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LNG decision making approaches compared

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Abstract

Hazard zones associated with LNG handling activities have been a major point of contention in recent terminal development applications. Debate has reflected primarily worst case scenarios and discussion of these. This paper presents results from a maximum credible event approach. A comparison of results from several models either run by the authors or reported in the literature is presented. While larger scale experimental trials will be necessary to reduce the uncertainty, in the interim a set of base cases are suggested covering both existing trials and credible and worst case events is proposed. This can assist users to assess the degree of conservatism present in quoted modeling approaches and model selections.

Keywords: LNG; Modeling; Risk; DNV; Spills

1. Introduction

There are close to 45 LNG projects proposed for North America, predominantly in the USA, but with additional terminals in Mexico and Canada. A key issue that has emerged is consequence zones from large LNG vessels used to deliver the LNG product to the terminals. It has been voiced that there is greater potential for releases that might affect people during shipping from marine accidents or from terrorism than from the terminal itself.

Two important factors cause confusion in decision making—the hole size and the model used to predict consequence effects. This paper reviews consequence modeling approaches and compares results from several publicly or commercially available models.

2. Hazardous area decision approaches

There are several approaches for establishing appropriate hazard separations between hazardous activities and nearby vulnerable installations or people. The main approaches are:

- Worst-case consequence based separations;
- Maximum credible event based separations;
- Risk assessment based separations.

Terminology can be difficult as there are no widely agreed definitions of these terms. To the public, a worst case release would be a total inventory release, regardless of the safeguards, occurring during the worst weather conditions. In reality, most worst case events are limited by the physics or the design to be less than the total inventory. The EPA RMP Regulations define the worst case event as the consequences from a total loss of containment within 10 min (interpreted as the largest isolatable section), and allowance can be made for administrative controls limiting the inventory. Outcomes are modeled to the ERPG2 toxic end-point, LFL, 5 kW/m^2, or 1 psi overpressure. These are mostly injury level outcomes. Under the regulations, lesser more frequent events can be modeled and these are termed Alternative Release Scenarios. In reality, there are events which are worse than this worst case definition—a failure the largest bottom connection to a large pressure vessel will often empty the vessel in less than 10 min. Also a common cause event (e.g. an airplane crash can affect several isolatable sections simultaneously) can be worse than this worst case. Therefore in practice, what is termed worst case events in regulatory parlance may be less than truly worst case, and implicitly include some aspect of safeguarding.

2.1. Worst case approaches

The worst case event can be defined [1] as the most severe incident, considering only incident outcomes and

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their consequences, of all identified incidents and their outcomes.

The worst case approach appears attractive as a decision support tool as "whatever happens, it can not be worse than this" and those responsible for public protection can be assured that the nominated consequence levels will not be exceeded. In reality, for major energy sources, it is often very difficult for industrial facilities located in proximity to people or infrastructure to demonstrate acceptability. This can apply to nuclear facilities, refineries, chemical plants, LNG terminals, and dams. A catastrophic failure of any of these, without any regard to the safeguards or barriers in place, is unlikely to be able to demonstrate no impact to infrastructure or people within possible hazard zones.

A disadvantage of the worst case approach is that ignoring safeguarding features (technical or people-based) tends to move public discussions away from safeguarding and specific means of improving these towards more mathematical definitions of the worst case event and modeling the outcomes.

2.2. *Maximum credible event approaches*

A maximum credible event can be defined [1] as the most severe incident, considering only incident outcomes and their consequences, of all identified incidents and their outcomes, that is considered plausible or reasonably believable. By bringing in the aspect of plausibility, the ability of safeguarding to reduce the scale of possible events from the maximum possible to some lesser scale is allowed. Safeguarding can reduce the likelihood of the event (prevention) or reduce its potential outcome (mitigation). The judgment of plausibility is imprecise, but would take account of the level of threat, the number and quality of safeguards, and the number of installations. What may not be credible at a single installation may be credible when taken over the entire USA.

2.3. *Risk assessment approaches*

A risk assessment approach should include the entire range of potential events from frequent small events, through infrequent but credible events, to much rarer worst case events. It combines each event scenario with its likelihood of occurrence and the multiple possible outcomes. The advantage of a risk assessment approach is that safeguarding is explicitly included in a manner that allows cost-benefit to be established. The USA currently does not use risk assessment approaches for process or LNG facilities, but the Office of Management and Budget does for medical investments at the national scale. Companies are concerned about public reaction and legal liability.

