GRI-86/0102.1

GUIDELINE FOR FLUID MODELING

OF

LIQUEFIED NATURAL GAS CLOUD DISPERSION
Volume I: Instruction Guide

FINAL REPORT

(August 1984 - May 1986)

Gas Research Institute
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Chicago, Illinois 60631

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FINAL REPORT
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by

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for

GAS RESEARCH INSTITUTE

Contract No. 5083-252-0962

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May, 1986

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CER84-85RNM-50a

GRI DISCLAIMER

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. GRI 86/0102.1	2.	3. Recipient's Accession No.

4. Title and Subtitle Guideline for Fluid Modeling of Liquefied Natural Gas Cloud Dispersion Volume I: Instruction Guide	5. Report Date May, 1986 6.
7. Author(s) Robert N. Meroney	8. Performing Organization Rept. No. CER84-85RNM-50A
9. Performing Organization Name and Address Fluid Mechanics and Wind Engineering Program Civil Engineering Department Colorado State University Fort Collins, Colorado 80523	10. Project/Task/Work Unit No. 5083-252-0962 11. Contract(C) or Grant(G) No. (C) (G)
12. Sponsoring Organization Name and Address Gas Research Institute 8600 West Bryn Mawr Avenue Chicago, Illinois 60613	13. Type of Report & Period Covered Final (August 1984-July 1985) 14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Measurements of the behavior of simulated liquefied natural gas clouds dispersing over small-scale models placed in meteorological wind tunnels provide an opportunity to evaluate the fluid physics of dense cloud movement and dispersion in a controlled environment. The data also provide guidance for health and safety engineers during plant design and an opportunity to confirm mitigation procedures. The capabilities and limitations of fluid modeling for dense gas cloud behavior are summarized and standards to be followed during such studies recommended.

The primary intent of this report is to provide an instruction guideline document which specifies (ranges over which scaling parameters must be maintained to produce credible) physical modeling for the prediction of liquefied natural gas (LNG) storage and transportation hazards.

17. Document Analysis a. Descriptors

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement:	19. Security Class (This Report)	21. No. of Pages
Distribution unlimited	Unclassified	60
	20. Security Class (This Page) Unclassified	22. Price

(See ANSI-Z39.18) See Instructions on Reverse

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

RESEARCH SUMMARY

Title	Guideline for Fluid Modeling of Liquefied Natural Gas Cloud Dispersion, Volume I: Instruction Guide Accession Code: GRI-86/0102.1
Contractor	Colorado State University Fort Collins, Colorado 80523
Principal Investigator	Robert N. Meroney
Report Period	August 1984 - May 1986, Final Report
Objective	The primary intent of this report is to provide a guideline document which specifies the capabilities and limitations of physical modeling techniques for the prediction of liquefied natural gas (LNG) storage and transportation hazards.
Technical Perspective	Measurements of the behavior of simulated liquefied natural gas clouds dispersing over small-scale models placed in meteorological wind tunnels permits evaluation of the fluid physics of dense cloud movement and dispersion in a controlled environment. Wind-tunnel data also provide guidance for health and safety engineers during plant design and an opportunity to confirm mitigation procedures. The capabilities and limitations of fluid modeling for dense gas cloud behavior are summarized, and standards to be followed during such studies are recommended.
Results	Simulation parameters for dense gas dispersion in the atmosphere such as specific gravity ratio; volume, mass and momentum source ratios; flux Froude number; Reynolds numbers; Peclet/ Richardson number ratios; specific heat capacity ratios; humidity; and terrain slope are examined. Ranges over which these parameters must be maintained or ignored are specified. Wind-tunnel performance envelopes are provided which stipulate values of model scale and prototype wind speed for accurate prediction of LNG gas cloud behavior.

Technical Approach

The open literature on the topics of wind tunnel simulation and dense gas dispersion were reviwed and critiqued for pertinent information relating to fluid modeling of LNG cloud dispersion. Additional model tests of the Burro 8, China Lake test, were completed to verify some conclusions concerning the simulation of releases at small model scales under conditions of low level speed prototype conditions.

Project Implications

This guideline for fluid modeling of LNG cloud dispersion outlines the capabilities and limitations of wind tunnel simulation of vapor dispersion in the event of accidental spills. Wind tunnel simulation is most useful for near field modeling where mechanically induced vortex turbulence is present from structures such as tanks, vapor detention systems, etc., and where the uncertainties in mathematical modeling of complex dispersion processes are greatest. This guideline is expected to provide the basis for the specification of standardized practices for wind tunnel modeling in future regulations.

GRI Project Manager
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LIST OF SYMBOLS

Symbol	Description
Br	Brinkman number
c	Concentration
CF	Correction factor for spatial resolution
Cp	Specific heat capacity
e	Voltage
Ec	Eckert number
Eu	Euler number
f_c	Coriolis parameter
Fr_a	Froude number, ambient reference density
Fr_f	Flux Froude number
Fr_s	Froude number, source reference density
g	Gravitational acceleration
Gr	Grashof number
I_F	Integral time scale of F
k	Conductivity
L	Length scale
M	Molecular weight
n	Number of test samples
P	Pressure
Pe	Peclet number
Pr	Prandtl number
Q	Source flow rate
R	Gas constant
Ra	Rayleigh number
Re	Reynolds number
Ri	Richardson number
Ro	Rossby number
Sc	Schmidt number
SG, sg	Specific gravity
t, T	Time
T	Temperature
U	Velocity
x, y, z	Cartesian coordinates
z_o	Roughness length

Greek symbols

α	Thermal diffusivity
γ	Specific heat capacity ratio
δ	Boundary layer depth
δ_{ij}	Kronecker delta
ε_{ijk}	Alternating tensor
η	Kolmogoroff microscale
Θ	Potential temperature
β	Terrain slope
λ	Microscale
λ_T	Taylor microscale
μ	Dynamic viscosity
ν	Kinematic viscosity
π	Pi (3.141)
ρ	Density
σ	Variance
τ	Time increment
χ	Concentration
Ω	Earth rotation rate

Superscript symbols

$\overline{\quad}$	Overbar denotes average
*	Molar value, or dimensionless
'	Fluctuating component

Subscript symbols

a	Ambient atmospheric conditions
g,o	Source gas
i,j,k	Summation coefficients
m	Model
p	Prototype
R	Reference

1.0 INTRODUCTION

This guideline contains specifications for the use of fluid modeling to determine the hazards associated with spills of Liquefied Natural Gas (LNG) resulting from transportation or storage accidents. The guidance is intended for use by industries and their consultants during the design and safety review of LNG installations and by regulatory agencies. The specifications in this guideline will help maintain consistency among studies.

1.1 Background

Natural gas is a highly desirable form of energy, since it is convenient to transport. Sophisticated distribution network already service industrialized countries. Recent efforts to expand this gas supply and its availability include the transport of natural gas in a liquefied state from distant gas fields and the storage of surplus capacity in "peak-shaving" facilities. Liquefield natural gas (LNG) is cooled to a temperature of $-162^{\circ}C$ for transportion and storage. If a storage tank or a pipe were to rupture and the contents spill out onto the earth's surface, rapid boiling of the LNG would ensue, and a flammable vapor cloud would result. Past studies have demonstrated that the cold LNG vapor plume will remain negatively buoyant for most of its flammable lifetime. The vapor cloud hazard will persist until the atmosphere has diluted the LNG vapor below the lower flammability limit (LFL; the maximum local concentration below which the gas is not flammable; 5 percent by volume for methane). The location of the LFL region in space and time determines regulatory and response strategies.

It is important that accurate predictive models for LNG vapor cloud physics be developed, so that the associated hazards of transportation and storage may be realistically assessed. Industrial and Government agencies have sponsored a combination of field measurements and analytical, numerical, and physical modeling studies to analyze such problems. Analytical and numerical solutions are valuable because of the phenomenological insight they provide, and the now general availability of computer facilities. But the more complex the boundary conditions, the less rewarding a theoretical or numerical solution becomes because of its lack of general validity, and the higher effort required to obtain the solution. Physical modeling permits a comparatively simple analog solution to a complex situation. The analog consists of the use of fluid models, in which the boundary conditions are simulated through a geometrical scale model, and the atmosphere is simulated by flowing of water or air in a laboratory apparatus. The primary intent of this report is to review the capabilities and limitations of physical modeling techniques for the prediction of LNG storage and transportation hazards.

Thermal effects, topography, the presence of obstacles and spray curtain mitigation devices can all affect the dispersion of dense gas clouds. Fluid modeling studies are desirable mostly because such variables can be controlled at will, with great savings in time and expense over full-scale tests. The physical model inherently includes fluid physics for which only limited understanding can presently be incorporated in numerical models.

1.2 Summary of Guideline Contents

Certain constraints exist on a physical model's ability to predict large scale atmospheric plume behavior. These constraints are due to the limited range of transport properties of air and water, the inherent characteristics of fluid turbulence, and the size range of available fluid modeling facilities. Section 2 considers the general similarity requirements associated with the governing equations of motion, thermodynamic state, and energy. Requirements for a fluid model program are outlined in Section 3, where a preliminary design philosophy is expressed, data acquisition and analysis techniques are suggested, wind tunnel performance envelopes are provided, and a model test program for an LNG model experiment is recommended.

2.0 GENERAL SIMILARITY REQUIREMENTS

The concept of similitude is basically simple. Two systems at different geometric scales will exhibit similitude if a one to one correspondence exists in space and time between fluid particle kinematics (locations, velocities, accelerations and rotations) caused by fluid particle dynamics (pressures, gravity, Coriolis forces, viscous forces, etc.), when properly scaled by characteristic scales of fluid properties, force, length and time. To achieve this similarity, however, is not trivial. The specification of dimensionless parameters which guarantee similarity has historically been the subject of much discussion and debate.

In the nineteenth century a number of workers (most notably Lord Rayleigh) commonly solved problems by direct use of the similarity principle with the intuitive identification of relevant force ratios. During the early twentieth century, the force ratio methods lost favor and were replaced almost entirely by dimensional analysis, as represented by the Buckingham Pi theorem. The most systematic and reliable method currently used to identify relevant scaling parameters is the "normalization" of the governing partial differential equations of motion. Normalization makes the equations and boundary conditions nondimensional in terms of scaling variables of standard magnitude. In the following sections the primary similitude parameters are identified by applying this technique. The chapter ends with a review of methods necessary to verify that similitude has indeed been achieved.

