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# AN ASSESSMENT OF PREDICTABILITY OF LNG VAPOR DISPERSION FROM CATASTROPHIC SPILLS ONTO WATER*

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## Summary

Predictions of the downwind travel of LNG vapor—air mixtures based on mathematical modelling by several groups have shown wide variations. A review and assessment of these predictions is summarized in this paper. Its objectives were to provide a detailed description of the models, and using them to estimate maximum downwind travel for a standard scenario, to enable valid comparisons to be made; to identify the reasons for differences found; to define the present "state-of-the-art"; and recommend further work.

Models produced by seven groups and the predictions which they give, are described and compared. The results of this comparison and the wide variations are discussed. The objectives of further work now in progress are given.

## Introduction

The degree of risk to the public associated with large scale importation of liquefied natural gas (LNG) by the United States continues to be debated. A frequently voiced concern is the formation of a large flammable cloud following accidental release of LNG onto water in the event that the gas is not ignited at the collison site. Although it is considered highly likely that immediate ignition would occur in a catastrophic collision-release, an accident scenario involving formation of a large vapor cloud which might travel a considerable distance downwind before dispersing is usually analyzed in assessing the risk of LNG importation.

Estimates of the extent of travel of a flammable vapor—air mixture following spillage of LNG onto water presuppose the amount and rate of the spill. Mathematical models have been used by several groups to predict the down-

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wind travel of LNG vapor—air mixtures. Although wide disagreement in the estimates published by such groups has been repeatedly cited as a basis for concern, an initial survey indicated that model predictions based on different scenarios involving different spill sizes and rates and weather conditions were being compared (contrasted). There appeared to be a need for a review and assessment of such predictions. This paper summarizes such a review recently conducted for the Cargo and Hazardous Materials Division, U.S. Coast Guard. [1].

The objectives of this review performed while the author was on sabbatical leave from the Department of Chemical Engineering, University of Arkansas, serving as Technical Advisor, Cargo and Hazardous Materials Division, U.S. Coast Guard Headquarters, Washington, D.C. were:

(1) To provide a detailed description of the mathematical models, upon which published predictions of LNG vapor travel downwind of catastrophic LNG spills onto water have been based.

(2) To estimate, using these models, the maximum downwind travel of flammable LNG vapor/air mixtures for a "standard" spill scenario, so that a valid comparison could be made of the results obtained when the different models are used to describe the same event.

(3) To identify the reason for differences in predictions which occur when the models are used to describe the same event, and to assess the technical credibility of the methodology which results in such differences.

(4) To define the present "state-of-the-art" in predictability of LNG vapor dispersion from catastrophic spills onto water.

(5) To provide recommendations for further work which would increase confidence in the predictability of vapor dispersion from catastrophic LNG spills onto water.

## Description of mathematical models reviewed and a comparison for "standard scenario" LNG spill

The predictions of the following groups have been repeatedly cited in the literature relating to the safety of marine LNG transportation.

(i) Cabot Corporation — Germeles and Drake [2]
(ii) U.S. Coast Guard CHRIS (Chemical Hazard Response Information System) — Arthur D. Little, Inc. [3]
(iii) Professor James Fay, Massachusetts Institute of Technology [4]
(iv) U.S. Bureau of Mines — Burgess et al. [5,6]
(v) American Petroleum Institute — Feldbauer et al. [7]
(vi) U.S. Federal Power Commission [8]
(vii) Science Applications, Inc. [9]

The "standard scenario" LNG spill which was assumed for purposes of comparison of the above models was an instantaneous release of 25,000 cubic meters of LNG (representative of the largest single-tank capacity of ships constructed to date or on order) onto water. Such an event was considered to provide a conservative upper limit on the size (and rapidity) of a spill which might conceivably occur, even though such a spill is considered highly unlikely.

The models used by the groups cited above can be categorized as follows:

(1) Models which utilize classical air pollutant dispersion equations which were developed to describe relatively near field dispersion of neutrally buoyant materials. These models are based on the general observation that the concentration profiles downwind of a pollutant source can be represented by a Gaussian distribution. This model type can be applied to two different dispersion phenomena:

> (a) Dispersion of an essentially instantaneous release of material *into the atmosphere*, the dispersion being associated with the growth of this "puff", or cloud, as it is being translated by the wind. Germeles and Drake, CHRIS, and Fay and Lewis utilize this type of model, with modifications.
>
> (b) Dispersion of material which is being emitted continuously, forming a "plume" downwind of the emission source. Burgess et al., Feldbauer et al., and the Federal Power Commission (FPC) utilize this type of model, with modifications. It should be emphasized that this type of model, although assuming instantaneous spillage of the LNG onto water, *does not assume* instantaneous release into the atmosphere. Instead, an estimate is made of the rate of LNG vapor flow downwind from the LNG pool and the dispersion is assumed to occur in the manner described by the classical "plume" dispersion mechanism.

