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Consequence Modelling of LNG Marine Incidents

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ABSTRACT

The LNG consequence analysis studies related to marine incidents are gaining prominence in the U.S. and some other countries due to the potential increase in LNG trade in the near future. To address the issues of LNG hazards associated with marine transportation, many safety assessment studies have been performed by various companies and organizations. These recently conducted studies related to LNG employ different methodologies and have published varying results. The disparity in results is mainly due to the difference in release sizes, modeling parameter assumptions and modeling tools used in calculating the hazard zone.

This paper reviews the modeling approaches used by different companies and organizations. A detailed discussion on critical modeling parameters and assumptions affecting the consequence analysis results are also presented in this paper.

KEYWORDS

LNG, consequence modelling

1. INTRODUCTION

There has been substantial debate in the U.S. over the potential consequences of a marine accident involving an LNG vessel at or approaching one of the four current U.S. import terminals or one of the up to 45 proposed new terminals in North America. This debate has occurred at public meetings associated with the approval process, in conferences, and published technical papers. Some recent publications on this topic include: Quest (Cornwell, 2001), Fay (Fay, 2003), ABS (ABS, 2004), DNV (Pitblado et al., 2004) and Sandia (Hightower et al., 2004).

The hazard zone distances reported from the above studies are quite varying. The disparity in results is due to the difference in release sizes, modeling parameter assumptions and somewhat due to modeling tools used in calculating the hazard zone distances. DNV and Sandia studies have a stronger basis for the hole size selection, while other studies do not provide the basis for the hole size selection. ABS used the discharge coefficient of 1.0 in estimating the release rate, while DNV and Sandia used 0.6 for discharge coefficient. Therefore, ABS's result is a conservative one.

There are many other critical parameters that affect the consequence modeling results. Investigation of these critical parameters provides better understanding and confidence on the results reported by different companies and organizations. This paper provides detailed discussions on the modeling approaches used by ABS, DNV, Sandia and Quest. The study done by Fay is excluded since the detail parameters used in the modeling are not available.

2. RESULTS OF RECENT STUDIES

The four recent studies reviewed in this paper are:

- DNV - A Joint Sponsor Project that involved a credible risk assessment approach of marine LNG release scenarios subject to external peer review.
- ABS - Federal Energy Regulatory Commission (FERC) sponsored this study with the goal of estimating flammable vapor and thermal radiation hazard distances for potential LNG cargo releases.
- Sandia - A work sponsored by the U.S. Department of Energy that provides guidance on appropriateness of models, assumptions and risk management to address public safety relative to a potential LNG spill over water.
- Quest - Quest Consultants Inc. provided a letter to the U.S. Department of Energy regarding the consequence of a potential release of LNG from a ship.

More details on the above studies including adopted modeling tools are given in Section 3. The latter section also includes further details of the modeling approaches for LNG discharge onto water, subsequent pool spreading/evaporation, the pool fire (case of ignition) and vapor cloud dispersion (case of no ignition).

The consequence results analyzed in this paper include:

- Thermal radiation hazard zones – distance to 5 kW/m^2 and 37.5 kW/m^2
- Flammability hazard zone – distance to LFL

Pool Fire Results

The pool fire radiation results from the above mentioned studies are presented below in Table 1 and also in the form of a graph in Figure 1 and Figure 2.

Hole size (mm)	Study	Pool Radius for Radiation (m)	Burning Rate (kg/m^{2}s)	Radiation Distance	
				5 kW/m^2	37.5 kW/m^2
250	DNV	15	0.353	194 m	70 m
750	DNV	43	0.353	451 m	169 m
1000	ABS	74	0.282	860 m	370 m
	Quest	n/a	0.089	433 m	n/a
1120	Sandia	74	0.128	554 m	177 m
1500	DNV	86	0.353	761 m	289 m
1600	Sandia	105	0.128	784 m	250 m
2523	Sandia	165	0.128	1305 m	391 m
5000	ABS	130	0.282	1400 m	600 m
	Quest	n/a	0.089	540 m	n/a