2.1 The Equations of Motion

The equations of motion are the starting point for the normalization procedure. Given a reference frame fixed to the surface of the Earth which is rotating at an angular velocity Ω, then for an incompressible atmosphere one can generate the following equations:

Conservation of Mass

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{2.1}$$

Conservation of Momentum

$$\frac{\partial U_i}{\partial t} + \frac{U_j \partial U_i}{\partial x_j} + 2\varepsilon_{ijk} U_k \Omega_j = - \frac{1}{\rho_o} \frac{\partial P}{\partial x_i} + \frac{g}{T_o} \delta T \delta_{3i} + \frac{\nu \partial^2 U_i}{\partial x_k \partial x_k} \tag{2.2}$$

Conservation of Energy

$$\frac{\partial T}{\partial t} + \frac{\partial T}{\partial x_i} U_i = \kappa \frac{\partial^2 T}{\partial x_i \partial x_i} + \frac{Ui}{\rho} \frac{\partial P}{\partial x_i} \tag{2.3}$$

Conservation of Species

$$\frac{\partial \chi}{\partial t} + U_i \frac{\partial \chi}{\partial x_i} = \alpha \frac{\partial^2 \chi}{\partial x_i \partial x_i} \tag{2.4}$$

Equation of State

$$P/\rho = RT/M \tag{2.5}$$

The Cartesian index convention has been used, where the x_3 axis is taken vertically upward, U_i is a component of the instantaneous velocity, ε_{ijk} is the alternating tensor (if any two of the indices i, j, or k are equal, the component is zero; if i, j, and k are all unequal and in cyclic order, the component is +1; but if not in cyclic order, the component is -1), δ_{ij} is the Kronecker delta (equal to 1 if the two indices are equal and 0 if unequal), and the summation convention is followed (whenever a suffix is repeated in a term it is to be given all possible values and the terms are to be added).

The next step is to identify characteristic scales through which the equations will be normalized. Reference quantities are usually identified through specified boundary conditions. Choosen are L, length; U_R, velocity; ρ_R, density; Ω_R, rotational speed; T_R, absolute temperature; ΔT_R, temperature deviation; g, gravitational constant; P_R, reference pressure; and μ_R, k_R, D_R, Cp_R, which are the reference viscosity, conductivity, diffusivity and specific heat capacity respectively. The dimensionless variables are:

$$x_i' = \frac{x_i}{L} \qquad U_i' = \frac{U_i}{U_R} \qquad P' = \frac{P}{\rho_R U_R^2} \qquad T' = \frac{T}{\delta T_R}$$

$$t' = \frac{U_R}{L} t \qquad \rho' = \frac{\rho_o}{\rho_R} \qquad \Omega_j' = \frac{\Omega_j}{\Omega_R}$$

Introducing these dimensionless variables in Equations 2.1 to 2.5 yields:

$$\frac{\partial U_i'}{\partial x_i'} = 0 \tag{2.1a}$$

$$\frac{\partial U_i'}{\partial t'} + U_j' \frac{\partial U_i'}{\partial x_j'} + \frac{2}{R_o} \varepsilon_{ijk} U_k' \Omega_j' = - \frac{Eu}{\rho'} \frac{\partial P'}{\partial x_i'} + Ri \ \delta T' \delta_{3i} + \frac{1}{Re} \frac{\partial^2 U_i'}{\partial x_j' \partial x_j'} \tag{2.2a}$$

$$\frac{\partial T'}{\partial t'} + U_i' \frac{\partial T'}{\partial x_i'} = \frac{1}{Pe} \frac{\partial^2 T'}{\partial x_i' \partial x_i'} + EuEc \frac{U_i'}{\rho'} \frac{\partial P'}{\partial x_i'} \tag{2.3a}$$

$$\frac{\partial \chi'}{\partial t'} + U_i' \frac{\partial \chi'}{\partial x_i'} = \frac{1}{ReSc} \frac{\partial^2 \chi'}{\partial x_i' \partial x_i'} \tag{2.4a}$$

$$P'/(\rho' T') = \rho_R^2 U_R^2 R \Delta T_R / M_o = 1/Eu \tag{2.5a}$$

where $Ro = U_R/L\Omega_R$ is the Rossby number,

$Eu = P_R/(\rho_R U_R^2)$ is the Euler number,

$Re = \rho_R U_R L/\mu_R$ is the Reynolds number,

$Ri = g_R \Delta T_R L/(T_R U_R^2)$ is the Richardson number,

$Pe = \rho_R Cp_R U_R L/k_R$ is the Peclet number,

$Pr = \mu_R Cp_R/k_R$ is the Prandtl number,

$Sc = \mu_R/(\rho_R D_R)$ is the Schmidt number, and

$Ec = U_R^2/(Cp_R \Delta T_R)$ is the Eckert number.

The physical significance of these parameters will be discussed at some length in later paragraphs.

"Exact" similarity requires equality of the nondimensional coefficients listed above for the physical model and the prototype situation. If separate length scales are chosen for the different coordinate directions additional parameters are generated; however, current wisdom is that distorted geometric scaling is not justified.

Furthermore boundary conditions governing the flow domain of interest must also be similar for the model and prototype. Surface boundary conditions would require similarity of the following features:

1) Topographical relief,
2) Surface roughness distribution,
3) Surface temperature distribution, and
4) Reproduction of associated obstacles, buildings, fences, source areas, etc.

Similarity of the approach-flow characteristics requires similarity of the following flow features:

1) Distributions of mean and turbulent velocities,
2) Distributions of mean and fluctuating temperatures and humidities, and
3) Distributions of turbulent scales and energies.

Similarity of the boundary conditions aloft would require similarity of the following features:

1) The upper stream line should follow a similar trajectory with respect to the ground surface, and
2) The longitudinal pressure gradient should be nearly zero.

These seven equations and associated boundary conditions contain seven unknowns, U_1, U_2, U_3, T, p, ρ , and χ , so that (in principle) their solutions can be determined. Any prototype and model flow which is constrained by the same scaled initial and boundary conditions, and for which all the dimensionless coefficients identified above are invariant, must have a unique solution in terms of the dimensionless variables. The non-dimensional equations apply to both laminar and turbulent flows; hence it is not necessary to know *a priori* whether the flow is laminar or turbulent.

It is not necessary to actually solve the differential equations if one uses a laboratory facility as an analog computer. If all the foregoing requirements could be met simultaneously, all scales of motion ranging from micro to mesoscale, ie. 10^{-3} to 10^{3} m, could be simulated within the modeled model flow field.

Unfortunately, all similarity requirements cannot be satisfied simultaneously and modelers must use partial or approximate similitude. Hence, model conditions must be chosen which are designed to simulate most accurately those scales of motion which are of greatest significance for the application (Cermak, 1975).

2.2 The Dimensionless Parameters

Kline (1965) observed that, in engineering work, it is often not feasible to mathematically model all aspects of the behavior of the prototype. Rather, it becomes necessary to determine under what conditions some parameters can be neglected. For example, this approach is the essence of perturbation analysis used for inner and outer expansions in boundary layer theory. In both mathematical analysis and physical modeling it is helpful to use order-of-magnitude analysis of the individual terms in the equations of motion to eliminate insignificant terms. Since the dimensionless variables have been scaled to be of order one, $O(1)$, the relative importance of each term lies in the magnitude of the associated dimensionless coefficients.

It is generally impossible to simultaneously match all of the dimensionless parameters when the ratio of the prototype and model length scales is greater than about 10. Consider the behavior of the Reynolds and Richardson numbers:

$$Re = \rho_R U_R L/\mu_R \qquad \text{and } Ri = g\,\Delta T_R L/(T_R U_R^2)$$

If one models an LNG spill in a wind tunnel, the property values of ρ , μ and g are identical, and T_R is roughly the same. Equality of Reynolds numbers between model and prototype then requires an increase of 10 fold in the flow velocity. But to match the Richardson number criterion if L is decreased by 10 and U_R is increased by 10, T_R must be increased by 1000! Such an increase in temperature difference (or density difference) is obviously impractical.

Because of the difference in kinematic viscosity between air and water, a factor of about 15 in Reynolds number may be gained by modeling an atmospheric phenomenon in a water facility, but then the Peclet number and Reynolds number criteria can not be met simultaneously. Also the Prandtl number in air is of order one, whereas its value in water is about 10.

Consider the roles played by each dimensionless parameter in some detail. Barnett (1964) summarizes the majority of the relevant dimensionless parameters used by fluid mechanists and meteorologists. Only those parameters identified during the normalization of the equations of motion in section 2.1 are considered.

<u>Rossby Number:</u> $[U_R/(L\Omega_R)]$

The Rossby number is a measure of the relative magnitudes of the advective or local accelerations as compared to Coriolis accelerations. Local accelerations result from unsteadiness or divergence in the flow field. Coriolis accelerations result from the fact that we all live a non-inertial reference system (the surface of the Earth). Since the Earth's Coriolis accelerations (or forces) are relatively small, they only become important when motions persist over distances long enough for the associated spatial deviations to become significant. If the Rossby number is large, Coriolis accelerations are small. A nearly infinite model Rossby number exists in most laboratory wind tunnels and water channels.

Euler Number: $[P_R/(\rho_R U_R^2)]$

The Euler number compares the relative magnitude of pressure fluctuations and inertial accelerations. Since P_R is usually of order $\rho_R U_R^2$, this parameter is of order one and is automatically simulated in air.

Reynolds Number: $[\rho_R U_R L/\mu_R]$

The magnitude of the Reynolds number indicates the relative importance of inertial forces and viscous or frictional forces. It imposes very strong limitations on rigorous simulation, since scale reductions of 1:100 to 1:1000 commonly result in model Reynolds numbers two to three orders of magnitude smaller than those found in the atmosphere. Thus the viscous forces are relatively more important in the model than in the prototype. If strict Reynolds number equality is required, no atmospheric phenomena could be modeled. Various arguments have been proposed to justify the use of smaller Reynolds numbers in model studies. Snyder (1972) reviews suggested concepts of the laminar flow analogy, dissipation scaling, and Reynolds number independence. He concludes that only Reynolds number independence is a viable possibility.