The models in this category have been modified in some cases in an attempt to allow for effects due to the differences in density between the initially evolved LNG vapor and the air.

(2) Models which include equations describing the momentum and energy *distribution* as well as the mass distribution in the developing cloud. (The classical air pollutant dispersion equations which are used as a basis for model development in category 1 above are a special case where energy effects and momentum effects are not considered). Science Applications, Inc. (SAI) utilizes this type of model.

### *Models based on "puff" dispersion equations*

Although the models used by Germeles–Drake [2], CHRIS [3] and Fay—Lewis [4], all use as a point of departure the classical "puff" model, modifications (and additions) of varying degree are incorporated in an effort to account for factors specific to the LNG—water spill vapor dispersion problem. These modifications are described in detail in the original report [1] but time and space constraints preclude detailed description in this paper. However, the modifications and additions incorporated can be identified with the following factors.

(1) The classical puff dispersion equations assume emission from a point source. Since an LNG spill forms a pool on the water, the vapor is actually

emitted from an *area source,* rather than a point source.

(2) The classical puff dispersion equations were developed for description of dispersion of neutrally buoyant materials. Since the LNG vapor emitted from the spill is initially cold and more dense than the air, the LNG cloud formed over the spill is expected to spread out due to gravity effects.

(3) The dispersion coefficients required as input to the puff dispersion model are based on field data taken over land under varying weather stability conditions. Such data is rather limited and dispersion coefficient data based on "plume" dispersion measurements have been recommended by Germeles and Drake as being more applicable for use in the puff model description of LNG vapor dispersion.

Table 1 gives LNG vapor dispersion predictions for a 25,000 -m$^3$ instantaneous spill using the Germeles—Drake, CHRIS, and Fay—Lewis models for neutral and stable weather conditions.

The predictions shown in Table 1 appear to indicate fair agreement. For example, the maximum variation in the predicted downwind distances to the 5% vapor concentration during stable weather conditions is about 25% of the mean value. However, the three models used make significantly different assumptions regarding the behavior of the LNG vapor cloud during the early stages of its development.

TABLE 1

**LNG vapor dispersion predictions for 25,000-m$^3$ instantaneous spill on water. Models utilizing "puff" dispersion equations**

| | Germeles and Drake | CHRIS | Fay and Lewis |
|---|---|---|---|
| Initial pure vapor cloud size | Radius = 383 m<br>Height = 13 m | Radius = 383 m<br>Height not used | Not used |
| Vapor cloud size at end of gravity spread | Radius = 950 m<br>Height = 22.6 m | Not used | Radius = 816 m<br>Height = 2.9 m |
| Concentration of vapor cloud at end of gravity spread phase | 22% | Not used | 100% |
| Maximum downwind distance to 5% vapor (average) | | | |
| Neutral weather | 3.0 miles | 3.2 miles | 1.6 miles |
| Stable weather | 11.5 miles | 16.3 miles | 17.4 miles |
| Maximum downwind distance to 2¼% vapor (average) | | | |
| Neutral weather | 5.6 miles | 4.8 miles | 3.0 miles |
| Stable weather | 22.1 miles | 24.4 miles | 31.0 miles |