Table 1. Pool Fire Results

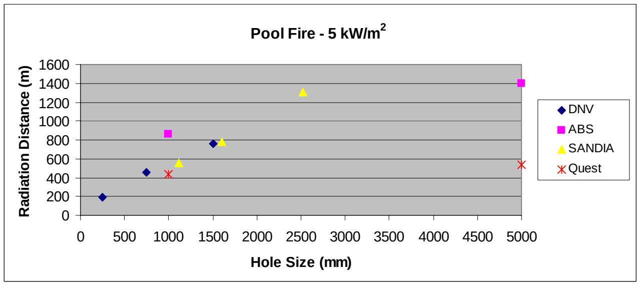

Figure 1. Pool Fire Results – 5 kW/m^2

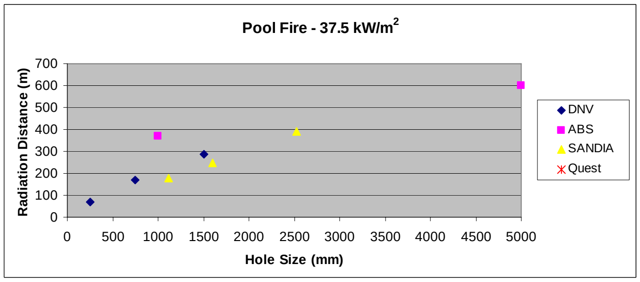

Figure 2. Pool Fire Results - 37.5 kW/m^2

As shown in Table 1, Figure 1 and Figure 2, each study used different hole sizes for their analysis. Therefore, a direct comparison of results is not possible.

Dispersion Results

The pool spreading/evaporation and dispersion results for all four cases are summarized below in Table 2 and also presented graphically in Figure 3. The graph shown below compares only the results for F stability and 2 m/s atmospheric conditions for all four studies, as Sandia provides the dispersion results only for that condition.

Hole size (mm)	Study	Pool Radius for dispersion (m)	Evaporation Flux (kg/m2s)	LFL distance (m)		
				F-2 m/s	D-3 m/s	D-5 m/s
250	DNV	29	0.179	790 m	370 m	380 m
750	DNV	59	0.179	1800 m	850 m	870 m
1000	ABS	130	0.072	3300 m	2000 m	n/a
	Quest	n/a	0.2	3733 m*	n/a	783 m
1120	Sandia	74	n/a	1536 m*	n/a	n/a
1500	DNV	117	0.185	3400 m	1600 m	1700 m
1600	Sandia	105	n/a	1710 m*	n/a	n/a
2523	Sandia	165	n/a	2450 m*	n/a	n/a
5000	ABS	170	0.075	3900 m	n/a	n/a
	Quest	253	0.2	4076 m*	n/a	1002 m

* Sandia and Quest modeled with F-2.33, F-1.5 respectively instead of F/2

Table 2. Dispersion Results

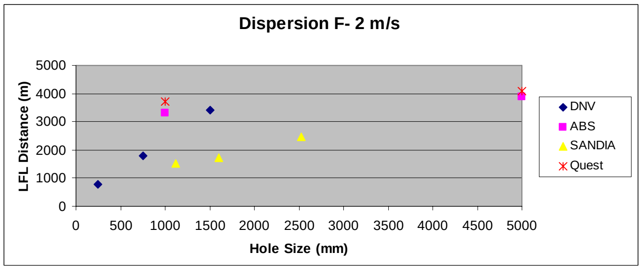

Figure 3. Dispersion Results for F stability and 2 m/s

Similar to the pool fire case, each study used different hole sizes for their analysis as shown in Table 2 and Figure 3. Therefore, a direct comparison of results is not possible.

3. CRITICAL PARAMETERS AFFECTING CONSEQUENCE RESULTS

The purpose of this paper is to analyze the results of the different studies based on the critical parameters affecting the consequence results. There are many parameters that could impact the final results. This paper will discuss the key modeling parameters used in each study and the significance of those key parameters on the consequence results.

The consequence models used for dispersion analysis in the four studies are listed as follows:

- DNV - PHAST
- ABS - DEGADIS
- Quest - CANARY
- Sandia - VULCAN

Of the four different studies, only Sandia used a CFD code (VULCAN) while others used similarity models. Both types of models are known to be adequate for modeling of dispersion over flat terrain.

For pool fire modeling, DNV, ABS and Quest used similar solid flame models, while Sandia used a CFD code, VULCAN.

3.1 Discharge Modeling

As shown in the tables and figures in Section 2, each study used different holes sizes for consequence modeling. Therefore, a direct comparison of the results is not possible. In general, DNV and Sandia studies have a stronger basis on the selection of hole sizes, while ABS and Quest studies used hole sizes selected purely based on the judgement. DNV determined the credible hole sizes based on the collision damage graph from IMO/MARPOL and Sandia determined the holes sizes based on the finite element modelling of ship collisions.