Richardson Number: $[g \Delta T_R L/(T_R U_R^2)]$

A large value of the Richardson number implies that buoyancy forces are very large compared to inertial forces. Thermal effects or density differences become less important as the Richardson number decreases toward unity. The Richardson number can also be considered as the inverse square of a densimetric Froude number,

$Fr = U_R/[g(\Delta T_R/T_R)L]^{0.5}$. Alternatively $Ri = Gr/Re^2 = Ra/(Re^2 Pr) = Ra/(RePe)$. In this case, Gr and Ra are known as the Grashof number and Rayleigh number, respectively. The Grashof number is generally understood to be important when flow motions are driven by free convection. The Rayleigh number is often used to typify the onset of cellular convections driven by temperature differences.

The Richardson number is not necessarily a difficult parameter to duplicate in a fluid model. Unfortunately, to match model and prototype Richardson numbers for typical scale reductions of 1:100 to 1:1000 using reasonable temperature or density differences, it is necessary to decrease the mean flow speeds substantially. Yet to match the Reynolds number requires that the flow speed in the model be increased; hence, a conflict arises.

<u>Peclet Number:</u> $[\rho_R Cp_R U_R L/k_R]$ or $[U_R L/D_R]$

The Peclet number can also be expressed as the product of a Reynolds number and the Prandtl number or the Schmidt number, ie., RePr or ReSc. The parameter is a measure of the ability of the fluid to advect heat or mass compared with its ability to disperse heat or mass by molecular transport. The Peclet number often becomes important when Reynolds number independence does not exist. In such cases the relative ability of the fluid to transport heat or mass by molecular collision and the rate of transport provided by turbulent motions become comparable. Such a situation can produce incorrectly simulated plume entrainment and transport rates.

<u>Prandtl Number:</u> $[\mu_R Cp_R/k_R]$

The Prandtl number is the ratio of the momentum diffusivity to the thermal diffusivity. It indicates the relative ability of the fluid to transport momentum as compared to heat via molecular processes. If air is used to simulate the atmosphere, this parameter is automatically satisfied. The Prandtl number is a weak function of air temperature. In water the Prandtl number is about 10 times larger than it is in air, and varies with temperature. This parameter always appears multiplied by the Reynolds number. The product or thermal Peclet number is, thus, the governing parameter.

Schmidt Number: $[\mu_R/(\rho_R D_R)]$

The Schmidt number is the ratio of momentum diffusivity to mass diffusivity. It also indicates the relative ability of the fluid to transport momentum versus mass species by microscopic processes. If air is used to simulate the atmosphere, then the magnitude of the Schmidt number will be dependent on the model tracer gas chosen; however, it will usually be close to a value of one. However, the Schmidt number for typical tracers such as sodium chloride or alcohol dispersing in water is nearly 800; hence, Schmidt number equality is unlikely in water facilities. This parameter always appears multiplied by the Reynolds number. The product or mass Peclet number is, thus, the governing parameter.

Eckert Number: $[U_R^2/(Cp_R \Delta T_R)]$

The Eckert number indicates the ratio of kinetic to excess internal energy. Eckert numbers are not normally equal when equal Richardson numbers are achieved. This compromise with exact similarity has not been found to have significant effect on the similarity of wind characteristics. The Eckert number is also equal to a Mach number squared, and this is generally small compared to unity for both laboratory and atmospheric flows. Its small value in the energy equation (2.3a) suggests dissipation and compression do not affect temperature distributions significantly. In some texts the

Eckert number is expressed as (Br/Pr), where Br = $[\mu_R U_R^2/(k_R \Delta T_R)]$ is the Brinkman number. The Brinkman number relates the rate of viscous dissipation to conductive heat transfer which will occur over the reference temperature difference.

3.0 REQUIREMENTS FOR A FLUID MODEL PROGRAM

This section reviews the characteristics of various fluid modeling wind tunnels and hardware. It also suggests check lists and quality control criteria necessary to permit independent duplication of experiments by other investigators. Since not all simulations are physically possible in conventional wind or water tunnel facilities, the concept of performance envelopes is introduced. Combined with some preliminary experimental design, these envelopes should define the productive and feasible test plan.

3.1 Preliminary Experiment Design

A fluid modeling experiment should be defined based on the intended use of the resulting data. The feasibility, value, cost, and time required by an experimental program will depend on pre-stipulated criteria concerning experimental complexity, resolution, and accuracy. It is not uncommon to impose unnecessary and stringent conditions on a numerical or fluid model due to unfortunate wording of the original motivation for the experiment. For example, in a hazard situation the following questions might be asked, but each demands quite a different model response:

1. Beyond what distances from a source will hazardous conditions not exist under defined spill conditions?

2. Beyond what distances from a source will hazardous conditions occur more than time T with a probability P?

3. Beyond what distances from a source will hazardous conditions occur more than time T with a probability P? The distances must be specified with only a possibility of error, E, that the distance is in error more than D.

4. What are the maximum values of concentrations which occur spatially around the source?

5. What is the actual time variation in concentrations which occur spatially around the source?

In other words, follow a practice of reasonable goals, that is:

1. Avoid stipulating acquisition of more information than you really need to make a decision.

2. Select credibility criteria for data statistics which are realistically obtainable (e.g., trying to avoid a small Type II error with great confidence results in very large data requirements.) Absolute assurance of safety is a myth. (A Type II Error is the failure to reject a false hypothesis).

3. Evaluate whether the time and effort in the experimental program is commensurate with expected results.

4. Do no overcomplicate the laboratory experiment. By including all possible perturbing forces, one is often unable to identify driving physical mechanisms.

5. Estimate probable results of the more expensive fluid modeling experiments in advance, using box or slab-type numerical models. Unnecessary or unfortunate experiments can be eliminated.

6. Consider a conservative approach. That is if no hazard exists for some situations, even when exaggerated scale accidents are examined, there is no need to know exact concentrations. This permits the experimenter to focus effort on the critical scenarios.

These matters are discussed at some length in papers by Hartwig and Flothman (1980), Wiersma (1983), and McQuaid (1985). The degree of satisfaction derived from a laboratory or numerical model will depend upon the original expectations and the clear specification of objectives.

3.2 Data Acquisiton and Analysis

The characteristics and capabilities of the fluid modeler's technical hardware determine whether program objectives can actually be attained in laboratory facilities. The present section considers the size and performance characteristics required of the facility and instrumentation. The material is primarily written with a view toward wind tunnels, but the principles also apply to water channels.

3.2.1 Fluid Modeling Laboratory Facilities

Available Facilities

Oral or written reports have been made about the results of dense gas dispersion experiments in at least fifteen laboratories. Table 3.1 describes the somewhat limited information which could be readily extracted concerning the type and size facilities used. Most wind-tunnel facilities used have been open-circuit test sections without thermal stratification. None of the equipment appears to have been designed specifically to operate at the low wind velocities frequently required for LNG spill simulation (i.e., <1.0 m/s). Water-type experimentation has tended to emphasize flow visualization with dyes; however, concentration measurements using conductivity probes would be possible. A variety of experimental configurations have been examined (See Table 3-2). A number of experiments are still considered proprietary in nature; hence, the results are not available to the scientific community.

Air versus Water Systems

The selection of an air versus water medium for modeling LNG dispersion will depend on the availability of the facility, economics, and the type of problem to be studied. The kinematic viscosity of water at normal room temperature is a factor of 16 less than that of air; hence, at the same scale and fluid speed the Reynolds number may be 16 times higher for a water experiment. Unfortunately, because water is so much heavier than air, structural and pumping requirements result in water facilities which tend to be much smaller than wind tunnels. Thus, the larger Reynolds number potential of water facilities is seldom attained.

Sometimes investigators have used water towing tanks to examine flow over hills or other obstacles. This method is really not appropriate for ground level releases of LNG, because the uniform approach profile simulated is not equivalent to the shear flow found near the earth's surface.

Air, with its low heat capacity, is comparatively easy to stratify using heat. A few special meteorological wind tunnels have been designed to reproduce some aspects of the stratified atmospheric boundary layer (Meteorological Wind Tunnel, Colorado State University; Environmental Wind Tunnel, Mitsubushi, Nagasaki, Japan; Meteorological Wind Tunnel, Bundeswahr Hochschule, Munich, BRD). Stratification in water is generally produced by layers of mixtures of water and salt. Large water facilities with recirculating stratified flow by conventional pumps are essentially impractical; since the pumps which produce recirculation tend to destroy the stratification.

In air it is possible to obtain specific gravity variations ranging from 1.0 to 5.0; hence, a significant distortion of buoyancy forces is possible. In water most experiments using salt as a density ingredient have been performed with specific gravities between 1.0 and 1.1. Indeed the highest relative density obtainable in a water soluble solution is about 1.4. Thus to model spills of source density greater than this (for example a pure Freon-12 spill (SG = 4.17), modified Froude number modeling must be used in a fashion reverse to that of a wind tunnel, reducing the water velocities to compensate for an insufficient spill source density, and reducing the operating Reynolds number yet further (Hall, 1982).

Consideration of the characteristics of each type facility leads one to conclude:

1. The ease and convenience of operating wind tunnels and associated measuring equipment and the ability to adequately simulate the neutral and stratified atmospheric boundary layer make the wind tunnel superior to the water tunnel or water towing tank for scale studies of LNG spill phenomena.

2. The excellent visualization capabilities and the increase in Reynolds number provided by water facilities suggest they are measurement platforms best used to study basic dense fluid flow and dispersion when quantitative measurements of velocities and turbulence are not so important.

3.2.2 Wind Profile and Turbulence Measurements

Hot-wire, hot-film, and pulsed-wire anemometers are available to measure wind speed and turbulence in wind tunnels. Hot-film anemometers are used in water, but require a great deal of care to get reliable results. Pitot tubes are rarely usable at the low speeds required during dense gas dispersion research in wind or water facilities. Laser anemometry at low flow velocities requires expensive equipment, and adequate traverse systems are rarely installed in the larger meteorological facilities.