3. Failure case selection for LNG vessels

3.1. *LNG vessels overview*

LNG shipments began in the late 1950s. The first commercial trades started in the early 1960s and by the 1970s international trades had been established with the subsequent requirement for LNG carriers. The LNG trade has been fairly stable in this period, characterized by long term supply contracts. Bainbridge (2003) reports the world fleet of LNG ships as 146, and about half of these are over 20 years old. Around 60 more are on order. A little more than half of these are GTT membrane designs (GazTransport Technigaz), and the bulk of the remainder are spherical designs (Kvaerner Moss). The current large LNG vessel size is 125–138,000 m^3 LNG, and concept designs exist for sizes up to 240,000 m^3 of LNG. All these vessels employ a double hull with additional barriers between the hull and the LNG cargo not present for crude oil tankers. While this is no absolute guarantee of safety, the current LNG fleet has substantial operating history with the full range of challenges (grounding, transfer accidents, etc.) with no bulk cargo loss of containment. There have been three serious grounding accidents, one vessel under full load and two empty. No cargo was lost from the El Paso Kayser event (the loaded case) in 1979, which ran aground onto rocks at 17 kts. This was a very serious grounding event. The unloaded cases had either no damage to the LNG containment (LNG Taurus in 1979) or as yet undetermined damage (Tenaga Lima in 2004).

Several safety studies have been completed for LNG risks. These include: Fay [2] Lehr and Simecek-Beatty [3] ABS [4,5], DNV (Pitblado et al. [8]), and Sandia National Laboratories [18] for DoE. A study by Sandia National Laboratories for the DoE is expected soon. Many earlier safety studies were completed in the 1960s and 70s [6].

3.2. *Worst case event*

Several studies quote a hole size of 5 m from a single 25,000 m^3 LNG tank [2,4,7]. In effect the 5 m is a worst case as it can potentially empty an LNG tank in 2 min, faster than the EPA definition of worst case. No specific mechanism is suggested in these papers as to how a 5 m hole would be caused and this is a deficiency. Studies do not normally assess a rapid total loss of inventory from an LNG vessel (e.g. 125,000 m^3 in five tanks).

3.3. *Maximum credible event*

Pitblado et al. [8] describe the hazard identification approach that yields a several maximum credible events for different threat types. The basis for maximum credible event was the potential for a loss of cargo during the foreseeable future of LNG operations in the USA. This was taken to be 30 terminals, for 30 years, with 100 deliveries/year—about 100,000 loaded visits. The current operational history of LNG vessels is about 80,000 loaded port transits, very close to the foreseeable LNG activity in the USA. As noted there has not been a case of loss of cargo from the cargo tanks to date, thus the simple historical projection would say the expected hole size in USA activities might be zero. A Hazid session, involving close to 20 industry specialists, however identified several maximum credible events that have never happened. Five specific holes sizes were developed from the Hazid based on different threats. These were:

Table 1
Models run or quoted in this review

Model	Author	Version/date	Comment
PHAST	DNV	V6.4/2004	Similarity type, full consequence suite (source term, aerosols, pool formation, dispersion, pool fire), commercial code
DEGADIS	J Havens and Spicer	V2.1/1985	Similarity type, funded by US Govt, dispersion only—dense or neutrally buoyant, publicly available
HG-SYSTEMS	Shell	V3.0	Similarity type, source term, aerosols, dispersion, publicly available
SLAB	Lawrence Livermore	1988	Similarity type. Dense or neutrally buoyant releases, dispersion only, publicly available
CANARY	Quest	Published results	Similarity type, source term, aerosols, dispersion, commercial code
	Fay 2004	Published results	Manual model based on dimensional limits for pool spread and fire
	Lehr Simecek-Beatty 2004	Published results	Manual model based on pool formation and fire

1	250 mm	Maximum credible puncture hole
2	750 mm	Maximum credible hole from accidental operational events
3	1500 mm	Maximum credible hole from terrorist events
4	7000 m^3/h	Maximum credible operational spillage event (10 min)
5	10,000 m^3/h	Maximum credible sabotage event (60 min)

The approach did not use the finite element approach to estimate hole size. This is a preferred approach but time consuming. DNV used a judgment based approach developed by experienced classification engineers, proficient in collision and grounding studies using FEM methods. Valuable input from a parallel DoE study by Sandia National Laboratories looking also at terrorism events is acknowledged. These hole sizes tend to bracket around the 1 m hole size quoted in several of the papers that nominated the worst case 5 m event [2,4,7]. The Hazard identification could not identify a credible mechanism leading to a 5 m hole size.