The discharge modeling for each study was performed using a similar approach. Bernoulli's equation was used in all these studies to estimate the discharge rate through the hole. However, the discharge coefficient used in the calculation was quite different.

Bernoulli Equation

$$Q = C_d A \rho[2 (Pi-Po)/ \rho + 2gH]^{0.5}$$

Where C_d is the discharge coefficient, A is the hole area, ρ the LNG liquid density, P_i is the storage pressure at the top of the LNG liquid, H is the LNG liquid head above the release height and P_o is the atmospheric pressure.
Table 3 shows the discharge coefficient C_d used in each study.

Study	Discharge Coefficient (C_d)
DNV	0.6
ABS	1
Sandia	0.6
Quest	n/a

Table 3 Discharge Coefficient Used in Each Study

As shown in Table 3, ABS used a discharge coefficient of 1.0, while DNV and Sandia used 0.6. The discharge coefficient of 0.6 and 1.0 represents a sharp-edged orifice (TNO, 1999) and a perfect discharge without any restriction, respectively. The ABS discharge rate was 40% greater than DNV and Sandia studies. This may be one of the reasons why the ABS result is more conservative than others. The information on discharge coefficient was not available from the Quest study.

3.2 Pool Fire Parameters

Some of the key parameters that have a significant impact in the LNG pool fire modeling have been identified to analyze the radiation hazard distance results published in these four studies.

Burning Rate

The burning rate is a critical parameter in pool fire modeling since it determines the amount of material which burns per unit area and per unit time. A higher burning rate provides a higher thermal radiation result.

Table 4 shows the burning rates used in each study.

Study	Burning Rate (kg/m^2/s)	Reference
DNV	0.353	Cook et al. 1990
ABS	0.282	Rew 1996
Sandia	0.128	Not provided
Quest	0.089	Not Provided

Table 4 Burning Rate Values

The burning rate of methane on land is known to be 0.141 kg/m^2/s. In case of fires on the water surface, the burning rate increases due to heat transfer from water. According to Cook et al. (1990), the burning rate on water is 2.5 times greater than the burning rate on land.

The DNV and ABS studies used a corrected burning rate in the pool modeling, while others had no indication of those corrections.

Surface Emissive Power

The Surface Emissive Power (E) is the power that is radiated per unit surface at the surface of the fireball. The intensity of thermal radiation (Q) that an individual may receive from a pool fire is directly proportional to the surface emissive power (E):

$$Q = E F \tau$$

where E is the Surface emissive power, F is the Geometrical view factor and τ is the transmissivity of atmosphere.

Table 5 summarizes the surface emissive power used in different studies and values obtained from LNG pool fire experiments.

Study	Surface Emissive Power (kW/m^2)
ABS	265
DNV	220
Sandia	220
Quest	Not available
USCG China Lake tests	220 ± 30
Maplin Sands	178 to 248

Table 5. Surface Emissive Power Values

As shown in Table 5, the ABS study used higher values than other studies. This can be a part of the reason why the ABS result is more conservative than others.

Pool Radius

Pool radius and burning rate are competing factors and if the burning rate is higher, then the pool size would be smaller and vice versa. The size of the pool has a direct effect on the predicted hazard distances and is very critical in pool fire modeling.

The pool size of an ignited pool is much smaller than that of an un-ignited pool due to the termination of pool spreading upon ignition. Therefore, the pool size needs to be corrected for an ignited pool. The simplest way of correcting the pool size is to use a burning rate assuming a steady state pool.

The DNV and ABS studies used similar approaches in correcting the pool size for hazard distance calculation of pool fires. However, Sandia used the same pool size for ignited pools and un-ignited pools. The information about the pool size is not available in the Quest study.

Wave Effect

The presence of waves on water will affect the spreading of LNG on its surface. The Quest study has incorporated this wave effect by using a conditional statement at the boundary of the pool; namely, the pool will stop spreading once the LNG drops below 60% of the wave height. Therefore, the wave effect would decrease the pool radius as the wave breaks the liquid pool formed on the surface and results in reduced thermal radiation hazard zone. This could possibly explain why Quest reported smaller thermal radiation hazard zone results compared to other studies.