Flow speeds required during LNG spill simulations are often less than 50 cm/s. Most conventional hot-wire or hot-film equipment was not intended to be used at such low velocities. Care must be taken to achieve reliable calibration, to correct for low-speed probe non-linearities, and to avoid electronic noise in the low-signal, low-wind-speed environment. The pulsed-wire anemometer is especially useful in low speed and reversing flows, as it is capable of detecting the direction of flow. Some investigators have found it sensitive to temperature variations in stratified flows.

Most laboratory flows used to examine dense fluid behavior have not been well documented with respect to turbulence characteristics.

The measurements of Neff and Meroney (1982) suggest that near ground velocity profiles have a significant effect on dense plume dispersion. Future studies should make every effort to measure accurate wind speed profiles, rms turbulence profiles, spectra, and integral scales.

3.2.3 Visualization and Concentration Measurements

By using different colors and densities of dye, hydrogen bubbles, potassium permanganate crystals, or neutrally buoyant particles a wide variety of visualization techniques is available in water tunnels. Low flow speeds permit excellent visualization and photographs of flow patterns. The comparable smoke type visualization procedures used in wind tunnels are notoriously cantankerous, dirty, and sometimes toxic. Nonetheless, the physical insight gained during flow visualization always justifies the effort. Television systems provide a recording medium for the visualization results which are convenient and inexpensive. Digitization and processing of images and patterns can now be accomplished inexpensively using desktop computers. This provides some opportunity for quantitative results from flow visualization.

Concentrations can be examined from a variety of simultaneous sources in wind tunnels using flame-ionization or electron-capture-techniques. Aspirated hot-wire anemometers or <u>insitu</u> flame-ionization devices can follow concentration fluctuations to at least 60 Hz. Salts in conjunction with conductivity meters, acids with pH meters, temperature with thermistors, and dyes with colorimeters and fluorometers have been used as tracers for quantitative measurements of concentration in water. Conductivity probes in water typically respond to frequencies of 10 to 20 Hz.

3.2.4 Averaging Times and Sampling Rates in the Laboratory

One may pose at least two questions with respect to averaging times associated with laboratory measurements. First, how long should one sample in the laboratory to obtain a stable average? And second, to what averaging time is the laboratory measurement equivalent?

Let us consider a prototype measurement made at a height of 10m for a wind speed of 3 m/s. Assuming a typical eddy scale for vertical movement of 10 m, one finds that a fifteen minute average allows one to sample 270 perturbations. Given a 1:200 scale, such that the equivalent boundary layer position is five centimeters (z_m = 5 cm), and a model wind of 0.5 m/s, then 30 seconds in the laboratory will sample an equivalent number of eddies. Of course the large (long time) eddies which result in nonstationarity in the atmosphere and the consequent long tails to probability distributions are missing in the laboratory; thus, laboratory turbulence only presumes to represent the atmospheric behavior below the "spectral gap". (See discussion in Meroney (1986), Technical Support Document, Section 3.3.2.)

Lumley and Panofsky (1964) showed how averaging time requirements can be related to turbulence scales. Presuming a stationary laboratory situation and a turbulent shear flow it is appropriate to begin by considering the turbulence present to be a Gaussian process. The variance, σ^2, of the difference between the ensemble (true) average of a quantity and the average obtained by integration over the averaging time, T, for some fluctuating quantity, F, is:

$$\sigma^2 = 2 \overline{f'^2} I_F/T, \qquad (3\text{-}1)$$

where I_F is the integral time scale of F, $f' = \bar{F} - F$, and $\overline{f'^2}$ is the ensemble variance of F about its ensemble mean. Since the fractional error, n, is given by $\varepsilon^2 = \sigma^2/F^2$, then the averaging time, T, required to stay below ε is:

$$T = 2\ (\overline{f'^2}/F^2)(I_F/\varepsilon^2). \tag{3-2}$$

Let

$$F = u = \bar{u} + u'$$

$$\bar{F} = \bar{u}$$

$$f = u'$$

$$\overline{f'^2} = \overline{u'^2}$$

Near a wall in a turbulent boundary layer one typically finds $\sqrt{\overline{u'^2}}/\bar{u} = O(0.1)$ and $I_u = O(\delta/\bar{u})$; thus

$$T_u = 2\ (0.1)^2(\delta/u)/\varepsilon^2 = 0.02\ (\delta/u)/\varepsilon^2. \tag{3-3}$$

Hence, for $\delta = 1$ m and $u = 0.5$ m/s then $T_u = 0.04/\varepsilon^2$. When ε is 1%, 5% or 10% then T_u will be 400, 16, and 4 seconds, respectively.

A similar result will hold for mean concentrations; however, the required averaging times for second and higher moments (ie. $\overline{u'^2}$, $\overline{c'^2}$, $\overline{u'v'}$, $\overline{u'w'}$, $\overline{w'c'}$, $\overline{u'^4}$, etc.) will normally take much longer. The method requires information about the integral scales of the variable F, but this is usually unknown for higher order moments. So further estimates by this method would be largely conjecture.

Alternatively, for normally distributed fluctuations, estimates of required sample sizes for the determination of mean quantities within pre-specified limits with stipulated levels of confidence can be calculated by the Student t-test method. For concentrations distributed normally about some mean value, the numbers of samples required for the determination of mean concentration and concentration intensity are:

$$n_C = t^2 \, (\overline{c'^2}/C^2)/[(\Delta C)^2/C^2], \text{ and}$$
$$n_{c'} = t^2/[2(\Delta \, (\overline{c'^2})^{1/2})^2/\overline{c'^2})]. \tag{3-4}$$

where n_i is the number of samples required to ensure that the estimates of mean concentration, C, and concentration intensity, $\overline{c'^2}$, are within a precision of Δ C and Δ $(\overline{c'^2})^{1/2}$, respectively, of the ensemble values. t is the Student t parameter; for a 95% or 90% probability of being within the interval, the t values are 1.96 and 1.645, respectively. For example, if the concentration fluctuation intensity is of order (0.1), then to determine the mean concentration within ±5% of the ensemble mean velocity with 95% probability, it would be necessary to average at least 15 samples. The concentration intensity determined with 15 samples would be within 36% of the ensemble intensity with 95% probability. Note, however, that if the concentration fluctuations are more extreme, e.g., the concentration fluctuation intensity is of order (0.5), then the required sample size is 384 and the concentration intensity would be within ±7% of the ensemble intensity with 95% probability. These estimates assume linearly independent samples, taken with error free-instrumentation. Hence, the samples must be taken from a time series far enough apart to have zero correlation.

Alternatively, one can think in terms of the number of replications required to attain a specified confidence. Carn and Chatwin (1984) calculated from t-test criteria that in order to have a

90% confidence that the ensemble value of $\overline{c'^2}$ is within 5% of its actual value requires 86 replications, whereas a 99% confidence requires 5300 experiments.

Presuming measurements are taken for a sufficiently long time in stationary laboratory flows generated in meteorological wind-tunnel facilities, then magnitudes measured should correspond to averaging over scales less than the spectral gap. Extensive comparisons between laboratory measurements in simulated boundary layers and atmospheric flows suggests the laboratory data correspond to field times of 10 to 30 minutes. Extended discussions of this subject are provided by Plate (1982) and Snyder (1981).

3.2.5 Spatial Resolution of Measurements

Recently, there has been considerable debate about the presence of fine concentration structure in field and laboratory plumes. Carn and Chatwin (1984), Jones (1983), and Hadjistfi and Wilson (1979), in particular, have been concerned that peak concentrations are not actually measured because available concentration instrumentation does not have the spatial resolution to detect undiluted cloud wisps.

These authors argue that elements of the cloud distorted and dispersed by turbulence will actually remain undiluted until eddy sizes are stretched to the order of a "conduction cut-off scale", $\lambda_c = (\nu D^2/\varepsilon)^{1/4}$, where ε is the local rate of dissipation of mechanical energy per unit mass, ν is the kinematic viscosity of air, and D is the molecular diffusivity. This length is similar to the Kolmogoroff microscale in the theory of turbulence. For gases, the conduction cut-off scale and the Kolmogoroff microscale are of the same order of magnitude, and in the atmosphere or the wind tunnel each is typically of the order of 1 mm. Instrument time response must also be fast in order to respond to an element convected by the sensor in time $\lambda_c/\overline{u}$, typically 400 Hz.

Although most of the arguments are theoretical (since no instruments exist which could verify the proposed cloud structure some indirect measurements may support their ideas. Carn and Chatwin (1984) predicted large magnitudes for centerline concentration fluctuation intensities downwind of continuous sources. Fackrell and Robins (1982b) measured fluctuating plume behavior downstream of elevated and ground level plumes in wind-tunnel boundary layers. For elevated source size to integral scale sizes of 0.026, they produced concentration fluctuation intensities near 25.0 at intermediate distance of 20 integral scales downwind. On the other hand, Fackrell and Robins found for gound level sources that concentration fluctuation intensity had no significant dependence on source size or distance, and measured intensity values were about 0.5.

Sawford and Hunt (1984) considered molecular diffusivity and instrument smoothing effects on concentration variations produced by a lagrangian stochastic model of particle-pair motions. Over the range of conditions they considered, they found concentration fluctuation intensities of order unity or less. Carn and Chatwin (1984) responded by arguing that a one-dimensional model was not adequate to predict three-dimensional phenomena. (Hunt 1984*) further argues that temperature scalar measurements in grid turbulence made by Warhaft and Lumley (1978) show that tracers initially very close together (less than the Kolmogorov scale distance) rather rapidly separate due to a combination of microscopic and eddy scale movements. Hence, filaments

*Hunt (1984) personal communication

of the uncontaminated source material will not remain together very long.

Even if the scientific community should finally conclude that elements of an LNG spill may remain undiluted in small eddies for large distances, the issue need not necessarily increase hazard areas substantially or diminish the value of experimental measurements. There is no evidence from field ignition experiments that such small high concentration eddies are ignitable, or provide ignition links to the main LNG cloud. In addition, there is some evidence that such high frequency eddy structure contributes minimally to concentration variance.

