UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION

Docket No. AD04-6-000

NOTICE OF AVAILABILITY OF STAFF'S RESPONSES TO COMMENTS ON THE CONSEQUENCE ASSESSMENT METHODS FOR INCIDENTS INVOLVING RELEASES FROM LIQUEFIED NATURAL GAS CARRIERS

(June 18, 2004)

The Federal Energy Regulatory Commission's staff researched and reviewed methodologies for modeling liquefied natural gas spills on water. The final report entitled *Consequence Assessment Methods for Incidents Involving Releases from Liquefied Natural Gas Carriers* was made available to the public on May 14, 2004, with comments due by May 28. The staff's responses to the comments are now available in PDF format from the Commission's website (http://www.ferc.gov/industries/gas/indus-act.asp).

Magalie R. Salas
Secretary

STAFF'S RESPONSES TO COMMENTS ON *CONSEQUENCE ASSESSMENT METHODS FOR INCIDENTS INVOLVING RELEASES FROM LIQUEFIED NATURAL GAS CARRIERS*

Comments on the ABSG Consulting Inc. report were filed by 49 parties, including 22 individuals, nine industry groups, three local governments, three environmental organizations, and 12 from the scientific community. The issues raised by the commenters included: the need for additional large scale testing and research; the development of new models; the need to consider liquefied natural gas (LNG) vessel design characteristics; and the need to proceed with a rulemaking process. While some commenters contend that the report should not be used for any realistic evaluation of existing or proposed LNG projects until further developed, other commenters assert that the report supports their claim that LNG projects should be denied in their area. The comments and staff's responses follow:

Comment 1

A number of commenters requested that the current regulations for LNG facility siting should be updated given the hazard impact areas stated in the report. Alternatively, the distances described in the report should be used as the minimum distance between new facilities and population, and that exclusion zones should be established around LNG tankers. In addition, the numbers suggested by the study indicate that locating these facilities near population is unacceptable and that they should be located offshore.

Response:

The intent of this study was to recommend modeling methods to be used by FERC staff in the site specific National Environmental Policy Act (NEPA) review of proposed LNG import facilities. The results shown do not provide a generic site assessment for all LNG import facilities. Credible worst-case scenarios, based on the most recent information available, will be used in site-specific analyses of each LNG import facility proposed before the Commission and will be issued in FERC NEPA documents. As stated in the final environmental impact statement (FEIS) for the Freeport LNG Project (Docket No. CP03-75-000), it should not be assumed that the hazard distances identified are the assured outcome of an LNG vessel accident or attack, given the conservatisms in the models and the level of damage required to yield such large scale releases. Further, these estimated "worst case" scenarios should not be misconstrued as defining an exclusionary zone. Rather the "worst case" scenarios provide guidance in developing the operating restrictions for LNG vessel movements within each shipping channel, as well as in establishing potential impact areas for emergency response and evacuation planning.

Comment 2

Information used in the determination of LNG facility site acceptability, including on-shore exclusion zones, and the Federal safety zones for LNG vessels, should be available to the public before any siting decisions are made. The public has a right to know the risks involved.

Response:
The results of every site-specific analysis performed with the recommended methods will be included in the Commission's NEPA documentation. Further opportunity for review and comment will be provided during the scoping period in each case and during the comment period for each of the Commission's environmental impact statements.

Comment 3

The study is too limited in the review of tanker failure and should examine more than just the loss of one cargo hold. Multiple hull breaches and the loss of multiple tanks should be considered. The use of 1- and 5-meter diameter holes should be justified and proven to be credible worst-case damage scenarios from an intentional attack. Real-life events, such as the USS Cole and the Limburg tanker attack, as well as the Skikda explosion, should be incorporated into the models. Clearly these events indicate that a terrorist could successfully attack an LNG ship and that LNG vapor clouds do explode.

Response:
The study was a review of consequence modeling methodology, rather than an evaluation of damage scenarios or a determination of the robustness of LNG carriers. The cargo tank hole sizes presented in the study were selected to represent values used in other studies and it was not an attempt to quantify the probability or extent of credible damage scenarios. In the final EIS for the Freeport LNG Project (Docket No. CP03-75-000, issued in May 2004), we identified a security analysis that analyzed a range of potential attack scenarios and estimated consequences. Subsequently, a detailed evaluation of the consequences of a terrorist attack on a modern membrane LNG tanker was prepared by Lloyds Register North America for the Weaver's Cove LNG Project (Docket No. CP04-36-000). These provide a basis for estimating the potential magnitude of a hazard from a successful terrorist attack, and for developing LNG vessel and waterfront security plans. There are other studies currently underway, by other government agencies and the natural gas industry, which are evaluating credible ship damage and effects. As those findings become available, we will continue to refine the site-specific analyses FERC staff is performing for each proposed project.

Comment 4

Modeling of the cryogenic effects of the spill on the tanker and a consideration of the effects of LNG vapors in tanker compartments should also be included.

Response:
The purpose of the study was to recommend methodology for modeling the consequences of an LNG spill on water. There are other studies underway that are evaluating credible ship damage scenarios.

Comment 5

The study is solely focused on the consequences of hypothetical cargo tank hole sizes which are not credible given the multiple layers of ship safety and security measures.

Response:
In addition to reviewing consequence methodology, section 4 of the study reviews LNG release prevention and mitigation measures, including design features of LNG vessels and security measures to deter potential attack scenarios.

Comment 6

The report does not assess the potential risks associated with LNG shipping, which must include the probability of potential incidents.

Response:
The focus of the study is the methodology that FERC staff will use to calculate the site-specific hazards from potential marine spills. The study also reviews the various layers of protection built into the LNG vessel and associated terminal operations that serve to avoid or minimize the likelihood of an incident, but was not intended to provide a measure of risk to the public. The operational safety of LNG ships is under the jurisdiction of the U.S. Coast Guard, an agency within the Department of Homeland Security (DHS). In a letter dated April 15, 2004 to Representative Edward Markey, the DHS stated that it believes that LNG tanker operations can continue to be safely conducted in U.S. ports.

Comment 7

The FERC should release information concerning the Skikda event and should consider the possibility of such an occurrence in siting new LNG facilities.

Response:

The intent of this study was to establish guidance on modeling methods to be used by FERC staff in analyzing marine spills of LNG. Information concerning the incident at the Skikda onshore liquefaction facility was summarized in the final EIS for the Freeport LNG Project. Further information, as it becomes available, will be included in subsequent NEPA documents for other projects undergoing Commission review.

Comment 8

Given the complexity of this issue, several parties stated that an extension of the comment period is needed to allow more thorough review of the study.

Response:

The intent of this study was to review existing consequence modeling methods, which in most cases have already been subjected to standard academic peer review. In addition, the results of every site-specific analysis performed with the recommended methods will be included in the Commission's NEPA documentation. Further opportunity for review and comment will be provided during the comment period for each of the Commission' environmental impact statements. The format of the study breaks the methodology into individual modeling components so that factors can be adjusted as the scientific community provides new experimental data or improved modeling approaches.

Comment 9

The report is limited in the number of models examined and in the depth of analysis (models and literature). Other research work should be used. There may be other studies that were not available at the time of the study and this information should be included in the review.

Response:

This report is a starting point in developing consequence assessment methodology that can be applied to projects before the Commission using supportable data and models, while recognizing that the results are conservative. We also recognize that improved modeling and additional research will allow for more refined consequence methodology. In effect, the development of our consequence models will be ongoing. With every advancement in these models, we will incorporate those improvements in our analyses.

Comment 10

Several commenters suggested that FERC, as well as the natural gas industry and other Federal agencies, fund or develop more experimental data to better quantify the "complex and disparate physical properties" used in modeling these spills.

Response:

Page iv of the Executive Summary recognizes the need for additional research and large-scale spill tests to provide better data and refine the models.

Comment 11

Commenters recognized that several modeling recommendations were made in an attempt to provide a measure of conservatism. Some commenters felt that the study was overly conservative, while others did not feel that every conservative assumption had been made.

Response:

Although the goal of the study was to select methods that provide the most accurate estimates possible, the lack of large-scale historical incidents and the need to extrapolate small-scale field test data lead to the use of conservative assumptions. As the scientific community provides new experimental data or improved modeling approaches, the methodology, which is broken into individual modeling components, can be adjusted to provide a more refined analysis.

Comment 12

Over-reliance on security protection to justify poor siting location decisions, such as siting in populated areas, can be highly deceptive. The U.S. Coast Guard cannot stop terrorist attacks on all ships.