Atmospheric Conditions

Atmospheric wind speed also has an effect on the predicted hazard distances in the case of pool fire modeling. The worst case atmospheric conditions for pool fires are during high winds. The wind allows the flame to tilt, thus allowing the flame to move further downwind. This results in higher downwind radiation flux levels than those attained under low wind conditions. All four studies used similar atmospheric conditions for pool fire modeling.

3.3 Vapor Cloud Dispersion Parameters

Pool Evaporation

In the case of vapor cloud dispersion, pool vaporization rate is one of the most critical parameters in estimating the hazard zone distance since it determines the mass that enters into the dispersion. The approaches used in the four studies for pool evaporation are quite different and this is an area that needs further improvement.

Table 6 shows the evaporation flux used in the different studies. Evaporation flux decides the amount of material that goes in to the vapor cloud dispersion calculations and this depends on the size of the pool.

Study	Source	Pool Size Used	Evaporation Flux (kg/m^2/s)
DNV	Dodge et al. method	Steady state pool size	0.182 (based on steady state evaporation rate)
ABS	Webber's method	Maximum pool size	0.072 (based on maximum evaporation rate)
Sandia	Vulcan CFD model has built in spreading model.	Maximum pool size	Not Available
Quest	Mechanism not known but includes wave effect.	Not Available	0.2 (based on maximum evaporation rate)

Table 6. Pool Spreading and Evaporation

As shown in Table 6, the evaporation flux used in dispersion modeling is quite varying. ABS and Quest used evaporation flux based on the maximum values, while DNV used the evaporation flux based on steady state value.

It should be noted that the amount of material that goes into the atmospheric dispersion is also dependent on the size of the pool. Therefore, the higher evaporation flux does not necessarily mean greater evaporation from the pool. When DNV's evaporation rate is re-estimated based on the maximum pool, the evaporation flux gets closer to the values reported by ABS.

The evaporation rate calculated based on the flux and pool size reported show that DNV's evaporation rate is little bit higher than ABS's value.

Atmospheric Conditions

In case of dispersion, an unstable atmospheric condition (higher wind speed) causes more turbulence and in turn results in quicker dilution of the hazardous material. In a stable atmospheric condition (lower wind speed), the hazard zone distances usually increase due to reduced mixing of hazardous materials in the air.

All four studies used similar atmospheric conditions for dispersion analysis as shown in Table 7.

Study	Atmospheric Stability and Wind Speed	Surface Roughness Length	Relative Humidity
DNV	F-2, D-3 ,D-5 m/s	0.3 mm	70 %
ABS	F-2, D-3 m/s	10 mm	50 %
Sandia	F-2.33 m/s	0.2 mm	Not available
Quest	F 1.5 ,D-5 m/s	Not available	70 %

Table 7. Atmospheric Conditions

Surface Roughness Length

The surface roughness length describes the roughness of the surface over which the cloud disperses. It alters wind velocity profile and consequently affects the dispersion result significantly. Therefore, it is important that proper roughness lengths are used in the dispersion analysis.

Review of the four studies shows that the roughness length values used in the different studies are quite varying. DNV and Sandia used a roughness length of 0.2 mm to 0.3 mm, while ABS used 10 mm.

According to literature, the roughness lengths of open sea are 0.1 mm to 1.0 mm, depending on weather conditions (Ermak, 1990) (EPA, 1995) (EPA, 2004). Therefore, the values used by DNV and Sandia are more appropriate than a value used by ABS for dispersion over open sea.

The surface roughness used in the four different studies is presented above in Table 7 for comparison.

Relative Humidity

The humidity is used in the dispersion calculations to determine the properties of the atmosphere (mainly the density of the air) and the density of the cloud. The higher the humidity, the sooner the plume becomes buoyant due to the heat transfer from moisture. Therefore, the hazard zone distance decreases with increased humidity.

The humidity varies a lot depending on the site location. Therefore, it is best to use the site specific data for humidity, particularly in cases where the site is located in an extremely humid or dry location. In open sea, the relative humidity is normally 70% or higher.

The atmospheric conditions used in the four different studies are presented in Table 7 for comparison.

4. SENSITIVITY ANALYSIS

In order to investigate the effect of different modeling parameters on the consequence results, a few sensitivity runs were performed.