Hinze (1975) has evaluated the effect of hot-wire length on the contribution of high frequency fluctuations to estimates of turbulent energy, $\overline{u'^2}$. Similar arguments apply for concentration variance, $\overline{c'^2}$. Assuming turbulence is homogeneous and isotropic, and that there are no spatial gradients in the mean concentration, then the transducer response of size η will be:

$$\overline{e'^2} = K^2 \eta^2 \overline{c'^2}, \qquad (3\text{-}5)$$

but when there are spatial non-uniformities in the concentration field, then the transducer response will be:

$$\overline{e'^2_m} = 2\, K^2\, \overline{c'^2} \int_{\eta}^{\eta} (\eta - x)\ g(x)\ dx \qquad (3\text{-}6)$$

where η is the transducer size, K is the transducer voltage response, and g(x) is eddy spatial correlation. In order to correct the transducer for spatial resolution the measured values, $\overline{e'^2}$, must be corrected by the factor CF:

$$CF = (2/\eta^2)\ \overline{c'^2} \int_{\eta}^{\eta} (\eta - x)\ g(x)\ dx \tag{3-7}$$

such that $\overline{e'^2} = \overline{e'_m{}^2}/(CF)$. When η >> integral scale, then correction is very large, and no turbulence is measured. When $\eta << \lambda_T$, the Taylor microscale, then $g(x) \simeq (1 - x^2/\lambda_T^2)$, and

$$CF \simeq (1 - \eta^2/(6\ \lambda_T^2))^{-1}. \tag{3-8}$$

Note that the correction is on $\overline{e'^2}$ not e'; that is, the smallest eddies may still actually be at conduction cut-off or Kolmogorov scales. Nonetheless, one sees that if $\eta < 0.5\ \lambda_T$ then only a 4% spatial resolution error exists in $\overline{e'^2}$, and if $\eta \simeq \lambda_T$ then a 20% error in $\overline{e'^2}$ would occur.

Li (1984) measured Taylor scales between 0.015 and 0.033 m in a meteorological wind tunnel at wind speeds below 2 m/s. Neff and Meroney (1982) estimated sampling areas of their aspirated hot-film katherometers to be less than 0.5 cm^2, or $\eta = 0.007$ m. Given $\lambda_T \simeq$ 0.02 and $\eta \simeq 0.007$, then the instrument would measure concentration variance with only a $\pm$2% error due to spatial resolution.

3.3 Wind-Tunnel Performance Envelopes

The viability of a given simulation scenario is not only a function of the governing flow physics but the availability of a suitable simulation facility and the measurement instrumentation to be employed. It is appropriate, therefore, to suggest bounds for the range of field situations which can reasonably be treated by physical modeling. A number of boundary layer wind tunnels exist at various laboratories (See section 3.2.1). Generally these tunnels range in size from facilities with cross-sections of 0.5 m x 0.5 m to 3 m x 4 m. Several of these facilities are equipped with movable side walls or ceilings to adjust for model blockage. By utilizing a variety of devices such as vortex generators, fences, roughness, grids, screens, or jets, a fairly wide range of turbulence integral scales can be introduced into the shear layer (See Figure 3-1). Varying surface roughness permits control of surface turbulence intensity, dimensionless wall shear, and velocity profile shape. Density stratification can be induced by means of heat exchangers, use of different molecular weight gases, or latent heat absorption or release during phase changes.

The major practical limitations of accurate wind tunnel simulation of LNG dispersion are operational constraints, particularly the inability to obtain a steady wind profile, or to accurately simulate atmospheric turbulence at the lowest wind speeds of interest, and Reynolds number constraints (as yet somewhat ill-defined) associated with the proper scaling of turbulence, diffusion, and frontal velocities. When combined with estimates of the restraint of plume expansion by the tunnel side walls, these considerations permit the development of performance envelopes for particular wind tunnel facilities (Meroney et al., 1977; Meroney and Neff, 1979; Meroney, 1980; Snyder, 1981; Puttock and Colenbrander, 1985).

3.3.1 Performance Envelopes: Land-Based Spills

It is instructive to consider the operational constraints on meteorological wind tunnels to determine those field situations which may be exactly simulated or marginally simulated. Several alternative performance curves are provided, including sets for undistorted and distorted scaling of density and curves in terms of prototype mean wind speed or prototype friction velocity. Operational limitations used to construct Figures 3-2 through 3-5 include:

1. Most large wind tunnels are unable to function satisfactorily at very low wind speeds (0.1 m/s). At low wind speeds the wind tunnels become sensitive to small disturbances, both external and internal, which lead to unrealistic perturbation of the mean flow.

2. The associated inability to maintain large Reynolds number.

   a. When the characteristic obstacle Reynolds number falls below 3300, wake turbulence no longer remains similar to field conditions (Golden, 1961). Figure 3-2 considers the limiting effect of a prototype obstacle 25 m in diameter.

   b. When the wall roughness Reynolds number falls below 2.5, then the near-wall region may not behave in a fully turbulent manner. The figures show curves presuming field roughness lengths of z_o = 1 cm and 10 cm.

3. A minimum spatial resolution for concentration measurements of 2.5 mm is likely in the laboratory. Minimum pertinent resolution required in the field may be 1 m.

4. Lateral interference with a spreading dense plume by wind tunnel walls. Calculations presume no wall interference before one reaches a distance of 20 diameters downwind of a 0.3 m diameter model source steadily boiling off LNG in a 4 m wide tunnel. Two boil-off rates are provided, 0.01 and 0.1 $m^3/s/m^2$. The lower value corresponds to typical LNG boil-off rates over soil or concrete, whereas the larger value is typical of boil-off rates over water. The interaction conditions are calculated using the spread formulae proposed and tested against laboratory and field spills by Britter (1980).

5. Mixing rates associated with molecular diffusion exaggerate dilution at low wind speeds. Molecular dispersion becomes

significant for unobstructed flows when the Peclet/Richardson number ratio, Pe/Ri, is less than 1500, or Pe_*/Ri_* is less than 0.2. (Note: This criteria only applies to spill scenarios in the absence of turbulence generated by cloud collapse, tanks, dikes, fences, buildings or water sprays. New experiments are required to define the actual errors associated with falling below Pe/Ri = 1500.)

Figure 3-2 presents guidelines for cases when undistorted density scaling of an LNG spill is intended (ie. $(SG)_m = 1.5$). Note that it is possible to meet roughness and Reynolds number constraints only for very modest scale ratios and high prototype velocities. Indeed most interesting field spills would not fit in conventional facilities if these constraints are retained. As discussed in Meroney (1986) Technical Support Document, Sections 3.6 and 5.4, strict observance of the roughness Reynolds number does not seem critical when self-generated turbulence dominates mixing. Many laboratory tests noted on the figures have given satisfactory results while disobeying this criterion.

Figure 3-4 presents guidelines for cases when distorted density scaling of an LNG spill is presumed (ie. $(SG)_m = 4.2$). In this case, prototype wind speeds less than 2 m/s can be simulated at scales greater than 1:200 without running at tunnel speeds less than 0.2 m/s; however, molecular diffusion will exaggerate dilution for scale ratios greater than 1:100 and prototype wind speeds less than 3 m/s. Obstacle Reynolds number remain above 3300 for 0.3 m diameter model obstacles, even at prototype wind speeds of 1 m/s and scale ratios of 1:200. The filled in data points, ■, are cases where the model source gas specific gravity was equal to 4.2.

Figures 3-3 and 3-5 are companion figures in terms of prototype friction velocity.

3.3.2 Performance Envelopes: Water-Based Spills

LNG spills on to water differ from their over-land counterpart because they

a) Boil-off at a maximum rate near 0.1 $m^3/s/m^2$ as long as LNG remains,
b) Generally involve larger volumes (e.g. 25,000 m^3 of LNG), and
c) The spill source may have a variable area in time.

Since it is desirable to contain the 5% lateral contour within a test region unaffected by wall reflections, a second set of calculations for performance envelopes were prepared assuming a transient spill configuration. Maximum pool radius after an instantaneous spill is calculated by the equations of Raj and Kalelkar (1973). A modified version of the method of Van Ulden (1974) was used to calculate the subsequent gravity spread radius. The gravity spread is assumed to occur until the frontal velocity equals the mean flow velocity; subsequently a 1.5 factor growth in radius is assumed before the 5% LFL condition is reached. Figure 3-6 presumes a 4 m wide wind tunnel is available.

This figure suggests a 20,000 m^3 LNG spill must be modeled at 1:800 to permit even a 4 m/s prototype wind speed. A 5000 m^3 LNG spill could be contained at scale ratios of 1:600 and prototype wind speeds down to 3 m/s, but laboratory flow speeds would be below 0.2 m/s. Unfortunately such large scale ratios preclude measuring with very good spatial resolution.

3.4 Test Program for an LNG Fluid Model Experiment

It is very important for both those conducting a fluid modeling study and those receiving the results to share a common set of criteria for reference. If all laboratories which conduct physical modeling of LNG hazards provide similar setup, wind tunnel calibration, and flow field information, it will provide an opportunity to detect anomalous flows and permit inter-laboratory comparisons of test results.

Different experimental programs will be required, depending upon the purpose of the measurement program. Different sets of measurements are appropriate for basic fluid research, safety design, or meeting regulatory standards. As noted in Section 3.1, the manner in which the driving questions are cast will determine the character and details of the measurements required. Nonetheless, some common elements exist in all such measurement programs, and these should be performed in such a manner that the data have maximum value.

A detailed formulation and discussion of the fundamental principles for fluid modeling of dense gas dispersion is provided in Meroney (1986) Technical Support Document, Sections 2 through 5. The necessary model scales, roughness, and flow conditions would be chosen to accommodate earlier arguments. To insure that a stationary, uniform, and homogeneous flow is produced, the following procedures and measurements are recommended:

1. A daily log of the experiment should be maintained, recording all normal and abnormal operating conditions encountered.

2. The size of all building structures and the general topography in the vicinity of the spill area should be examined. Upstream sharp-edged buildings and 3-dimensional topography should be included if their height exceeds 1/20th of the distance from the source. Two-dimensional obstructions (ridges, fences, etc.) should be included if their height is greater than 1/100th of the distance from the source. Topography height should be based on elevation difference between hill peaks and local troughs. For tall thin structures the width is the pertinent scaling dimension. Wind tunnel blockage should be kept below 5% for an ordinary wind tunnel and 10% for a tunnel with a properly adjusted ceiling.