Response:

The focus of the study is the methodology that FERC will use to consistently calculate the site-specific hazards from potential spills. Credible worst-case scenarios, based on the most recent information available, will be used in site-specific analyses of each facility proposed before the Commission and will be issued in FERC NEPA documents. The operational safety of LNG ships is under the jurisdiction of the U.S. Coast Guard. While the risks associated with the transportation of any hazardous cargo can never be entirely eliminated, they can be managed.

Comment 13

The heat flux levels of concern listed in the report are not appropriate. The 1,600-, 3,000-, and 10,000 Btu/hr-ft^2 levels listed in NFPA 59A do not provide protection for the public, and are established by a committee which does not include fire service members. A lower level heat flux should be used as an acceptable level. How does the 10,000 Btu/ft^2-hr level protect property when this level can ignite structures? This level is also too high for fire-fighting and rescue attempts.

Response:
The intent of this study was to establish guidance on modeling methods to be used by FERC staff in the NEPA review of proposed LNG import facilities. In selecting incident flux levels to evaluate damage to structures, including residences, and injuries to the exposed public from LNG spills on water, the flux levels specified by the U.S. Department of Transportation's (DOT) regulations under 49 CFR Part 193, which incorporates NFPA 59A, have been used in the recently issued Freeport LNG Project final EIS. These specific incident flux levels have more than a 25-year regulatory history, including several rulemaking processes with multiple opportunities for public input. Since the safety of both onshore LNG facilities and marine transportation are assessed in a single environmental impact statement, the use of the NFPA 59A levels allows a consistent treatment of hazards from both components of an LNG import facility.

Comment 14

FERC should apply this study to existing facilities such as Everett LNG facility in Boston and should periodically review response and evacuation plans for existing facilities.

Response:
As the Lead Federal Agency responsible for the preparation of NEPA documentation required for the siting and construction of onshore LNG facilities, the FERC conducts environmental, safety, and security reviews of proposed LNG plants and related pipeline facilities. This analysis includes LNG tanker operations, which are not under the jurisdiction of the FERC, as part of the overall safety review shared with the DOT and the U.S. Coast Guard in accordance with the 2004 Interagency Agreement. The intent of this study was to establish guidance on modeling methods to be used by FERC staff in the NEPA review of proposed LNG import facilities. Once a proposed facility has been constructed and placed in operation the marine hazards are managed by the U.S. Coast Guard through port-specific LNG operating plans. The U.S. Coast Guard exercises regulatory authority over LNG vessels which affect the safety and security of port areas and navigable waterways and is responsible for matters related to navigation safety, vessel engineering and safety standards.

Comment 15

The Boston Fire Department questioned the continued use of acceptable risk levels that were determined for LNG transit in Boston Harbor since these were based solely on the probability of ship accidents. The threat of a deliberate action such as sabotage precludes such risk estimates. They also stated that structures used as emergency shelters may burn, increasing the number of potential fatalities.

Response:
These comments concern issues which are outside the scope of this study.

Comment 16

The Boston Fire Department also commented that agency jurisdiction over the Boston facility is unclear and asked for clarification of the regulatory roles between the FERC, the U.S. Coast Guard, the Department of Energy, and the State of Massachusetts.

Response:
The FERC, the U.S. Coast Guard (within the DHS), and the Office of Pipeline Safety under the Research and Special Programs Administration (RSPA) within the DOT are responsible for exercising regulatory authority over certain aspects of liquefied natural gas facilities, and related land and marine safety and security issues. The FERC is responsible for authorizing the siting and construction of onshore LNG facilities under Section 3 of the Natural Gas Act (15 U.S.C. § 717 et seq.). FERC also authorizes the construction and operation of interstate natural gas pipelines that may be associated with the LNG facilities under section 7 of the Natural Gas Act. RSPA has authority to promulgate and enforce safety regulations and standards for the transportation and storage of LNG in or affecting interstate or foreign commerce under the pipeline safety laws (49 U.S.C. Chapter 601). RSPA's authority extends to the siting, design, installation, construction, initial inspection, initial testing, operation, maintenance of LNG facilities. The U.S. Coast Guard exercises regulatory authority over LNG facilities which affect the safety and security of port areas and navigable waterways under E.O. 10173, the Magnuson Act (50 U.S.C. § 191), the Ports and Waterways Safety Act of 1972, as amended (33 U.S.C. § 1221, et seq.) and the Maritime Transportation Security Act of 2002 (46 U.S.C. Section 701). The U.S. Coast Guard is responsible for matters related to navigation safety, vessel engineering and safety standards, and all matters pertaining to the safety of facilities or equipment located in or adjacent to navigable waters up to the last valve immediately before the receiving tanks. The U.S. Coast Guard also has authority for LNG facility security plan review, approval and compliance verification as provided in Title 33 CFR Part 105, and siting as it pertains to the management of vessel traffic in and around the LNG facility.

Comment 17

The Boston Fire Department questioned why this study was not funded until 2 years after 9/11. They also requested information as to whether periodic reviews of existing facilities were conducted using the latest technical information.

Response:
This study was intended to review modeling methodology so that FERC staff could prepare its site-specific review of each proposed terminal.

Comment 18

The Boston Fire Department faulted FERC for having little interaction with the public, for not committing to applying the report's conclusions to existing facilities, and for not pursuing a "vigorous" program of system improvement. They recommend that FERC prepare a report that analyzes the risks and hazards of a worst case release. The report should include consideration of damage to surrounding infrastructure and should detail the on-site capabilities required at a LNG terminal as well as a review of existing LNG facilities to determine if they meet the latest safety standards. They maintain that this report should cover both land and water based vehicles that transport LNG. Also, the operator of each facility should provide funds for the local community to conduct their own independent review of the report.

Response:
These comments concern issues which are outside the scope of this study.

Comment 19

The report states that there are no models to account for many of the phenomena and scenarios to be examined. However, higher-level modeling tools, such as Computational Fluid Dynamics (CFD) modeling could be used to perform these analyses, but is not addressed in the study.

Response:
The report states that fire modeling can be preformed using CFD methods, but that they are not normally used for typical pool fire hazard assessment because they require significantly more effort to apply but provide little or no benefit over the solid flame model when the goal is prediction of heat flux at significant distances from the fire. Similarly, the federal regulations for siting LNG facilities in 49 CFR Part 193 allow the use of both the DEGADIS, a dense gas dispersion model, and FEM3A, a CFD model. While recognizing that FEM3A may more realistically depict terrain and building effects, DEGADIS provides acceptable and conservative results that are widely used rather than the more complex FEM3A. For additional discussion, see the responses to Analytical & Computational Engineering, Inc. in Comment 27.

Comment 20

The thermal radiation effects on people in Section 2.7 showing the 99% fatality conditions need to show both distance and time. This information indicates that emergency service responses, as well as evacuation plans, would be ineffective given the large impact areas associated with a potential release.

Response:

The thermal dosage data in Table 2.4 represents the cumulative heat received over time and corresponding type of injury. For example, exposure to 12 kW/m^2 for 100 seconds results in the 99% fatality level. Table 2.4 is not used to define the intensity of a specific fire or the distances to specific thermal radiation levels.

Comment 21

The study did not include a comparative analysis between LNG and other hazardous cargos also carried in large tankers through shipping channels and deepwater ports.

Response:

The purpose of the study was to provide the methods for calculating site-specific hazards from an LNG spill on water. The modeling of other hazardous cargoes and a comparison with LNG was beyond the scope of the study.

Comment 22

According to a U.S. Coast Guard study, vapor clouds from mixtures of LNG containing 85% methane are susceptible to explosion. However, the report states that LNG vapor will not explode.

Response:

The report notes that a larger volume fraction of heavier hydrocarbons in LNG reduces the minimum ignition energy required for detonation and increases the likelihood of generating damaging overpressures.

Comment 23

A wider range of comparison of dispersion modeling should have been performed and should reference more recent work on the validation of these models. Recent work was not considered.

Response:

The report surveyed a representative sample of flammable vapor dispersion models focusing on those that are widely used in available software. For example, the federal regulations for siting LNG facilities in 49 CFR Part 193 specify the use of DEGADIS as one of the two approved models.

Comment 24

The models should recognize that rapid phase transitions (RPTs) are explosions and should be modeled with a great deal of conservatism.

Response:
Section 2.6 of the report was devoted to a review of the current knowledge of RPTs, including the explosive yield from RPTs that was observed in the field. Recommendations for modeling the effects of RPTs on vapor dispersion were performed using several scenarios.

Comment 25

Given the errors and shortcomings of the ABSG Consulting study identified by commenters, FERC should issue a corrected version of the study before using it as guidance in siting decisions.