Pool Fire

The pool fire scenario of 1 m hole reported by ABS was modelled using DNV's PHAST program, with same pool radii as ABS and by setting the burning rate, surface emissive power and wind-speed equal to the ABS value. The same modeling was performed using PHAST for pool fire scenario of 1.12 m reported by Sandia and the results are shown in Figure 4 and Figure 5.

The result clearly shows a drastic reduction in the deviation of ABS and Sandia's results from the DNV value for the same hole size. The circled points show the change in ABS and Sandia values. At this stage, there is still a small deviation in results between ABS and DNV after fixing the parameters and this difference can be clearly attributed to the difference in the consequence models used in these studies. However, the DNV and Sandia results become almost the same when the same modeling parameters are used.

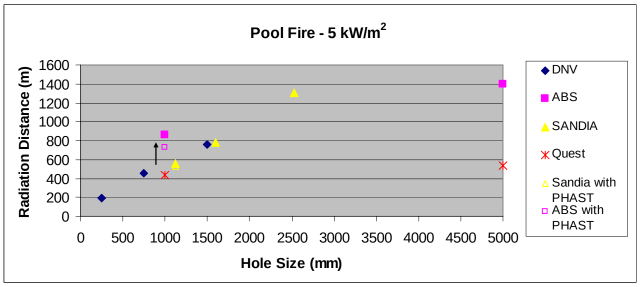

Figure 4. 5 kW/m^2 Sensitivity Run

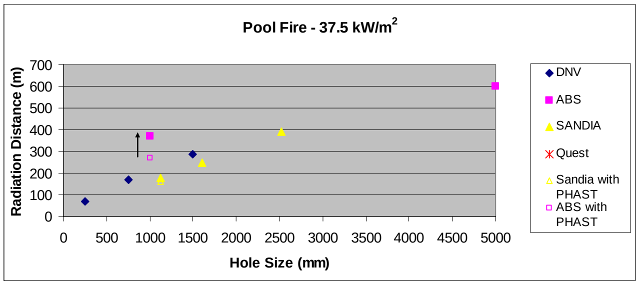

Figure 5. 37.5 kW/m^2 Sensitivity Run

Dispersion

For the dispersion modeling, ABS and Sandia cases were modeled using DNV's PHAST program by fixing the evaporation rate and atmospheric conditions such as surface roughness, relative humidity, stability wind speeds.

The dispersion scenarios of 1m hole reported by ABS and 1.12 m hole reported by Sandia were modeled using SAFETI and the result is presented in

Figure 6.

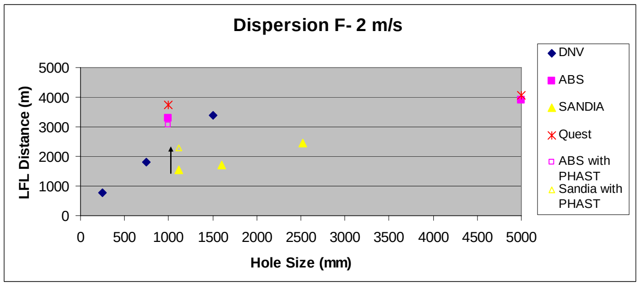

Figure 6. Dispersion Results Sensitivity Run

As shown in

Figure 6, the dispersion case re-runs also showed a reduction in the deviation of results when the same modeling parameters are used. The DNV and ABS results become almost the same when the same modeling parameters are used. However, there is still a quite large deviation in results between DNV and Sandia even though the same modeling parameters are used.

This difference can be clearly attributed to the difference in the consequence models used in these studies. Sandia used a CFD code in the dispersion calculation, while others used similarity models. In order to answer whether this difference in results is due to the difference between similarity and CFD codes, further study is required.

5. CONCLUSIONS

The detailed investigation for consequence modeling approaches of recent studies shows that the varying results are due to the differences in modeling assumptions and the modeling tools used in estimating the hazard zone distances. The deviation in results between the studies reduces significantly when the same modeling assumptions are used. Therefore selection of the appropriate modeling parameters is a critical step in consequence modeling.

Further, the deviation of dispersion results between Sandia and others were significant. It may be due to the difference between models used (CFD vs. similarity). However, further study is required to confirm this.

Moreover, the scales of LNG releases modeled in these studies are much less than the scale of existing field experimental data. Therefore, additional large scale experiments will provide more confidence in the modeling methods. However, that should not prevent valid decision making today, since uncertainties that exist here are no worse than the uncertainties in many other high hazard activities.

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