3.4. Modeling

There are several types of model available for LNG modeling. These range from the simplest gaussian model, through simplified dense gas models (usually termed similarity models), through computational fluid dynamics codes. Gaussian models assume dispersion is dominated by atmospheric turbulence and ignore dense gas effects. For this reason they are not considered appropriate for dense gas dispersion consequences. Most work is done with various simplified models. There some current use of CFD codes for LNG and Havens et al. [9] report on preparatory wind-tunnel work he is carrying out to develop a suitable LNG optimized CFD code based on the FEM3C engine. Much work uses standard CFD engines (e.g. CFX, FLUENT, FLOW-3d) and then implements all the necessary equations in the code. CFD is potentially attractive as it directly employs the fundamental equations of fluid flow (Navier Stokes) and by working with a customized grid and boundary conditions local geographic features (shoreline, ship structure) can be included. However, there are many additional modeling issues that must be addressed and generally these aspects are less well validated and CFD is not yet a routine tool for LNG spill modeling.

The key features of public and proprietary models are well summarized by Hanna et al. [10] (in Tables7.1 and 7.2 of that text). Models run here or for which results have been published are listed Table 1. Caution should be used when quoting older model comparisons as many models, particularly the commercial codes, are updated regularly as part of a continuous improvement process, based on findings of previous validations. This was an important function of the benchmarking exercises carried out by Hanna and by Britter for example.

Britter [11] notes that a good dispersion model should predict concentrations downwind within a factor of 2 either way.

4. Validation for LNG spills on water

The European Model Evaluation Committee [11] set out its view that validation is more than simply matching experimental data. Three important aspects include:

Assessment	Does the model include the full range of phenomena and equations necessary to simulate all important mechanisms?
Validation	Does the model accurately predict concentrations obtained from suitable trials?
Verification	Does the model accurately implement the phenomena and equations it contains and does model development conform to good modern IT systematics (to avoid introducing errors)?

PHAST is one of the best validated consequence codes, with one or more validations of each aspect. A listing of validations is provided in Pitblado et al. [8]. The final aspect must not be underestimated in importance. DNV's experience with over 15 years of commercial support to PHAST with over 600 users is that every year bugs are reported and these must be addressed and closed out. It is not clear how some of the publicly available codes, which are not supported, address the issue of bug reporting and rectification.

4.1. Data sets

Hanna et al. [10] and Thyer [12] reviewed well known cryogenic gas validation trials. The best known trials and those used extensively for validation of LNG spills onto water include the work of Koopman et al. [13] and Goldwire et al. [14] of Lawrence Livermore in the US and Shell at Maplin Sands in the UK (e.g. [19]). Ten specific LNG onto water trials were available and have been used before for validation: Burro (trials 3, 7, 8, 9), Coyote (5, 6), and Maplin Sands (27, 29, 34, 35). These are all for LNG spills onto water. Weather conditions covered well unstable and neutral stability, but only one trial covered E stability, none cov-

Table 2
LNG spills on water validation results compared for four models

Trial	PHAST (%)	DEGADIS (%)	HGSYSTEM (%)	SLAB (%)
Burro 8	4.4	−6.0	−53.0	−10.0
Coyote 6	63.9	143.5	121.7	78.3
Maplin Sands 29	−32.2	16.7	27.8	−5.6
Mean bias	12.0	51.4	32.2	20.9

ered F stability. The scale of LNG spilled was mostly 10–20 m^3, well below the size of accidental or terrorism events modeled here.

4.2. *Results of trial comparisons*

Four models were run under the trial specifications for one case each from the three trials (see Table 2). Distances are measured at the most important concentration—the Lower Flammable Limit (LFL, taken as 4.4% methane in air). On average, all the models tended to over-predict these trial results, PHAST the least, the others longer. Coyote 6 was by far the most difficult trial to simulate for all the models.