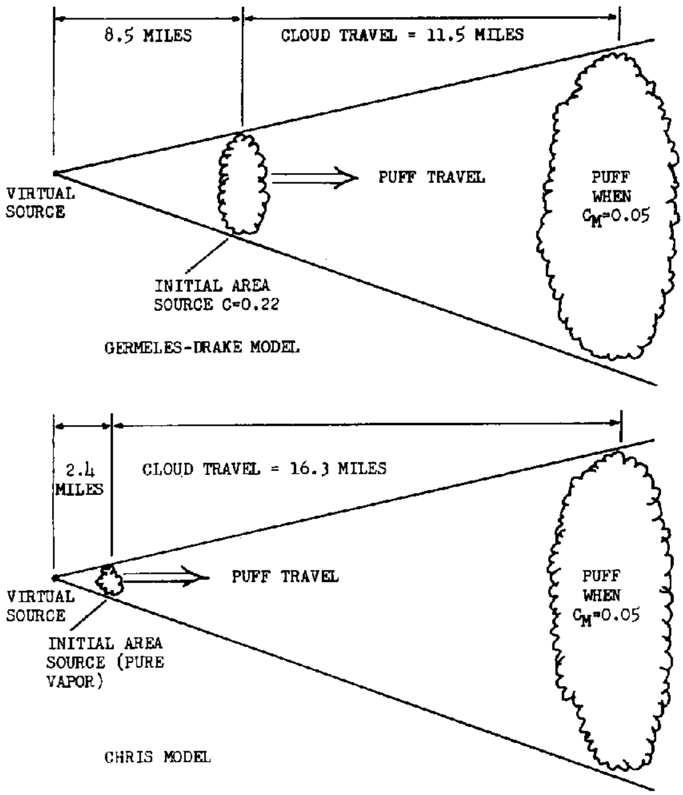

Fig. 1. Comparison of Germeles—Drake and CHRIS models.

Some insight into the difference in the predictions of the Germeles—Drake and CHRIS models can be gained by reference to Fig. 1 which compares the virtual source location (used to correct for the area-source vs. point-source effect) for the two models for stable weather conditions. The larger virtual source correction results from the Germeles-Drake model provision for cloud dilution in the early stages due to gravity spread and heat transfer effects.

A comparison of the Germeles—Drake and Fay—Lewis models is more difficult. Four factors affecting the predictions of these models must be recognized.

(1) Fay and Lewis's modification of the classical dispersion equation to force a unity concentration at the source tends to shorten their distances in comparison to those obtained with simple application of the puff model and the model of Germeles—Drake.

(2) The Fay—Lewis model has been used in this report assuming the volume of vapor released from the spill to be the saturated vapor volume of LNG at 1 atmosphere pressure, or approximately 240 times the liquid volume.

The Germeles—Drake prediction assumes the total volume of vapor as calculated at 70°F (21°C) and 1 atmosphere pressure, or approximately 630 times the liquid volume. If the larger volume is used in the Fay—Lewis model, as suggested by Fay in a recent communication to this author [10], a much longer distance (approximately 28 miles to 5% vapor in stable weather) results.

(3) Fay and Lewis use the "very stable" category puff dispersion coefficients presented by Slade [11]. Gerneles and Drake argue that the very stable puff dispersion coefficients correlation suggested by Slade is not sufficiently justified by the original data, and that the Pasquill F stability coefficients which represent "plume" dispersion data are more applicable in their analysis for stable weather conditions. This choice, however, considerably shortens the downwind distance to the 5% level when using the Germeles—Drake model. If the very stable puff dispersion coefficients of Slade are used in the Germeles—Drake model the calculated distance to the 5% vapor level is approximately 40 miles. Conversely, if the Pasquill F stability coefficients are used in the Fay--Lewis model instead of the "very stable" puff coefficients cited by Slade, the predicted distance is cut roughly in half.

(4) Fay and Lewis's model does not include provision for air entrainment during the gravity spread. This factor considered alone would suggest a longer distance with the Fay—Lewis model than with the Germeles--Drake model.

In view of these important differences in the models, the "agreement" indicated in Table 1 must be considered fortuitous. Similar agreement would not necessarily result for other "scenarios".

*Models based on "plume" dispersion equations*

Although the models used by Burgess et al. [5,6] Feldbauer et al. [7] and the Federal Power Commission [8] all are based on the classical "plume" dispersion models, modifications of varying degree are incorporated in an effort to account for factors specific to the LNG—water spill vapor dispersion problem. These modifications are described in detail in the original report [1] but time and space constraints preclude detailed description in this paper. However, the modifications and additions incorporated can be identified with the following factors.

(1) The vapor flow rate into the atmosphere has been estimated by different methods, with widely varying results.

(2) Some models have included effects due to gravity spreading of the cold LNG vapors; others did not. Where included (Feldbauer et al. and Federal Power Commission), the methods used were dissimilar.