Response:
As discussed in greater detail in the response which follows, ABSG Consulting has revised various components of its consequence assessment methodologies. These changes include: the orifice discharge coefficient for calculating spill rates has been changed from 1.0 to 0.65; the approximate pool shape of an uncontained LNG spill on water is now represented as a semicircle instead of a circle; the estimated effects of friction between the LNG pool and the water surface on pool spread have been reduced; the relationship between decreasing spill rate and pool size has been refined; the rate of heat influx from water has been set at 85 kW/m^2; and the solid flame model has been modified to represent a two-zone pool fire. As new research, data and improved modeling techniques appear, the methodology will be revised as appropriate.

Comment 26

We received several comments on factors in the model regarding: A) selection of the discharge coefficient; B) pool shape; C) film boiling effects on viscous spreading; D) effect of decreasing spill rate on pool spread; E) film boiling heat flux; F) pool fire flame length; G) pool fire smoke production; H) pool fire burning rate and surface emissive power.

Response:
Individual discussion of items A-H are provided below. A summary of the modifications to the recommended consequence modeling methods, as well as revised example calculations, are also included.

A. Selection of Discharge Coefficient

In the orifice flow model used to estimate outflow from a hole in an LNG tank, a discharge coefficient can be used to account for the fact that friction retards the flow. The report employed a discharge coefficient of 1.0; however, several comments recommend use of a lower value.

The literature review did not identify any methodology or empirical results to support a lower value, particularly with regard to holes in ships, so a value of 1.0 was used. This is also consistent with guidance of Lees (1996), which states "For cases where the discharge coefficient is unknown or uncertain, use a value of 1.0 to maximize the computed flows to achieve a conservative result." This same guidance is repeated in Crowl (1990) and AIChE (2000).

In spite of this, an argument can be made for using a value lower than 1.0, which represents the ideal (frictionless) case.

The comments of the International LNG Alliance and the International Gas Union suggest a value of 0.65, and the comments of the Center for LNG suggest that "a reasonable, conservative estimate of discharge coefficient ranges from 0.6 to 0.8." However, references were not provided for these values.

As additional guidance, Lees (1996) states that:

(1) For sharp-edged orifices and for Reynolds numbers greater than 30,000, the discharge coefficient approaches the value 0.61. For these conditions the exit velocity is independent of the hole size.
(2) For a well-rounded nozzle the discharge coefficient approaches unity.
(3) For short sections of pipe attached to a vessel with a length-diameter ratio not less than 3, the discharge coefficient is approximately 0.81.

AIChE (2000) also presents an estimate of the discharge coefficient based on the 2-K method. In this method the coefficient is calculated and accounts for contributions to friction from the entrance to the hole and exit from the hole. The calculated discharge coefficient value is 0.63.

In the case of a rough, irregular hole that would be expected in a spill from an LNG carrier, the friction would be expected to be larger than in the case of a sharp-edged orifice. On this basis, and the guidance of Lees (1996) and AICHE (2000), the suggested value of 0.65 can be defended as a reasonable estimate, and this value is recommended.

B. Pool Shape

Dr. Fay's comments recommend modeling the LNG pool on water as a "semicircle with base diameter located at the vessel side and center of radial symmetry at the vessel orifice." He presents this approach in a recent paper (Fay 2003). Drs. Havens and Spicer also comment that "ship tank spills would more probably than not occur to one side of the vessel, resulting in the spill resembling an expanding half-circle (bounded by the side of the ship) more than a circular spill."

In general, the pool shape employed in modeling should be selected based on the specifics of the scenario being evaluated. In the case of the types of spills from LNG carriers that are being addressed, a semicircle is a more realistic representation.

Dr. Fay's methods of estimating spread (Fay 2003) is applicable to this situation. Also, as he points out in his comments, the methodology employed for the examples in the report can be modified easily to model a semicircle. In fact, this is simply a matter of introducing a factor of 1/2 in the appropriate equations to account for the fact that the area of the pool is half the area of a circle with the same radius. This approach is recommended as it still allows use of the integral solution, which has the advantage of accommodating a transient spill source and avoiding the need to characterize spills as either instantaneous or continuous.

C. Film Boiling Effects On Viscous Spreading

The comments of Drs. Havens and Spicer and comments of Dr. Fay question one specific aspect of the application of the Webber pool spread methodology (which is outlined in TNO 1997). In particular, the commenters indicated that the friction between the water and spreading LNG pool was overestimated, causing a tendency to retard spreading of the pool. While less specific, the comments of the Center for Liquefied Natural Gas also express the concern that the Webber model may overestimate viscous effects.

The estimate of friction is based on equations 3.70 and 3.71 in TNO (1997), along with the recommended turbulent friction coefficient of 0.0015. Commenters pointed out that this approach does not account for the fact that film boiling is taking place. In film boiling, a thin layer (film) of LNG vapor forms between the water surface and liquid LNG pool. This vapor has a viscosity that is two orders of magnitude less than the viscosity of the liquid LNG and three orders of magnitude less than the viscosity of the water. Webber does take the friction coefficient to be a constant value, which is probably justified for many circumstances. However, he also points out that the value "may depend on the nature of the surface under the pool and whether or not film boiling is taking place" (Webber 1987, p. 5).

The thin layer of vapor would be expected to significantly reduce the friction between the two liquid surfaces, and further review of Webber's work indicates that the methodology employed overestimated the friction.

For purposes of analysis, many authors (Fay 1969, Hoult 1972, Webber 1986, and others) discuss pool spread in terms of various flow regimes, such as the 'gravity-inertia' (or 'inviscid') regime and 'gravity-viscous' regime. In the gravity-inertia regime (i.e., early in a spill), gravitational spreading forces are balanced by fluid inertia. In the gravity-viscous regime, gravitational spreading forces are balanced by viscous forces. These are useful concepts, but it is important to keep in mind that they are simplifications.

In the gravity-inertia regime, frictional forces are still present but are generally small compared to inertia forces. Likewise, later in a spill, inertial forces are still present but are generally small compared to viscous forces. The point of transition between these regimes is typically taken as the point where inertial and viscous resistance forces are equal. So, at that instant, ignoring one of these two forces means ignoring half of the resistance force.

Because LNG vaporizes rapidly when spilled on water, most spills will evaporate completely before friction forces become important. However, very large and rapid spills may exist long enough for frictional forces to become important.

The literature review did not identify a recommended methodology for estimating friction in the case of film boiling. However, a straightforward approach is to assume complete slip between the LNG pool and water surface and estimate the friction from the shear stress in the vapor film. The assumption of complete slip means that water surface remains stationary and that the velocity profile in the leading edge of the pool is uniform. This approximation is justified by the fact that the viscosity of the vapor is much lower than that of either of the liquids.

As Fay points out in his comments, the thickness of the vapor film can be approximated as

$$\delta = \frac{\lambda_v (T_w - T_p)}{Q} \qquad (1)$$

where

δ = Thickness of the vapor film
λ_v = Thermal conductivity of the vapor
T_w = Temperature of the water
T_p = Temperature of the LNG pool
Q = Film boiling heat flux from the water to the LNG pool

The shear stress in the film is then

$$\tau = \frac{\mu_v u}{\delta} \qquad (2)$$

where

τ = Shear stress
μ_v = Viscosity of the vapor
u = Speed of the LNG pool front

This shear stress represents the friction force on the pool, per unit area of pool surface. The corresponding acceleration on the pool provides a resistance term analogous to equation 3.70 in TNO (1997).

$$C_{FF} = \frac{\tau}{\rho_l h} \tag{3}$$

where

C_{FF} = Frictional resistance term with film boiling
ρ_l = Density of the liquid LNG
h = Pool depth

Before this method can be applied, an appropriate heat flux must be selected for use in estimating the vapor film thickness. Choosing a flux of 85 kW/m² (see Item E), assumes that localized breakdown of the film accounts for a portion of the heat transfer, so basing the film thickness estimate on this heat flux value is inappropriate. However, where breakdown of the film does not occur, the heat flux from heat transfer theory probably provides a reasonable estimate of the flux and can allow a reasonable estimate of the film thickness (in areas where breakdown does not occur). Where film breakdown does occur, friction will be higher, so basing friction on a fixed film thickness (calculated using heat transfer theory) is a reasonable and probably somewhat conservative approach.

The thickness is calculated using equation 1 above, along with the method of Klimenko (1981) for film boiling heat transfer. The thickness is a very weak function of water temperature, and over the range of water temperatures from 10 °F (-12 °C) to 90 °F (32 °C), the calculated film thickness is 0.063 mm; it is therefore taken as a constant (independent of water temperature) for purposes of LNG consequence assessment. Note that this value can be used for both the fire case and non-fire case and is used only for purposes of estimating friction between the LNG pool and water surface.