3. Since dense plumes travel directly over the ground surface local irregularities may be important in deflecting or augmenting plume growth. Models should not be terraced. Model roughness should not normally be exaggerated such that

it exceeds gas layer depths. Even modest terrain slopes can be important during dense gas dispersion; hence, model terrain should include slope if it exceeds 1°.

4. The model should be immersed in an appropriate boundary layer that can be characterized by surface roughness, z_o, friction velocity, u_*, and stability, Ri or L_{mo}. Alternatively, one may specify depth, k, and velocity power-law coefficient, p.

5. Laboratory wind speeds should be high enough such that obstacle Reynolds numbers exceed 11,000 for sharp-edged objects, or 100,000 for rounded objects. Peclet/Richardson number ratios for the simulant gas should exceed 1500.

6. Wind profile and concentration measurements should be made in the wind tunnel in the absence of buildings, large terrain, or other large structures to provide an evaluation of the model flow in absence of such perturbations. Such tests will ensure that no longitudinal or cross-wind aberrations exist in the flow field.

   a.) As appropriate provide vertical profiles of the mean temperature, T ($^{\circ}$K), and the intensity of temperature fluctuations, (T'_{rms}/T) at the spill location.

   b.) Provide vertical profiles of the mean velocity, U (m/s), and the longitudinal and vertical turbulent intensity, (u'_{rms}/U) and (w'_{rms}/U), at the spill position, downwind of the planned study area, and midway between the two positions. Repeat profiles at position midway between the tunnel walls to both the left and right (9 profiles).

   c.) Provide vertical profiles of the shear stress $-\overline{u'w'}$ (m^2/s^2) at the spill position, downwind of the planned study area, and midway between the two positions (3 profiles).

   d.) Release dense gas continuously from the spill site at some representative rate. Take vertical and lateral profiles of concentration through the plume centerline at least at the quarter intervals between the source and the end of the planned study area. Take ground-level longitudinal profiles of concentration downwind along the plume centerline to the end of the study area (9 profiles).

   e.) Convert model concentrations to equivalent field values. Check at each downwind position of measurement for conservation of mass by estimating Q from the integration:

$$Q = \int_{o}^{+1}\int_{-1}^{+1} C(y,z)U(z)\,dy\,dz$$

7. Install terrain, buildings and other structures in wind tunnel, and pursue measurement program by measuring comparable profiles of temperature, velocity, concentration, turbulence,

and shear as appropriate. At a minimum, measure meteorological variable profiles over spill location.

8. During studies of the transient behavior of instantaneous or finite-time release LNG spills, multiple replications of each spill will be necessary to establish ensemble mean conditions and associated variances. The total number of replications will be determined by the acceptable errors and confidence limits specified; however, it is likely at least 3 to 5 replications of each scenario will be required.

3.5 Check List for Reporting Laboratory Experiments

Any fluid modeling report should completely document the design and operation of the model study. The facility and any modifications should be described; features of the model should be reported; instrumentation character, manufacturer and model calibration, and accuracy recorded; behavior of the facility in the absence of model perturbations verified; character of the background simulated meteorological field documented; and, finally, results of the specified experiments tabulated. All too often, one or more of these ingredients are missing, making it very difficult for data users to establish the value of the information.

An archive report should include:

1. Detailed topographical maps of the area studied, and discussion concerning the selection of the model area.

2. Description and references to the mode of operation, calibration, sensitivity, and resolution of instrumentation.

3. References to the construction details of the simulation facility, and documentation of any unique modifications to the test section which modify operational characteristics.

4. Documentation for the dispersion comparability test in absence of buildings, structures, large terrain features, or unusual roughness should include:

   a.) Detailed description of the fluid model, including features of the scale model, surface roughness, freestream wind speed, and methods used to provide the simulated boundary layer,
   b.) One vertical profile of mean temperature over the spill site,
   c.) One vertical profile of temperature fluctuation intensity

over the spill site,

d.) Nine vertical profiles of mean velocity distributed over the test area,

e.) Nine vertical profiles of vertical and longitudinal turbulence intensity at similar locations,

f.) Three vertical profiles of shear stress along the tunnel centerline,

g.) Four vertical and lateral profiles of concentration through the plume center line,

h.) One ground-level longitudinal profile of concentration downwind along the plume center line, and

i.) Evaluation of the effective surface roughness length, z_o, friction velocity, u_*, velocity power law coefficient, p, determined by evaluating the mean velocity profiles and the shear stress profiles.

(Additional valuable information could include velocity spectra, velocity correlations, and integral scales.)

5. Documentation for the experimental situations where the model structure and terrain are in place should include parallel measurements to those taken under Number 4 above.

6. Comparison figures which examine the differences measured during items Number 4 and 5 above.

Table 3-1a PARTICIPANTS IN PHYSICAL MODELING

GROUPS	LOCATION	FACILITY	TYPE
WIND TUNNELS			
Hall et al. (1974, 79, 82, 85)	Warren Springs U.K.	4.3mx1.6mx12m	Open
Meroney et al. (1973, 76, 77, 79, 80, 81, 82, 83)	Col. State Univ. U.S.A.	1.83mx1.83mx24m 2.44mx3.66mx18m	Closed Open
Ohba (1978)	Misubushi Ind. Nagasaki, Jap.		Open
Lohmeyer et al. (1980,82)	U. of Karlsruhe F.R.G.	0.5mx2mx5m	Open
Builtjes, et al. (1980, 82,82,84)	T.N.O. Apeldoorn, Neth.	1.2mx2.65mx6.8m	Open
Krogstad (1980)	SINTEFF Trondheim, Norwy	Air flume	
Colenbrander et al. (1980-84)	SHELL Res. Lab. Amsterdam, Neth.		
Reithmuller (1982)	VonKarman Inst. Belgium		
Bradley & Carpenter (1983)	Nat. Mar. Inst. U.K.	2.4mx4.8mx15m	
Schatzman et al. (1984)	U. of Hamburg F.R.G.		Open

Table 3-1b PARTICIPANTS IN PHYSICAL MODELING

GROUPS	LOCATION	FACILITY	TYPE
WATER TUNNELS & FLUMES			
Britter (1980)	Cambridge U. U.K.		Open
Hanssen (1981) Wighus (1982)	Norwegian Hydro Norway	0.5mx2mx5m	Closed
Alessio (1983)	U. Torsino Italy		
Bradley & Carpenter (1983)	Grenoble France	0.75mx3mx15m	
Cleaver et al. (1983)	U. of Liverpool U.K.	0.84mx1.4mx4m	Closed

Table 3-2 Summary of Physical Modeling Experiments of Dense Gas Dispersion

PHYSICAL MODELING EXPERIMENTS

ORGANIZATION	IDEALIZED CONTINUOUS	IDEALIZED FINITE	IDEALIZED INSTANTANEOUS	TANKS & DIKES	TERRAIN	FENCES	SHIPS	WATER SPRAY	AIR CURTAINS	STACKS
Warren Springs, U.K.	1974,79	1974,79	1982,85		1974					
Col. State U., U.S.A.	1982,83	1982	1982	1976,77,80,82	1977,81	1981,82		1983,84		1973,80
Mitsubushi Ind, Japan				1978 UP				1978 UP		
Cambridge U., U.K.	1980									
U. of Karlsruhe, F.R.G.			1980							
T.N.O., Apeldoorn, Neth.	1980 UP		1984,85	1980 UP,82		1980 UP	1980 UP			
SINTEF, Norway			1980							
SHELL Research, Neth.	1980-84 UP						1980 UP			
Norwegian Hydro, Norway				1982						
Von Karman Inst, Belgium				1982						
U. of Torsino, Italy					1981					
Nat. Maritime Inst., U.K.			1984	1983	1983					
U. of Arkansas, U.S.A.			1983							
U. of Liverpool, U.K.	1983					1983				
U. of Hamburg, F.R.G.			1985							

Table 3-3 POTENTIAL PERFORMANCE OF MATHEMATICAL AND PHYSICAL MODELLING (Modified from Duijm et al, 1985)

ASPECT	BOX MODEL	3D - MODEL *	PHYSICAL MODEL
Main model assumption	Rate of entrainment	Turbulence closure assumption	Similarity of full-scale and model-scale flow field
Model results	Averaged concentrations	Averaged concentrations	Visualization (film/video) Averaged and instantaneous concentrations
Spatial resolution	Low	Depends on grid size	Depends on measurement technique
Modelling Dispersion over flat terrain	Good	Good	Good
Modeling dispersion over obstacles	Impossible	Possible but difficult	Good
Modelling effects of atmospheric stratification	Fair to good	Fair to good	Possible but requires special facilities
Modelling effects of surface heat transfer	Good	Good	Difficult, requires special equipment. Limited conditions
Modelling effects of ambient humidity	Good	Good	Reasonable over limited conditions
Time needed, initialization of model included	Less than one day	Days to weeks, depends upon terrain complexity	Model making: weeks Separate experiment: minutes to day
Costs	Low	Medium to high	Reasonable in wind tunnel Higher in water tunnel

* Presumes problems with grid resolution, gradient transport assumptions, and numerical diffusivity are solved.