(3) The dispersion coefficient data used were not always the same. Different sources of these data have been used and "adjustments" have been made to these data in an effort to more accurately reflect the expected cloud behaviour. Finally, the predictions made have not always assumed applicability of the same meteorological conditions, e.g., neutral vs. stable.

TABLE 2

**LNG vapor dispersion predictions for 25,000 $m^3$ instantaneous spill on water. Models utilizing "plume" dispersion equations assuming 5 MPH wind**

| | Burgess et al. | Feldbauer et al. | Federal Power Commission |
|---|---|---|---|
| Spill evaporation time (minutes) | 11.9 | 15.0 | 4.5 |
| Downwind vapor flow rate ($ft^3/s$ at ambient conditions) | $7.5 \times 10^5$*<br>$2.0 \times 10^6$** | $6.3 \times 10^5$ | $1.4 \times 10^5$ |
| Meteorological stability conditions used | Singer—Smith D (worst case) | Pasquill C/ Singer—Smith D (horizontal/ vertical) | Pasquill D |
| Maximum downwind distance to 5% vapor (average) | 25.2 miles*<br>50.3 miles** | 5.2 miles | 0.75 miles |
| Maximum downwind distance to 2½% vapor (average) | 38.2 miles*<br>76.2 miles** | 9.5 miles | 1.6 miles |

*Average over evaporation period.
**Peak rate during evaporation period.

(4) Modifications have been made in some cases to account for the area nature of the source. Where included (Feldbauer et al. and Federal Power Commission), the methods used were dissimilar.

Table 2 gives LNG vapor dispersion predictions for a 25,000 cubic meter "instantaneous" spill using the Burgess et al., Feldbauer et al. and Federal Power Commission models. The largest predicted downwind distance to the 5% (average) concentration level, 50.3 miles obtained using the Burgess et al. model with the predicted peak evaporation rate used as the downwind vapor flow rate, is almost 70 times greater than the 0.75 mile prediction of the FPC model. The downwind distances calculated using Burgess' model with a vapor flow rate equal to his predicted time averaged evaporation rate and with Feldbauer's model lie in between.

The downwind distances to the time average 5% concentration given in Table 2 are plotted in Fig. 2 as a function of vapor flow rate used in the predictions. The uppermost line in Fig. 2, drawn through Burgess' predicted distances, represent a "worst case" downwind distance as predicted by the classical point source plume dispersion model. It is "worst case" because it does not account for area source or gravity spreading effects,and because it is based on Singer and Smith D-gustiness category dispersion coefficients, which are a fairly close approximation to the most stable weather category (F) of Pasquill. The sensitivity of the predictions to the choice of dispersion coefficients is shown by the lower line on Fig. 2 which is obtained using

Burgess' model with Singer and Smith $B_2$ dispersion coefficients which represent unstable meteorological conditions. (Burgess set the vertical dispersion coefficient $\sigma_z$ equal to 0.2 $\sigma_y$, based on experimental spill data, to better describe the vertical dispersion of the dense LNG vapors). All of the predictions of the distance to the 5% concentration level fall between the two lines on Fig.2, and the primary reasons for the different values predicted are indicated by the location of the particular prediction in relation to these "bounding" cases.