The Webber spread method was modified to use this friction estimate, and calculations were made for the two example scenarios presented in Section 3.3 of the report. For comparison purposes, calculations were also made for these scenarios with the friction term set to zero. The resulting maximum pool radii and evaporation times are shown in Table 1. Note that the calculations of these results also incorporate the modifications discussed in Items A, B, D, and E.

Table 1 Comparison of Pool Behavior for Various Friction Models

Hole diameter	1 m			5 m		
Friction model	Ignoring Film Boiling[1]	Film Boiling[2]	Inviscid Flow[3]	Ignoring Film Boiling[1]	Film Boiling[2]	Inviscid Flow[3]
Maximum pool radius	420 ft (130 m)	420 ft (130 m)	420 ft (130 m)	600 ft (180 m)	1,100 ft (350 m)	1,200 ft (370 m)
Total evaporation duration	51 min	51 min	51 min	13 min	5.3 min	5.2 min

1 Original method in the report, which ignores the effect of the vapor film on friction
2 Friction based on shear stress in the vapor film
3 Setting the friction term to zero

Comparing the results for the 1-m diameter hole show that the results are identical (to two significant figures) regardless of which of these models is chosen for friction. The results for the 5-m hole show that basing friction on shear stress in the vapor film results in a pool radius 83% larger than when effects of film boiling are ignored, and they show that accounting for friction based on shear stress in the vapor film does have a small effect over assuming inviscid flow.

These results support the conclusion that friction is unimportant for many spills, including the 1-m hole example shown here. They also support the conclusion that for large and rapid spills, friction effects do begin to have an effect on pool spread. Friction effects would also become more important if modeling an even larger or more rapid spill.

While the effects of friction will be small in many cases, accounting for these effects can improve the analysis for large, rapid spills, and the straightforward method presented here (with friction based on shear stress in the vapor film) is recommended.

D. Handling of Effect of Decreasing Spill Rate on Pool Spread

Drs. Havens and Spicer commented that “the assumption that the spreading will stop when the evaporation rate of the pool becomes equal to the release rate is incorrect.” This comment refers to a simplification made in the spread calculations for spills from 1-m holes. In this scenario, as the pool spreads, the spill rate into the pool is decreasing (as the LNG liquid height in the storage tank decreases). As the comment indicates, the report methodology made the simplification that spreading stops once the pool grows to the point where the evaporation rate is equal to the current spill rate. In reality, the pool would continue to spread for a short time and then regress to the point where the evaporation and spill rates matched. Due to computational difficulties caused by the dynamic nature of the spread model combined with the decreasing spill rate, the recommended methods take the simplification of assuming that the pool stops spreading. Without the simplification, the pool spreads to the point that all of the LNG evaporates before the spill has stopped, which is also clearly incorrect.

While this simplification has little impact on the overall consequence assessment results, it may result in slight underprediction of peak pool size. Therefore, the recommended approach has been modified to handle the computational difficulties in a different and probably more realistic manner.

Specifically, the methodology is modified to allow the pool to continue to spread beyond the point where the evaporation and spill rates match. Beyond this point, the evaporation rate will exceed the spill rate, so the pool will begin to thin rapidly. The computations monitor for the condition where the pool would be emptied while the spill is still in progress, and the pool size is decreased immediately to the size that can be supported by the spill rate occurring at that moment. From this point on, the pool size will decrease as the spill rate decreases.

This revised method is also a simplification but is more realistic than the previous approach. It approximates the situation where the pool thins at the edge (after the spill rate decreases below the evaporation rate) and the radius of the pool decreases rapidly to the value sustainable by the spill rate at that point.

E. Film Boiling Heat Flux

The comments of Dr. Koopman and the comments of Dr. Raj point out that the heat flux estimate based on heat transfer theory (~37 kW/m^2) is significantly lower than estimates from LNG spill tests, such as some of those listed in Table 2.1 of the report. This is true, but the value is also higher than some of the test results.

As pointed out in the report, the spread in experimental values causes uncertainty in the appropriate value, and heat transfer theory is a reasonable approach to help fill in the gap in experimental data. Other researchers have taken this approach, and Waite (1983) concluded that simulation using a film boiling heat flux better matches experimental data than simulation with a 100 kW/m^2 flux.

On the other hand, Dr. Raj's comments point out three factors that may result in higher heat flux than predicted with film boiling heat transfer theory:

> *(i) the water layer immediately beneath the LNG layer cools off rapidly resulting in the temperature difference between the water and LNG to be reduced. This will result in the occurrence of nucleate boiling phenomenon with very large increase in heat flux. Convective cells in water will not form quickly enough to prevent the nucleate boiling to occur. (ii) the film in the film boiling is very unstable even in laboratory conditions. The break up of film is more or less certain in ocean conditions with currents and waves, (iii) The violence of boiling creates smaller chunks of LNG which may intimately "mix" with water thus increasing the effective boiling area compared to the nominal area of spreading.*

On the whole, this is a convincing argument for why the heat flux is expected to be higher than predicted by film boiling alone. Unfortunately, this still does not point to an appropriate selection.

The experimental data do indicate that the value is probably below 100 kW/m^2 (assuming ice does not form). Dr. Koopman's comments state that "at China Lake an evaporation rate of about 0.17 $kg/m^2/s$ was observed for the tests, which corresponds to a heat flux of about 85 kW/m^2." This value appears reasonable given the inferred upper and lower bounds (37 to 100 kW/m^2) and is recommended in place of the previously recommended heat transfer theory.

F. Pool Fire Flame Length

Several comments suggest that the use of Thomas' correlation for flame height significantly overestimates this height.

For very large fires, Thomas' correlation may overestimate flame length; however, there are no data for such fires to confirm or deny this hypothesis. The argument that reduced air entrainment (that accompanies increased pool diameter) will tend to reduce the flame height is a reasonable argument; however, the review of current data and modeling methods did not identify a way to account for this in large LNG pool fires on water.

In addition, both Mudan (in SFPE 1995) and Rew (1986) have reviewed the available correlations for flame length, and both concluded that Thomas' correlation is the best available choice. The use of Thomas' correlation remains the recommended method.

G. Pool Fire Smoke Production

Several comments point out that for large LNG pool fires, significant smoke production is expected, and this will tend to obscure the flame and reduce the thermal radiation emitted from the fire. Even with a 'clean burning' fuel like LNG, this is expected and can be seen in still and motion pictures of pool fire tests.

The difficulty lies in quantifying the effect of smoke on emission of thermal radiation, not accounted for in the recommended methods, principally because of the limited amount of available experimental data for large LNG pool fires.

Upon further review, the two-zone flame model, as recommended by Rew (1996), can be defended for use with large LNG pool fires. This model divides the cylindrical fire into two zones: (1) a lower 'clear' zone, where smoke does not obscure the flame and (2) an upper zone where smoke does obscure the flame and reduce the amount of thermal radiation emitted.

A correlation used by Pritchard and Binding and recommended by Rew (1996) is recommended for estimating the length of the lower (clear) zone. While the data for

LNG alone are probably insufficient to support such a correlation, the smoke production phenomenon is a result of processes not confined to LNG, and this correlation's basis on a broader set of data can be defended for use with LNG. The correlation (Rew 1996, equation 2.27) is a function of pool diameter, non-dimensional burning rate, non-dimensional wind speed, and carbon to hydrogen ratio for the fuel.

Rew also reviewed data for estimating the effect of smoke (i.e., in the upper zone) on emission of thermal radiation and recommends values of the unobscured ratio for pool diameters less than 10 m (0.77), 10 to 20 m (0.69), and more than 20 m (0.55). These values are adopted.

H. Pool Fire Burning Rate and Surface Emissive Power

Several comments suggest that the selected burning rate (0.282 $kg/m^2/s$) and selected surface emissive power of the flame (265 kW/m^2) are overly conservative (i.e., too high). As pointed out in the report, these may be somewhat conservative, based on review of the experimental data for the larger pool fires. However, these are reasonable choices (adopted from the work of Rew 1996), and as Dr. Koopman pointed out in his comments, generally consistent with the China Lake experiments.

In addition, given the uncertainty in the two-zone flame model, it is recommended that these burning rate and emissive power values be retained to help ensure that the model is balanced and can still be easily defended as leaning toward conservatism.

As a final note, the sensitivity analyses in the report, as well as in this response, indicate that final results are relatively insensitive to the choices of these values (particularly the burning rate).

G. Summary of Modifications to Recommended Consequence Modeling Methods

In accordance with the discussions in the previous sections of this response, the following modifications to the report's consequence analysis methods are recommended:

- Apply a discharge coefficient of 0.65 to the calculations of outflow from the ship;
- Approximate the pool shape as a semicircle, rather than a circle;
- Estimate friction between the LNG pool and water surface based on shear stress in the vapor film;
- Use improved method of handling effect of decreasing spill rate on pool spread;
- Adopt a value of 85 kW/m^2 for heat flux from the water to the LNG pool; and
- Incorporate two-zone pool fire model.