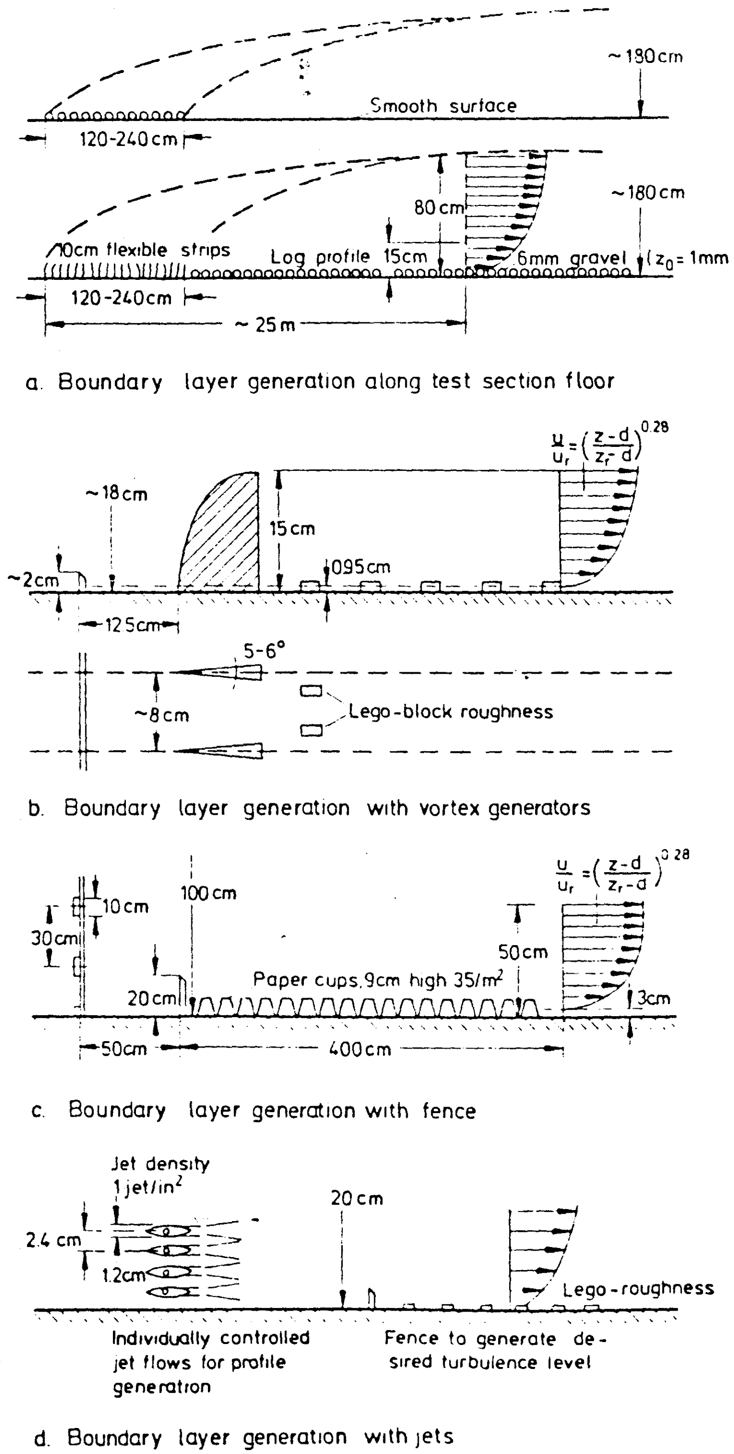


Figure 3-1. Methods for generating boundary layer flows in a wind tunnel (Plate, 1982).

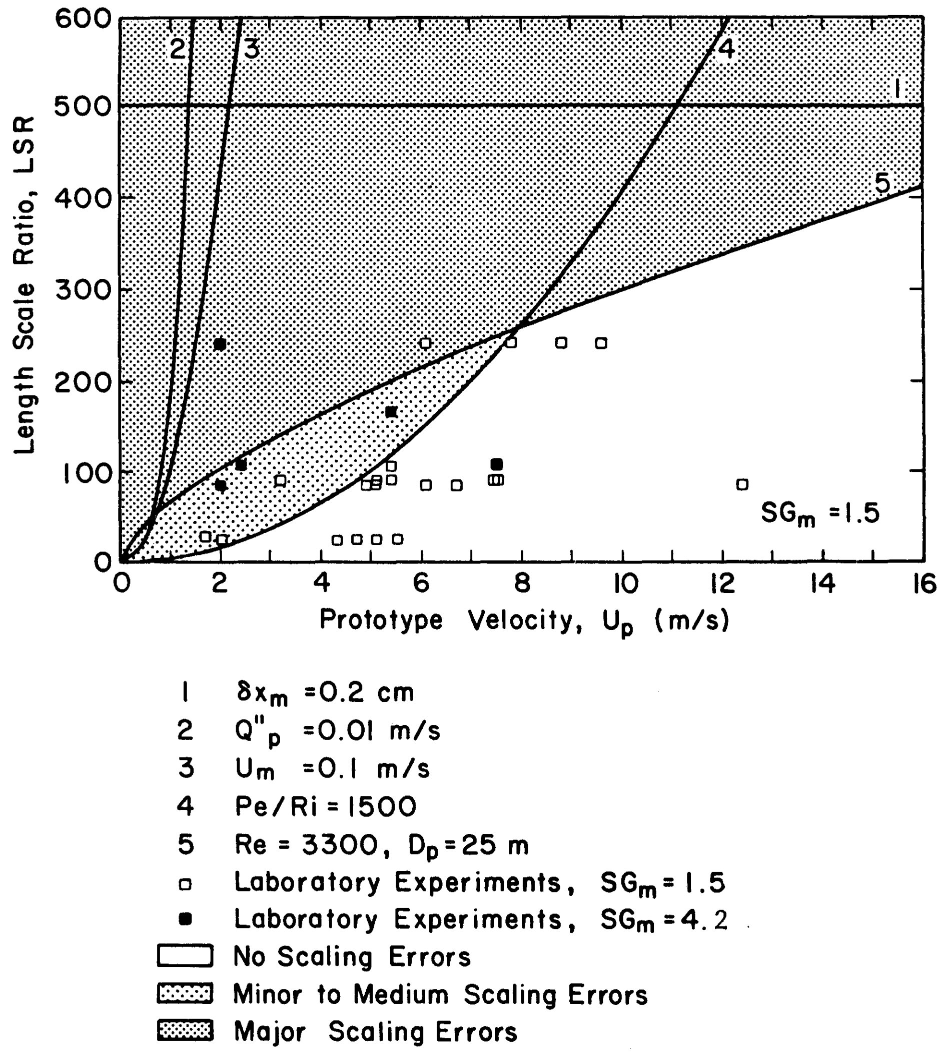


Figure 3-2. Performance envelope to simulate LNG spills -- constant boiloff conditions, SG = 1.5, tunnel width = 4 m. Length scale ratio vs. prototype wind speed.

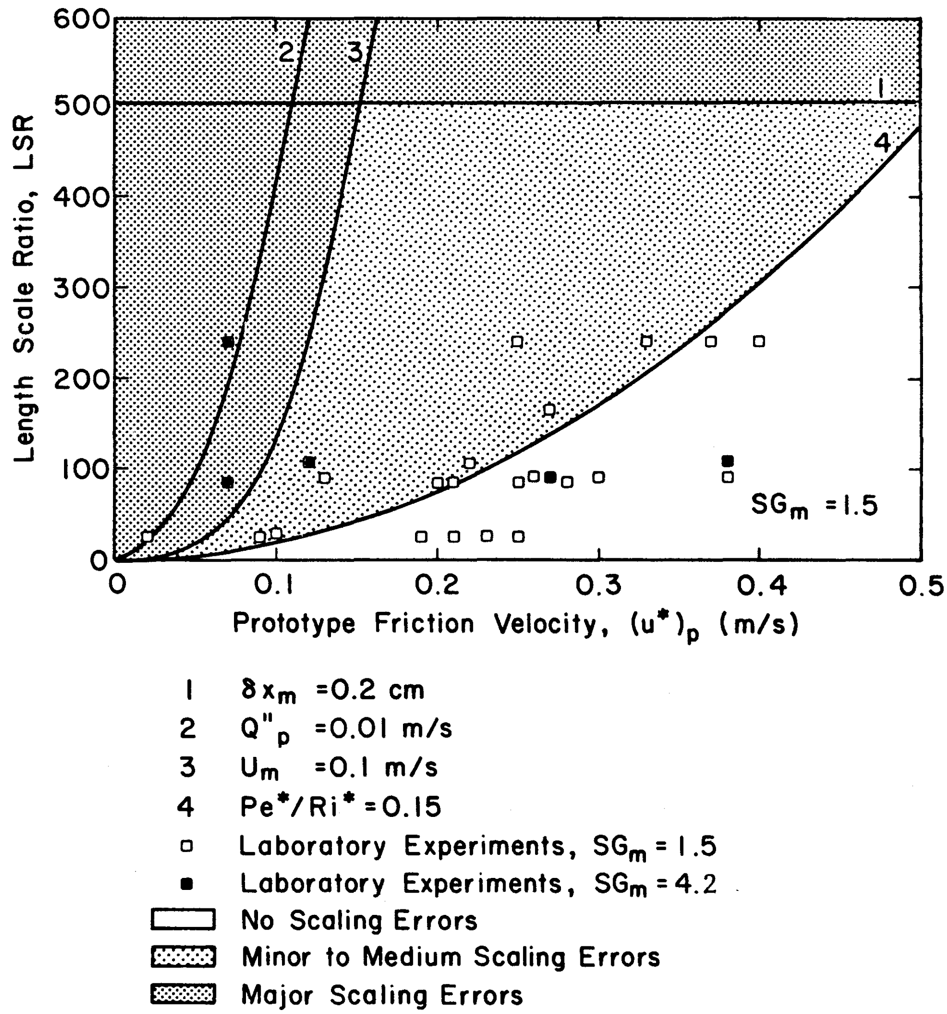


Figure 3-3. Performance envelope to simulate LNG spills -- constant boiloff conditions, SG = 1.5, tunnel width = 4 m. Length scale ratio vs. prototype friction velocity.