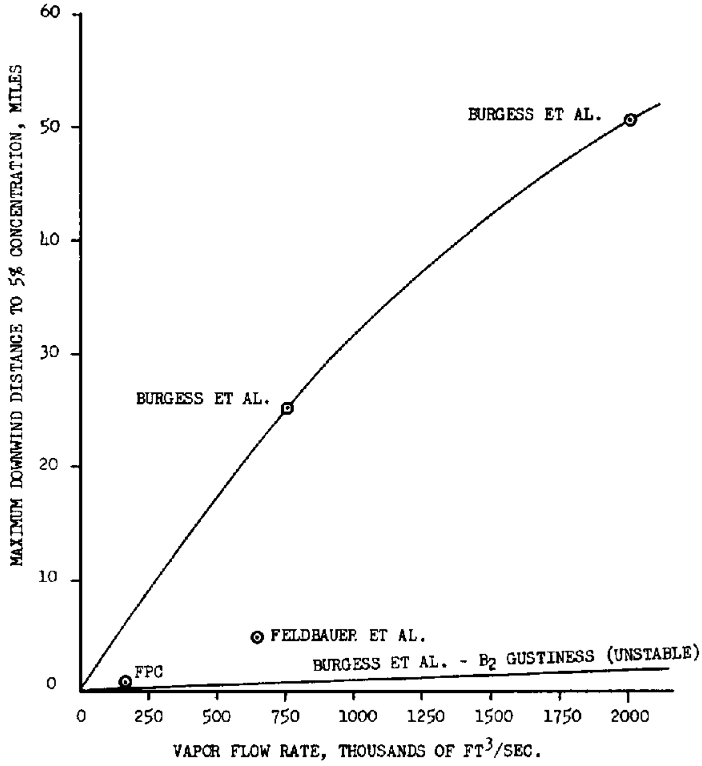

**Fig.2. Comparison of downwind distances to the time average 5% concentration level for continuous release models.**

The prediction of 5.2 miles with the Feldbauer model can be contrasted with the other predictions by considering two primary factors. First, Feldbauer's estimate of a much lower downwind vapor flow rate due to the accumulation of the vaporized LNG over the spill site leads to a shorter distance. Secondly, the Feldbauer model predicts a gravity spread period ending with a LNG vapor cloud approximately 10,000 feet wide having an average vapor composition of about 22%. Feldbauer assumes this vapor source (for the subsequent dispersion calculation) to be represented by a line source almost 2 miles wide. This treatment markedly reduces the downwind distance below that which is predicted using the point source equations. Since this line source width results directly from the treatment of the gravity spread phase, the Feldbauer model allowance for gravity spread is a strong factor in the shorter predicted distance.

The smallest downwind distance to the 5% concentration level, 0.75 miles using the FPC model, can be attributed primarily to two factors. First, the low value utilized for the vapor flow rate, 143,000 $ft^3/s$ (70°F, 1 atm), is the primary reason for the short distance predicted. This estimate is based on the assumption that the vapor flow rate is limited by heat transfer from the atmosphere above to the pure vapor cloud initially formed. Secondly, the use of Pasquill D (neutral) stability category dispersion coefficients rather than the "worst case" F (stable) coefficients also contributes importantly to the short distance.

### *Science Applications, Inc. model*

The Science Applications, Inc. LNG vapor dispersion model is a finite difference approximation to the mass, momentum and energy balance equations applied to the atmospheric boundary layer with boundary conditions simulating the LNG vapor source. The original report of this study describes the equations and boundary conditions used in the model. The SAI model (or any other model of similar approach) differs from the previously described models utilizing the classical pollutant dispersion equations in several ways.

(1) The technique allows for a more representative description of the transient nature of the LNG spill phenomena. For example, the rate of vapor production from the spill can be represented in a more realistic time varying form.

(2) Inclusion of the energy balance equations allows description of the temperature development of the cloud in a more realistic way. In the SAI model, the temperatures and vapor concentrations in the cloud are considered to be functions of both time and location, whereas even the most sophisticated previous models (Germeles and Drake) assume the cloud temperature and concentration during the initial phases of development to be uniform while varying with time.

(3) Phenomenological relationships, particularly the "coefficients" of turbulent diffusion, can be specified as a function of both time and position. The simpler classical models assume implicity that the turbulent diffusion of the vapors occurs without affecting the pre-existing turbulence patterns in the atmosphere.

Independent calculations by the author of the vapor dispersion following a 25,000 $m^3$ instantaneous spill were not possible due to the proprietary nature of SAI's computer programs. However, the maximum downwind distance to the time average 5% vapor concentration for a 25,000 $m^3$ spill in a 5 mile per hour wind with Pasquill D (neutral) atmosphere stability conditions is reported by SAI to be approximately 1.4 miles [12].

The SAI model gives results which are in marked contrast to those obtained from the "classical" models:

(1) The predicted downwind distances to the 5% concentration level are much shorter than suggested by most of the "classical equation" based models.

(2) The results obtained are not affected strongly by the specification of different atmospheric stability conditions.

(3) In general, for large instantaneous spills, longer downwind distances are predicted for higher wind velocities, in direct contrast to the classical "plume" models.

The primary reason for the much shorter downwind distances to the 5% concentration level predicted by SAI for a catastrophic spill appears to be enhanced dispersion associated with the gravity spread phase. Since the predicted turbulence is primarily induced by the spreading action of the cloud, this provides an explanation for why the turbulence properties assigned to the surrounding atmosphere at the time of the spill (i.e. neutral vs. stable) do not markedly affect SAI's predicted results. The predictions indicate that the principal dispersion of the vapor to the point where the concentration is below 5% is associated primarily with effects caused by the cloud-spread itself, rather than the prevailing atmospheric conditions.