With these refinements, the methods suggested here will produce more realistic results than those described in the original report but are still defendable and will still tend to provide conservative estimates. Furthermore, there appears to be little room for further improvement in the short term (i.e., based on currently published methods). Modeling techniques must be defendable based on science but not to the extent that they are grossly conservative; the study's recommendations strike an appropriate balance between these conflicting goals.

Evaporation Heat Flux Sensitivity Analysis
Given the recommended modifications to modeling methods, it is important to revisit the sensitivity analysis for evaporation heat flux presented in Section 2.3.3 of the original report. This analysis examines the sensitivity of final consequence analysis results (such as distance to the LFL predicted by an atmospheric dispersion model) to the heat flux. To examine the sensitivity, calculations were performed with three different heat flux values to see the effects on pool radius, evaporation time, and dispersion distance. The heat flux values examined are 15,800 BTU/ft^2/hr (50 kW/m^2), 26,900 BTU/ft^2/hr (85 kW/m^2), and 31,700 BTU/ft^2/hr (100 kW/m^2). The scenario and results are as follows:

<u>**Scenario for Evaporation Heat Flux Sensitivity Analysis**</u>

Hole diameter: 3.3 ft (1 m)
Initial liquid height above hole: 43 ft (13 m)
Total spill quantity: 4.4×10^5 ft^3 (12,500 m^3)
Air temperature: 71 °F (22 °C)
Relative humidity: 50%
Wind speed: 6.7 mph (3.0 m/s) and 4.5 mph (2.0 m/s)
Surface roughness: 0.03 ft (0.01 m)
Pasquill-Turner stability class: D and F
Averaging time: 0 sec (i.e., peak concentrations are used)

Results for Evaporation Heat Flux Sensitivity Analysis

Hole diameter	3.3 ft (1 m)		
Initial spill rate	7,600 lb/s (3,400 kg/s)		
Total spill duration	51 min		
Film boiling heat flux to pool	15,800 $BTU/hr/ft^2$ (50 kW/m^2)	26,900 $BTU/hr/ft^2$ (85 kW/m^2)	31,700 $BTU/hr/ft^2$ (100 kW/m^2)
Evaporation mass flux	0.020 $lb/ft^2/s$ (0.098 $kg/m^2/s$)	0.034 $lb/ft^2/s$ (0.17 $kg/m^2/s$)	0.040 $lb/ft^2/s$ (0.20 $kg/m^2/s$)
Maximum pool radius (semicircular pool)	520 ft (160 m)	420 ft (130 m)	390 ft (120 m)
Total evaporation duration	51 min	51 min	51 min
Wind speed and stability class	**6.7 mph (3.0 m/s) and D stability**		
Downwind distance to LFL	6,300 ft (1,900 m)	6,500 ft (2,000 m)	6,500 ft (2,000 m)
Time at which LFL reaches maximum distance	18 min	16 min	15 min
Wind speed and stability class	**4.5 mph (2.0 m/s) and F stability**		
Downwind distance to LFL	10,000 ft (3,100 m)	11,000 ft (3,300 m)	11,000 ft (3,300 m)
Time at which LFL reaches maximum distance	29 min	29 min	29 min

For this scenario, the downwind distances are insensitive to variations in the heat flux estimate. This is largely a result of the fact that in all of these cases the evaporation is limited by the spill rate. That is, for a significant portion of the spill (following the initial spread), the evaporation rate is the same for all three heat fluxes. The different heat flux values result in different pool areas, each giving the same evaporation rate.

While this example provides valuable insights about the recommended methodology, it is important to note that it does not represent a comprehensive sensitivity analysis; sensitivity may be different for other types of scenarios and with other input parameter values.

Burning Rate and Surface Emitted Flux Sensitivity Analysis

This section presents a sensitivity analysis like that presented in Section 2.4.2 of the original report. It examines the sensitivity of final consequence analysis results (such as distance to a heat flux level of concern) to the values of the burning rate and surface emitted flux. To examine the sensitivity, calculations were performed using the revised methods recommended in this response for an example scenario. As in the original report, the burning rates examined are 0.041 lb/s/ft^2 (0.20 kg/s/m^2), 0.057 lb/s/ft^2 (0.28 kg/s/m^2), and 0.074 lb/s/ft^2 (0.36 kg/s/m^2). The surface emitted fluxes examined are 63,000 BTU/ft^2/hr (200 kW/m^2), 84,000 BTU/ft^2/hr (265 kW/m^2), and 95,000 BTU/ft^2/hr (300 kW/m^2). The scenario and results are as follows:

Scenario for Burning Rate and Surface Emitted Flux Sensitivity Analysis

Hole diameter: 3.3 ft (1 m)
Initial liquid height above hole: 43 ft (13 m)
Total spill quantity: 4.4×10^5 ft^3 (12,500 m^3)
Air temperature: 80 °F (27 °C)
Relative humidity: 70%
Wind speed: 20 mph (8.9 m/s)

Results for Burning Rate Sensitivity Analysis

Hole diameter	3.3 ft (1 m)		
Initial spill rate	7,600 lb/s (3,400 kg/s)		
Total spill duration	51 min		
Flame surface emitted flux	84,000 BTU/ft^2/hr (265 kW/m^2)		
Burning rate	0.041 lb/s/ft^2 (0.20 kg/s/m^2)	0.058 lb/s/ft^2 (0.28 kg/s/m^2)	0.074 lb/s/ft^2 (0.36 kg/s/m^2)
Maximum pool radius	390 ft (120 m)	340 ft (100 m)	310 ft (93 m)
Total fire duration	51 min	51 min	51 min
Maximum flame length (height)	790 ft (240 m)	920 ft (280 m)	1,000 ft (310 m)
Clear flame length at maximum	430 ft (130 m)	590 ft (180 m)	730 ft (220 m)
Flame tilt at maximum radius	35 deg	36 deg	37 deg
Downwind distance to 12,000 BTU/hr/ft^2 (38 kW/m^2)	920 ft (280 m)	910 ft (280 m)	900 ft (280 m)
Downwind distance to 7,900 BTU/hr/ft^2 (25 kW/m^2)	1,100 ft (340 m)	1,100 ft (340 m)	1,100 ft (340 m)
Downwind distance to 3,800 BTU/hr/ft^2 (12 kW/m^2)	1,500 ft (450 m)	1,500 ft (460 m)	1,500 ft (470 m)
Downwind distance to 1,600 BTU/hr/ft^2 (5 kW/m^2)	2,100 ft (630 m)	2,100 ft (650 m)	2,200 ft (670 m)

Results for Surface Emitted Flux Sensitivity Analysis

Hole diameter	3.3 ft (1 m)
Initial spill rate	7,600 lb/s (3,400 kg/s)
Total spill duration	51 min
Burning rate	0.058 lb/s/ft^2 (0.28 kg/s/m^2)
Maximum pool radius	340 ft (100 m)

Results for Surface Emitted Flux Sensitivity Analysis (cont'd)

Total fire duration	51 min		
Maximum flame length (height)	920 ft (280 m)		
Clear flame length at maximum	590 ft (180 m)		
Flame tilt at maximum radius	36 deg		
Flame surface emitted flux	63,000 BTU/ft^2/hr (200 kW/m^2)	84,000 BTU/ft^2/hr (265 kW/m^2)	95,000 BTU/ft^2/hr (300 kW/m^2)
Downwind distance to 12,000 BTU/hr/ft^2 (38 kW/m^2)	780 ft (240 m)	910 ft (280 m)	970 ft (300 m)
Downwind distance to 7,900 BTU/hr/ft^2 (25 kW/m^2)	980 ft (300 m)	1,100 ft (340 m)	1,200 ft (360 m)
Downwind distance to 3,800 BTU/hr/ft^2 (12 kW/m^2)	1,400 ft (410 m)	1,500 ft (460 m)	1,600 ft (490 m)
Downwind distance to 1,600 BTU/hr/ft^2 (5 kW/m^2)	1,900 ft (580 m)	2,100 ft (650 m)	2,200 ft (690 m)

As discussed in the original report, variation in burning rate has competing effects on pool size and flame length. As a result, final consequence results (distances) are insensitive changes in burning rate.

Also as shown in the original report, results are affected more by the choice of surface emitted flux. However, the results are still somewhat insensitive: increasing the value by 50%, from 63,000 BTU/ft^2/hr (200 kW/m^2) to 95,000 BTU/ft^2/hr (300 kW/m^2), increases the distance estimates by only 19% to 25%.

