists. Considering each model test point individually for case 18, reasonably comparable results, i.e. within 50% of the field values, are found for the near-field grid points 1, 2, and 3, and poor comparison for grid point four. The reason for these discontinuities in field/model comparisons may be any combination of the factors mentioned previously. In this case the differences appear to be caused by the small number of measurement locations in both field and model tests, and the variability of wind direction in the field.

For case 19 the quality of the comparison between the model and field data is not as good. The decays of concentration with distance from the source appear to agree, but the directions of the plume appear to be different. This result suggests a difference between the wind direction in the field data and that modeled. Here again, as in case 18, an insufficient number of model or field measurement locations were used to define the concentration field properly.

In case 20 the comparison between the field and model results again appears poor. The laboratory model predicts that at the higher wind speed (12.4 m $s^{-1}$ at 2 m) for this case, the LNG plume has very little lateral spread, whereas the field measurements showed significant concentrations at large distances from the plume's mean axis. This suggests large variation in the wind direction or an error in the mean wind direction. For this test and test 21 a sufficient number of measurement locations were used to define the model ground-level contours properly, i.e. 47 and 91 points, respectively. Of the four tests modeled, test 21 shows the greatest comparability between the model and field results. All measurement locations can be considered to give acceptable comparability considering the variation of wind direction and velocity in the field and the insufficient number of field data points.

## Conclusions

A series of six-cubic-meter liquid natural gas (LNG) spills were performed in 1978 at the China Lake Naval Weapons Center, CA. A parallel set of modeled spills were simulated in meteorological wind-tunnel facilities to provide field-test planning information, to extend the value of the limited set of field measurements, and to evaluate the concept of physical modeling of LNG plume dispersion as a predictive hazard analysis tool. Comparison of measurements over 1 : 170 and 1 : 85 scale models of the China Lake site with field measurements revealed that: (a) when the wind field conditions were nearly stationary, the resultant plume structure was reproduced by the model plume within field instrument resolution; (b) measurements made over 1 : 170 and 1 : 85 scale models produced similar concentration variations when scaled by the densimetric Froude number; and (c) topography effects are significant. Modest hill slopes of 1 : 10 can detain dense plumes and reduce the longitudinal distances covered before dilution to the lower flammability limit of flammable gases. Shallow valleys and gorges channel the plume and sustain high concentrations.

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