## Summary — Assessment

Table 3 shows the maximum downwind distance to the time average 5% vapor concentration level following an instantaneous 25,000 m$^3$ spill onto water as predicted by the seven models discussed in this paper. In reviewing Table 3 it should be noted that meteorological conditions suggested by some of the groups were not necessarily the worst that might have been assumed.

Comparison of these results identifies the sensitivity of such predictions to the following factors.

(1) Characterization of atmospheric stability.
(2) Allowances for area source effects
(3) Specification of vapor flow rates
(4) Allowances for gravity spread/air entrainment effects

The 0.75 mile distance predicted by the FPC model results primarily from the use of unrealistically low vapor flow rates and the use of neutral atmospheric stability characteristics. This estimate, in the author's opinion, is not justified.

At the other extreme, distances of the order of tens of miles are predicted under stable weather conditions using plume models which do not account for any heat transfer or momentum transfer effects (Bureau of Mines). Such estimates are not justified, in this author's opinion.

Intermediate distances are predicted for a 25,000 m$^3$ spill during stable weather conditions by Germeles and Drake (11.5 miles), CHRIS (16.3 miles) and Fay and Lewis (17.4 miles). In the author's opinion, the model of Germeles and Drake provides a more plausible estimate of the LNG vapor dispersion process following a large rapid spill than the Fay and Lewis or CHRIS models, since the Germeles and Drake model incorporates a rational,

TABLE 3

Maximum downwind distance to time average 5% concentration level following 25,000 $m^3$ instantaneous spill of LNG onto water

| Model | Atmospheric conditions | Distance (miles) |
|---|---|---|
| Cabot Corporation (Germeles and Drake) | Pasquill F (stable)<br>5 mph wind | 11.5 |
| U.S. Coast Guard (CHRIS) | Pasquill F (stable) | 16.3 |
| Professor James Fay (Fay and Lewis) | "Puff coefficients"<br>(Very stable) | 17.4 |
| U.S. Bureau of Mines (Burgess et al.) | Singer and Smith D (Stable)<br>5 mph wind | 25.2—50.3* |
| American Petroleum Institute (Feldbauer et al.) | Singer and Smith D/ Pasquill C (vertical/horizontal)<br>5 mph wind | 5.2 |
| U.S. Federal Power Commission | Pasquill D (neutral)<br>5 mph wind | 0.75 |
| Science Applications, Inc. | Pasquill D (neutral)<br>5 mph wind | 1.4 |

* Range presented to indicate vaporization rate uncertainty.

if simplified, description of an anticipated gravity spread phase. Further effort to verify and improve this type model as an alternative to a more complex numerical procedure has merit, particularly for routine usage where time and expense constraints are important.

In the author's opinion, the predicted maximum distances of about 5 miles by Feldbauer et al. and about 1 mile by SAI for flammable cloud travel following instantaneous release of 25,000 $m^3$ of LNG onto water cannot be rationalized on the basis of any argument thus far advanced except that of gravity spread/air entrainment effects, and experimental verification of these effects has not been adequately demonstrated. However, Feldbauer's representation of the approximately 2-mile-wide gravity spread cloud as a series of dispersed point sources on a line perpendicular to the direction of cloud travel does not appear realistic in view of the resulting prediction of shorter distances with increasing atmospheric stability [1].

It was not possible within the limits imposed by this review to evaluate the accuracy of the SAI model predictions. However, the author has reviewed the methodology published by SAI and believes that such techniques hold the most promise for accurate prediction of catastrophic spill behavior.

Recommendations for further evaluation of the SAI model made in the report of the original study are now being followed through a Coast Guard contract with the author. The primary objectives of this work, now in progress, are:

(1) To evaluate the methodology used by SAI to describe the turbulent mass, momentum and energy transfers in an LNG vapor cloud.

(2) To provide some means for estimating the confidence level in the techniques used to assign numerical values to the turbulence model transfer coefficients.

(3) To determine the sensitivity of the results predicted by the model to uncertainties in the transfer coefficients.

(4) To evaluate the liquid spread, vapor generation and heat transfer model used in the specification of boundary conditions to determine the sensitivity of the model predictions thereto.

(5) To evaluate the stability and accuracy of the algorithm used for computer solution of the model equations.

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