While this example provides valuable insights about the recommended methodology, it is important to note that it does not represent a comprehensive sensitivity analysis; sensitivity may be different for other types of scenarios and with other input parameter values.

Consequence Assessment Examples for Pool Fires

This section presents the example scenarios from Section 3.2 of the report with calculations modified as described herein. The scenarios examined are fires following spills from 3.3-ft (1-m) and 16-ft (5-m) holes in an LNG carrier just above the waterline.

These example calculations are intended only as demonstrations of the modeling methods. The results should not be taken as a consequence assessment for any specific facility. Evaluation of a specific facility requires input parameter values based on site-specific conditions, and analysis of different or additional scenarios may be appropriate.

For these examples, it is assumed that the amount of LNG above the hole is 4.4×10^5 ft^3 (12,500 m^3), and the orifice model is used to estimate outflow, with flow rate dropping as the liquid level above the hole drops. It is assumed that the spill is ignited immediately upon release. The scenarios and input parameters are listed below, and Table 2 summarizes the results of the pool fire calculations for these scenarios.

Scenarios

Hole diameters: 3.3 ft (1 m) and 16 ft (5 m)
Initial liquid height above hole: 43 ft (13 m)
Total spill quantity: 4.4×10^5 ft^3 (12,500 m^3)
Air temperature: 80 °F (27 °C)
Relative humidity: 70%
Wind speed: 20 mph (8.9 m/s)

Table 2 Summary of Results for Example Pool Fire Calculations

Hole diameter	3.3 ft (1 m)	16 ft (5 m)
Initial spill rate	7,600 lb/s (3,400 kg/s)	190,000 lb/s (86,000 kg/s)
Total spill duration	51 min	2.0 min
Maximum pool radius (semicircular pool)	340 ft (100 m)	1,000 ft (310 m)
Total fire duration	51 min	4.2 min
Maximum flame length (height)	920 ft (280 m)	2,100 ft (630 m)
Clear flame length at maximum	590 ft (180 m)	890 ft (270 m)
Flame tilt at maximum radius	36 deg	27 deg
Downwind distance to 12,000 BTU/hr/ft^2 (38 kW/m^2)	910 ft (280 m)	2,000 ft (620 m)
Downwind distance to 7,900 BTU/hr/ft^2 (25 kW/m^2)	1,100 ft (340 m)	2,500 ft (760 m)
Downwind distance to 3,800 BTU/hr/ft^2 (12 kW/m^2)	1,500 ft (460 m)	3,500 ft (1,100 m)
Downwind distance to 1,600 BTU/hr/ft^2 (5 kW/m^2)	2,100 ft (650 m)	5,000 ft (1,500 m)

Consequence Assessment Examples for Flammable Vapor Dispersion

This section presents the example scenarios from Section 3.3 of the report with calculations modified as described herein. The scenarios examined are spills that are not immediately ignited and subsequently disperse downwind. Spills are from 3.3-ft (1-m) and 16-ft (5-m) holes in an LNG carrier just above the waterline. For these examples, it is assumed that the amount of LNG above the hole is 4.4×10^5 ft^3 (12,500 m^3) and the orifice model is used to estimate outflow, with flow rate dropping as the liquid level above the hole drops.

These are the same scenarios presented in the previous section for pool fires, except in this case it is assumed that ignition does not occur immediately and ambient conditions are different. Also, as stated above for pool fires, these example calculations are intended only as demonstrations of the modeling methods. The results should not be taken as a consequence assessment for any specific facility. Evaluation of a specific facility requires input parameter values based on site-specific conditions, and analysis of different or additional scenarios may be appropriate.

The scenarios and input parameters are listed below, and Table 3 summarizes the results of the source term and dispersion calculations for these scenarios.

Scenarios

Hole diameters: 3.3 ft (1 m) and 16 ft (5 m)
Total spill quantity: 4.4×10^5 ft^3 (12,500 m^3)
Air temperature: 71 °F (22 °C)
Relative humidity: 50%
Wind speed: 4.5 mph (2.0 m/s)
Surface roughness: 0.03 ft (0.01 m)
Pasquill-Turner stability class: F
Averaging time: 0 sec (i.e., peak concentrations are used)

Table 3 Summary of Results for Example Dispersion Calculations

Hole diameter	3.3 ft (1 m)	16 ft (5 m)
Initial spill rate	7,600 lb/s (3,400 kg/s)	190,000 lb/s (86,000 kg/s)
Total spill duration	51 min	2.0 min
Maximum pool radius (semicircular pool)	420 ft (130 m)	1,100 ft (350 m)
Total evaporation duration	51 min	5.3 min
Downwind distance to LFL	11,000 ft (3,400 m)	13,000 ft (4,100 m)
Time at which LFL reaches maximum distance	29 min	29 min
Time at which entire cloud drops below LFL	54 min	30 min
Downwind distance to ½ LFL	15,000 ft (4,600 m)	19,000 ft (5,900 m)
Time at which ½ LFL reaches maximum distance	35 min	37 min
Time at which entire cloud drops below ½ LFL	56 min	38 min

Comment 27

We also received numerous specific comments on the technical aspects of the ABSG Consulting study.

Response:

This section provides responses to some specific technical comments on the report. This does not include responses to all comments; in particular, it does not include responses to issues already addressed above. Responses are limited primarily to modeling issues that are within the scope of the original report.

Responses to Comments of Dr. Jerry Havens and Dr. Tom Spicer

> **Comment**
>
> *Our review of the flame radiation modeling procedure used in the report suggests that an error has been made in the computer coding of the equations that assign values of the transmissivity factor. We have notified ABS of this concern and have asked for clarification.*
>
> **Response**
>
> Drs. Havens and Spicer are correct in that the calculations for the example problems included an error in the equations for calculating the transmissivity of the atmosphere. The result of the error caused the calculation to underestimate the amount of thermal radiation that would be absorbed by the atmosphere (i.e., between the fire and the downwind distance to the level of concern). This error resulted in reporting hazard zone distances that were longer than they should have been. It is important to note that this was only a calculation error in the example problems and not an error in the actual recommendation of modeling methods. This error has been corrected.

Responses to Comments of Dr. Phani K. Raj

> **Comment**
>
> *The models used are not balanced or accurate to the same degree of confidence. The description of the source of LNG (i.e., the rate of spill, quantity of spill, interaction between LNG and any water that may flood the inter-hull space, etc) is too simplistic, devoid of realism, whereas the spread of liquid on the water is described by a model that can be solved only numerically. Similar is the situation with respect to the consideration of the evaporation rates, pool fire size and the thermal radiation calculations. Real phenomena have been neglected in preference to ease of calculations.*

Response
The models recommended are based on currently available techniques, which some people might consider simplistic. However, these techniques can help provide decision makers with useful information about the possible impact of large incidents involving spills of LNG on water. The source characterization is more appropriate for some types of scenarios that can be postulated than for others. For example, in the case of a scenario involving a significantly larger hole in the outer hull than in the inner hull, with the outer hole perhaps reaching the water level, the recommended approach is a reasonable approximation.

Comment
In paragraph 2 of section 1.4, page 2, the following statement is made; "As the cloud mixes with air, it will warm up and disperse into the atmosphere." Dispersion in the atmosphere has nothing to do with warming up. It is aided by the entrainment of air due to atmospheric turbulence. Also, the implied statement that the cloud warms up and therefore becomes buoyant is a thermodynamically incorrect statement. When a cold vapor (LNG vapor) mixes with warm air, the vapors heat up; but the air that is mixed with the vapor cools down. The net result is that the mixed gas (vapor-air mixture) is ALWAYS heavier than air if the original vapor is heavier than air. The only way a heavy gas, such as LNG vapor, can become buoyant after mixing with air is if an additional source of heat exists, such as the ocean or the sun. In the experiments in hot desert conditions no lifting of the LNG vapors was observed.

Response
For the types of LNG spills considered, dense-gas effects will remain important until after the cloud disperses below the lower flammability limit. However, at some point the cloud will be neutrally buoyant; stated simply, the cloud will no longer have sufficient density to affect its own dispersion.

Comment
The description of the flame spread in a vapor air mixture cloud indicated in 2nd paragraph of page 3 is also incorrect. Flame spread rate in the open atmosphere is NOT a function of the laminar-burning rate; it is entirely dependent on the wind speed and the intensity of turbulence generated either by wind or obstructions in the path of the flame.

Response
The statement in the report is that "The rate at which this flame front travels relative to the unburned gas is called the laminar burning velocity." This statement is correct and consistent with commonly used terminology; examples of the definition of burning velocity are available in many references, such as NFPA (2002) which defines burning velocity as "the rate of flame propagation relative to

the velocity of the unburned gas that is ahead of it." Similarly TNO (1997) defines burning velocity as "the velocity of a propagating flame, measured relative to the unburnt gases immediately ahead of the flame front."