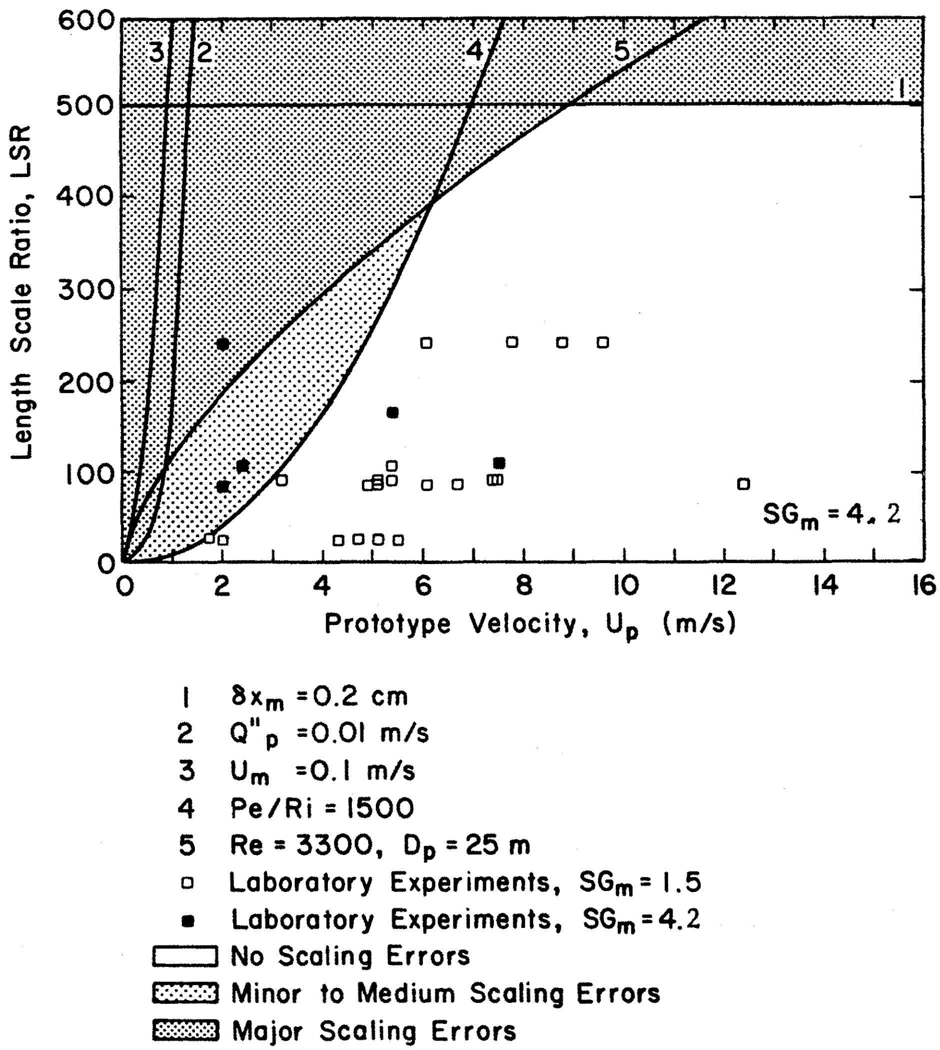


Figure 3-4. Performance envelope to simulate LNG spills -- constant boiloff conditions, SG = 4.2, tunnel width = 4 m. Length scale ratio vs. prototype wind speed.

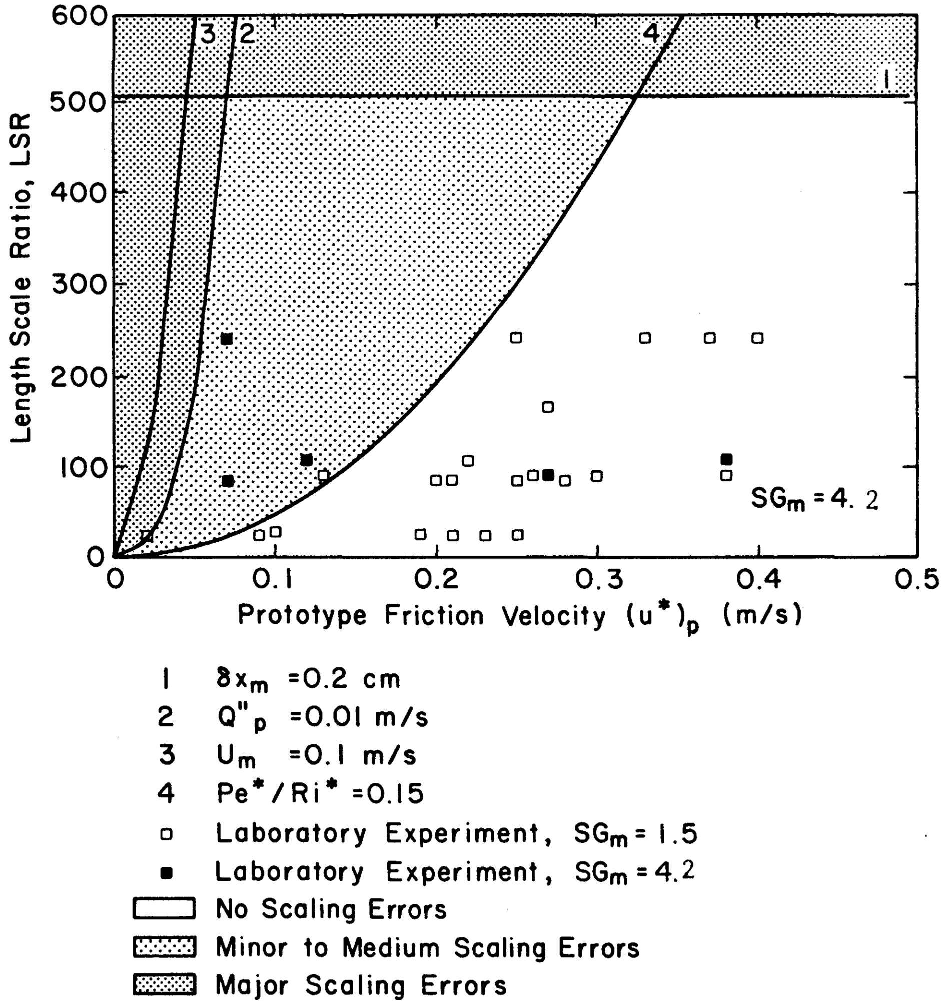
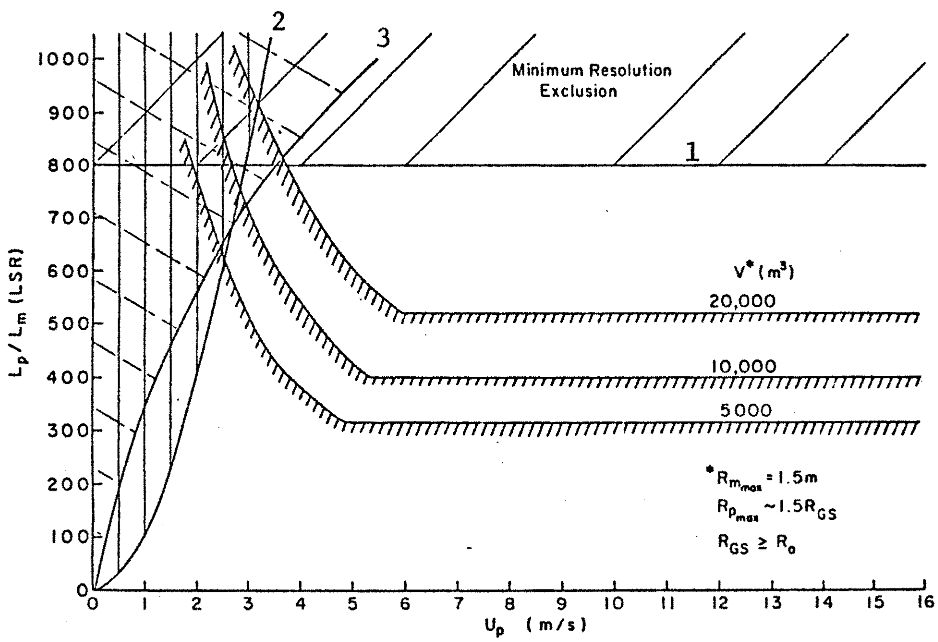


Figure 3-5. Performance envelope to simulate LNG spills -- constant boiloff conditions, SG = 4.2, tunnel width = 4 m. Length scale ratio vs. prototype friction velocity.



1 $\delta\chi_m = 0.125$ cm

2 $U_m = 0.1$ m/sec

3 Re = 3300, Lp ≃ 300 m (LNG Carrier length)

Figure 3-6. Performance envelope to simulate LNG spills -- transient boiloff conditions over water, SG = 1.5, tunnel width = 4 m. Length scale ratio vs. prototype wind speed. Final radius = 1.5 R_{GS} > 1.5 R_o.

4.0 CONCLUSIONS

This guideline report has sought to define the conditions for fluid-model experiments such that their predictions for hazard assessment work are valid. By 'valid' is meant that the fluid-model predictions of the quantities needed to assess the hazard of an LNG release agree with the results of large scale experiments to the extent consistent with the uncertainty in the available field data and the accuracy required for useful hazard assessment predictions. Standardized practices for wind tunnel modeling are recommended which will improve simulation usefulness and accuracy.

Perfect agreement is, of course, not reasonable, but it appears agreement in concentration levels within a factor of two is often possible. The mean deviation of fluid-model predictions of LFL distances from observed field values is less than 1% over the cases surveyed, and the standard deviation is only about 20%. The uncertainties in failure probabilities, toxicity data, and source conditions suggest that the ability to predict concentrations levels at a particular point following a full-scale release to within a factor of 2 to 3 and LFL distances within 20% standard deviation is quite adequate.

Wind tunnels are, in effect, analog computers which have the advantage of "near-infinitesimal" resolution and "near-infinite" memory (Snyder, 1981). A fluid modeling study employs real fluids not models of fluids; hence, the fluid model is implicitly non-hydrostatic, non-Boussinesqu, compressible, includes variable fluid properties, non-slip boundary conditions, and dissipation. Real fluids permit flow separation and recirculation. All conservation equations are automatically included in their correct form in a laboratory model without truncation or differencing errors, and there are no missing terms or approximations.

The fluid model bridges the gap between the fluid mechanician's analytic or numeric models of turbulence and dispersion, and their application in the field. One might observe that "If a numerical model cannot predict results of an idealized fluid experiment, what hope does it have of application to atmospheric scales?" Duijm et al. (1985) prepared Table 3-3 comparing potential performance of mathematical and physical modeling based on the present state-of-the-art. Note that fluid modeling does some things better and some things worse than the numerical alternatives examined. Wind-tunnel simulation is likely to be most useful for near field modeling where mechanically induced vortext turbulence is present from structures such as tanks, vapor detention systems, water sprays, etc., and where the uncertainties in mathematicalmodeling of complex dispersion processes are greatest.

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