Comment

No discussion has been provided to contrast the commonly used term "explosion" and detonation. The discussion in section 1.4.2, paragraph 1 is too simplistic and confusing. The statements imply that if there is some obstruction or small confinement, methane air mixture will "explode." For a detonation wave to be sustained in a methane air mixture requires the simultaneous occurrence of several conditions, namely, long transition length for deflagration to transit to detonation, methane concentration between 9 % and 12 % in air, and no venting of the pressure in front of the deflagration fire. None of these conditions are likely to be fulfilled in an open or semi open atmospheric environment. That is why one does not have any records of methane-air detonations in the open. However, explosion is a phenomenon in which the local pressure increases due to the hot gases (produced by the fire) confined in a weak enclosure whose walls give way quickly relieving the pressure. Building collapses due to methane (natural gas) releases into basements and the subsequent ignition is an example of the commonly referenced "explosion." What should be of interest for the LNG hazard is the occurrence or not of a detonation type of combustion of a vapor cloud which then propagates a blast wave in the air affecting structures and people at large distances from the fire. This type of burning has not happened in methane-air mixtures even when ignited by an explosive charge. Therefore, the allusion (by the authors of the FERC report) to a potential methane air explosion implying that " … the portion of the cloud within that congested area may generate damaging overpressures" is inappropriate.

Response

Use of the term "explosion" can be problematic. In some literature, the term explosion is used to mean "detonation," while in other literature the term is used more generally to refer to an event that leads to generation of a pressure wave. The key point of the paragraph 1.4.2 is that when ignited in open areas, large overpressures are not expected; however, when ignited in confined areas or areas congested with equipment, higher overpressures can occur. This is consistent with guidance on use of the so-called multi-energy techniques widely used for explosion modeling (see TNO 1997). While NOT intended to imply that congestion will cause a detonation, the statement that portions of the cloud within a congested area may generate damaging overpressures is appropriate and supported by information in Table 5.5 of TNO (1997).

Comment

The statement "The combustion normally occurs within only portions of the vapor cloud (where mixed with air in flammable concentrations), rather than the entire cloud." in the paragraph on Flash Fire, page 4, is incorrect. Methane air mixtures can be IGNITED only when the methane concentration in the mixture is between 5 % and 15%. However, when a cloud is ignited it burns even the vapor that is at concentrations higher than 15% by ingesting air into the burning plume. Hence, once the cloud is ignited (at any concentration between 5% and 15%) it will burn all vapors above the LFL concentration and not just the ones in the flammable range as implied by the authors.

Response

The statement that "combustion normally occurs within only portions of the vapor cloud" is supported by evidence from LNG spill experiments. However, as Dr. Raj points out, ingestion of air into the burning plume can result in combustion in a larger portion of the cloud than is within the flammability limits at the time of ignition.

Comment

The spreading model attributed to Weber is "solved" numerically without describing the procedure properly. For example, the procedure requires the specification of the value of radius and the velocity of spread at the initial time (second order differential equation in the radius). The authors seem to use an initial radius of Volume (1/3) as the starting radius. It is unclear what spill volume they use initially. Similarly, the "spread front" thickness is estimated by assuming that the layer is viscous/surface tension force controlled. It is well known that when the spread starts it is controlled by inertial forces and not viscous or surface tension. There are a number of questions on the use of the Weber model that have not been explained by the authors.

Response

A full description of the Webber model may be found in TNO (1997) and the original work published by Webber (1986, 1987). The implementation presented in the report does estimate the radius at the very beginning of the spill as the volume to the 1/3 power. The starting volume is the amount spilled during the first time-step. After the first time-step, the radius is calculated using the Webber model equations. Estimating the starting radius using volume to the 1/3 power is an approximation, but because it only affects the radius very early in the spill, it is judged a reasonable approach. It is notable that others have also used volume to the 1/3 power as a starting point, including the authors of SOURCE5 who use this approximation for the starting radius for 'instantaneous' spills. Regarding control of spread by viscous or inertial forces, the Webber model allows the user to avoid artificially choosing which of these dominates by including both throughout the spread. It is true that the inertial forces dominate initially, but that does not mean that friction forces are not present.

Comment
After going through significant spread calculations using numerical solution techniques, the authors make the following statement (last but one paragraph of page 13): "It is also useful to note -----. In a case such as this, the pool area can be estimated using the spill rate and the evaporate rate per unit area…" This statement has no meaning. When the spill rate is changing with time (as the square root of the head of liquid depth in the tank) what spill rate is to be used to calculate the maximum area? Certainly not the initial maximum spill rate! Secondly, the authors do not define quantitatively the conditions under which the above "approximation" can be used to calculate the maximum pool dimensions.

Response
As the example problem presented for a spill from a 1-m hole shows, there can be a point in time where the spill and evaporation rates match, after which the pool radius decreases with the decreasing spill rate. However, without performing detailed spreading calculations, it is not possible to identify when or if this will occur.

Comment
The authors provide a table of comparison of LFL distances obtained for different assumptions for the value of the heat flux from water to LNG pool. The results presented in the table on page 18 are some what counter intuitive. As the heat flux increases (making the vapor generation rate higher) the down wind flammable distance for an unignited cloud decreases. This is completely contrary to what one expects; as the source rate increases, all things about the weather conditions being the same, the down wind LFL distance increases.

Response
While the spill rate and duration are the same for all three cases, the transient evaporation rate looks different for each case because of the differences in heat flux values and corresponding differences in pool spread. Figure 1 shows the evaporation rate versus time for all three heat flux values.

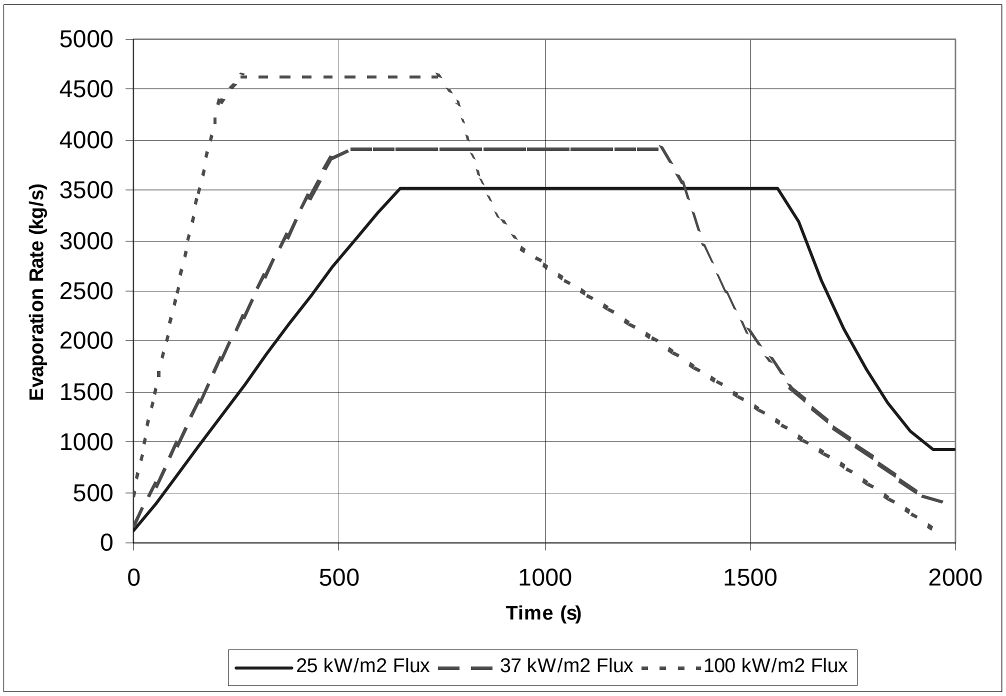

Figure 1 Evaporation Rate Versus Time for Heat Flux Sensitivity

These differences in transient evaporation account for the counterintuitive trend in heat flux and downwind distance to the LFL.

However, this issue is somewhat moot because the modeling improvements recommended in this document (see Items C and D in particular), result in evaporation rate curves that are more realistic and different from these.

Comment
The authors base all of the hazard area calculations on the basis of the maximum pool diameter. It is noted that the fire lasts only a fraction of a second at this maximum diameter after which it extinguishes itself. All thermal radiation hazard criteria have some exposure time requirements (skin burn about 30 seconds). An exposure time of 30 s or 45 s forms a substantial fraction of the pool spread time. Hence, basing the hazard area on the maximum diameter is incorrect.

Response
For purposes of providing information to assist decision makers with facility siting issues, a thermal flux level of concern is appropriate. The recommended value of 1,600 BTU/hr/ft^2 (5 kW/m^2) is also used in other regulatory applications, such as with onshore facility siting (49 CFR 193 and NFPA 59A) and EPA risk management programs (40 CFR 68).

It is true that the pool fire is predicted to last for only a very short time at the maximum diameter, and as discussed in the report, it is also important to consider exposure time; Table 2.6 in the report lists some expected effects of a 1,600 BTU/hr/ft^2 (5 kW/m^2) thermal flux level for various exposure times. For example, second-degree burns are expected in approximately 30 seconds. So, basing the level of concern on thermal flux at the maximum diameter is conservative.

A useful question then is: just how much conservatism is introduced by use of the maximum diameter? The answer of course depends on the scenario being considered. If the thermal flux is close to the level of concern for a significant time, then basis on maximum diameter does not introduce much additional conservatism, and if the thermal flux is not close to the level of concern except for a very short time, basis on maximum diameter is more conservative.

Looking at the example problems presented in Item I can provide some insights to the degree of conservatism. To do this, a thermal dose criterion of 13 BTU/ft^2 (150 kJ/m^2) for second degree burns, as suggested by Prough (1994) and given in Table 2.4 of the report, was selected. This thermal dose corresponds to an exposure to 1,600 BTU/hr/ft^2 (5 kW/m^2) for 30 seconds, so with short exposure, it can be argued that this dose criterion is roughly equivalent to the 1,600 BTU/hr/ft^2 (5 kW/m^2) flux criterion. Using an exposure time of 30 seconds and the actual (transient) pool diameters for the example problems, the distance to the thermal dose criterion was calculated. In the case of the 1-m hole, the 30 seconds was taken as 15 seconds before and 15 seconds after the peak thermal flux, and in the case of the 5-m hole, the 30 seconds was taken as the final 30 seconds of the fire event (since the maximum occurs at the end of the event). The resulting distances to these levels of concern are shown in Table 4.

Table 4 Comparison of Thermal Flux and Thermal Dose Levels of Concern

Hole diameter[1]	3.3 ft (1 m)	16 ft (5 m)
Downwind distance[2] to thermal flux of 1,600 BTU/hr/ft^2 (5 kW/m^2)	2,139 ft (652 m)	5,008 ft (1,527 m)
Downwind distance[2] to thermal dose of 13 BTU/ft^2 (150 kJ/m^2)	2,096 ft (639 m)	4,936 ft (1,505 m)

[1] Scenario details are given in Item I.

[2] Calculated downwind distance values are shown for comparison purposes; values would not normally be reported with this number of significant digits

These results show that for the types of scenarios considered here, basing the level of concern on thermal flux introduces very little additional conservatism, even though the fire is predicted to be at its maximum diameter for only a very short time.

Comment
It is unclear whether the authors used the criterion of heat energy dosage (and the probit equations) that are discussed in the report in calculating the hazard zone dimensions instead of the damage heat flux criterion. If the dosage models are not used, then they should not be indicated in the report.

Response
Section 2.7 of the report provides an overview of the data and methods available for estimating the effects on people and structures that result from thermal radiation exposure. Dosage or probit methods were not used in the examples in the report, but these are important data to include in any overview of the topic.

Responses to Comments of Analytical & Computational Engineering, Inc.

Comment
Submitted comments include several recommendations for use of computational fluid dynamic (CFD) modeling.

Response
While the recommended methods can provide useful information to decision makers, there is certainly room for future improvement of modeling of events involving LNG spills on water, and CFD approaches could well prove to be useful tools in such efforts. However, the work described here focused on identifying currently available methods for assessing consequences of such spills. With regard to the problems of spread of LNG on water and modeling of pool fires, the literature review did not identify any CFD models that could be readily applied and defended.

With regard to pool fires, the statement in the report that CFD models provide little or no benefit over the solid flame model is based largely on the conclusions of Cowley (1992). This work was sponsored by 29 (mostly industry) organizations and published by the Health and Safety Executive. It involved an evaluation of semi-empirical models (like the recommended solid flame model), field models (e.g., CFD models), and integral models. This report states that:

> *Well validated, soundly based semi-empirical models are currently the best models which are available for the prediction of heat fluxes to objects outside flames. They can only be used however within the range of conditions given by the experimental data used in their derivation. Thus, for example, they are only applicable for open fires which are unaffected by the presence of structures nearby or within the flame.*

In addition, regarding field models the report states that:

> *Current models are essentially research tools. In general they have weak descriptions of the gaseous combustion, the soot production and oxidation and the radiative heat transfer sub-models. These are not criticisms of the models as research tools under development. As such they test combustion knowledge and provide pointers for experimentalists to tackle. They demand a fundamental knowledge of combustion and heat transfer hitherto somewhat ignored in large-fire science.*
>
> *Our criticisms are directed rather towards the use of these models as commercial hazard analysis tools. For most of the problems where they have been applied they have* <u>*not*</u> *been validated properly. They are* <u>*not*</u> *capable of producing accurate quantitative predictions.*

While it is likely field models have improved significantly in the 12 years since publication of this report, as previously stated, the literature review did not identify any CFD models that could be readily applied and defended.

Cowley's caution to only use the semi-empirical models with the range of conditions given by the experimental data is not taken lightly, and in recommending such an approach for very large LNG pool fires, it is recognized that the empirical correlations used are based on smaller pool fires than the sizes considered here. However, the application of the methods recommended by the study will tend to be conservative (i.e., overestimate rather than underestimate the hazard zone).

For those not familiar with CFD, it is worthwhile to mention that such modeling approaches do not provide a panacea for some of the tough problems in modeling LNG spills. For example, in modeling pool spread and evaporation, the recommended approach uses a value for heat flux from the water to the pool that is an estimate based largely on experimental data. In applying CFD methods, an analyst will have essentially two options (1) select a heat flux value as was done in the study or (2) attempt to model the complex boiling process in a detailed manner. If the first option is selected, the results will suffer from uncertainty because of uncertainty in the selected value (as the recommended approach does). If the second option is selected, the analyst has significant challenges in modelling the complex process correctly, which will include identification of the correct set of physics equations (i.e., from first principals) that must be solved and applying the correct boundary conditions. With a turbulent, multi-phase problem such as this, the analyst may also be required to use some empirical data to solve the problem, even numerically.

CFD models do have the potential to provide more detailed information, such as a more realistic pool shape (accounting for factors such as wind and currents). In addition, one particular area where CFD methods have potential to improve modeling results (or at least decrease uncertainty) is in applying more fundamental physics to help overcome the need to use empirical correlations (e.g., Thomas' correlation for flame length) outside the range for which they were designed.

Comment
Please provide backup calculation to the assertion that LNG will stay negatively buoyant until after it disperses below the LFL. ACE performed simple hand calculation and obtained a much different result.

Response
This assertion was based primarily on review of the results of the dispersion modeling performed for the examples included in the report.

Responses to Comments of Project Technical Liaison Associates, Inc.

Comment
The spread on water uses essentially smooth surface and only mentions the effect of a non-smooth surface. But the effect of even small waves was shown to be dramatic. There is no guidance as to how FERC should take into account waves. As even small waves will effect the peripheral portions of the pool, this factor must be considered.

Response
It is not clear where the commenter believes that "the effect of even small waves was shown to be dramatic." The only model of waves identified was that presented by Quest (2001, 2003), and the smallest waves considered in that study were over 1.89 ft (0.575 m) tall. Typical harbor areas will often have waves significantly lower than this, and in many harbors calm waters are not uncommon.

Comment
The model for thermal radiation flux from a sustained pool fire may be satisfactory but the application to a spreading pool of LNG is not a convincing picture of reality, considering:

- *The pool is not ignited until it reaches maximum diameter*
- *A pool of a few millimeters thickness at the edge will not create a fully developed cylindrical flame above the pool or burn long enough to establish the model's flame geometry*
- *Adequate air will not be available to create the same flame size and intensity as modeled.*

Response
In the pool fire examples presented, it is assumed that the fire is ignited immediately upon release. The pool spread algorithm takes this into account in estimating the pool radius and pool thickness as a function of time. Regarding adequacy of air, the recommended modification to use a two-zone flame model helps address this issue.

Comment
The common portrayal of the vapor dispersion hazard area is a circle around the release point whose radius is the maximum dispersion distance at the most unfavorable conditions. The actual area at risk for an incident is the area of the plume (based on width at distance) of the LFL concentration. No consideration of this limitation is given in the report.

Response
Carefully defining the area that could be within a flammable cloud would be an important part of a detailed quantitative risk assessment. However, when providing facility siting decision makers with information about distances to which effects of interest might reach, representing the hazard zone as a circle will usually be adequate.

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