PHAST was further run for all 10 trial cases and these results are summarized below (Table 3). This table shows several important results:

(1) All results fall within the accepted error band of a factor of 2 in either direction. (The highest deviation was +64% and the lowest was −47%.)
(2) The average bias was close to zero (here 8% under predicted versus 12% over predicted for the three trials quoted in Table 2).

Given the uncertainty in the data sets, DNV regards this as a good result. However, it is possible to achieve a zero bias on the validation data sets by running PHAST to 85% of the LFL rather than 100%. Thus, all further runs of PHAST are based on prediction to 0.85LFL rather than LFL.

Table 3
PHAST dispersion results for 10 LNG spill trials onto water (distances taken to LFL 4.4% methane)

Distance to LFL (m)			Actual		
Trial	PHAST	Field Exp.	Prediction	% Bias	LFL Fraction
Burro 3	256	210	Over Prediction	22	1.25
Burro 7	266	265	Good Prediction	0	1.00
Burro 8	522	500	Over Prediction	4	1.09
Burro 9	281	320	Under Prediction	−12	0.80
Coyote 5	255	250	Over Prediction	2	1.02
Coyote 6	377	230	Over Prediction	64	1.82
Maplin Sands 27	123	230	Under Prediction	−47	0.39
Maplin Sands 29	122	180	Under Prediction	−32	0.57
Maplin Sands 34	105	180	Under Prediction	−42	0.43
Maplin Sands 35	117	210	Under Prediction	−44	0.34
			Mean Bias	−8	

Fire validation was done for PHAST against the largest LNG fire trial—a 35 m diameter fire on land [15]. The model validated well (7% overprediction of downwind distance to 5 kW/m^2) and a similar under-prediction of the less important smaller cross wind thermal radiation distance. No correction was applied. Fires on water assume a 2.5× increase in burning rate compared to land (based on a median of published opinion) and this higher rate is used with no change to emissivity. This is likely to be conservative in prediction as a larger burning rate without a mechanism for extra air entrainment is likely to generate more smoke. Smoke absorbs thermal radiation within the fire, reducing the amount emitted externally, converting that into convective heat.

4.2.1. *Scenarios results*

DNV modeled all the events as a combination of spillage, pool formation and evaporation, dispersion to LFL, flash-back to source, sustained pool fire. This is shown in Fig. 1.

This full modeling scenario is pessimistic as it assumes that LNG spills will pour unignited onto the water and the LNG boil-off vapor (methane) will disperse to its maximum extent (lower flammable limit) and then be ignited. In reality factors affecting this are terrain (the shoreline may require the cloud if still heavy to rise rather than travel transversely), conversely if the cold methane has warmed sufficiently to become buoyant it may rise safely above ignition sources. A terrorist attack on the vessel using explosives or other weapons would be highly likely to lead to immediate ignition and at least the 1500 mm case would be most likely only to lead to a major fire, not to a dispersion event (see Table 4).

5. Comparison of results

What we see in the dispersion results is that at the LNG trial scale (10–30 m^3) most of the codes predict reasonably well, with PHAST a little better than the others, and generally PHAST predicts the longer distance trials better than the shorter trials. DEGADIS tends to predict longer distances than the other codes. For the full scale cases, the results are more different, with CANARY and PHAST predicting shorter distances than most the other codes.

DEGADIS predicts longer distances than PHAST for the validation trials and thus it is not surprising that it predicts longer on the accidental cases as well. Models are sensitive to the source term and parameters used. The authors obtained different results to ABS when running DEGADIS. The source term definition was not fully defined in ABS [5], and the surface roughness parameter specified was considerably larger than those in the validation work (10 mm versus 0.3 mm). Higher surface roughness would tend to reduce the dispersion distance. Surface roughness is not a physical measure of roughness dimension although it correlates with this.

HGSYSTEM and SLAB tended to predict higher than CANARY and PHAST for all runs, with SLAB predicting particularly long distances for F2 weather conditions. Canary predicts longer distances for D5 weather compared to F2 and this is a reverse of the trends reported by all the other models.

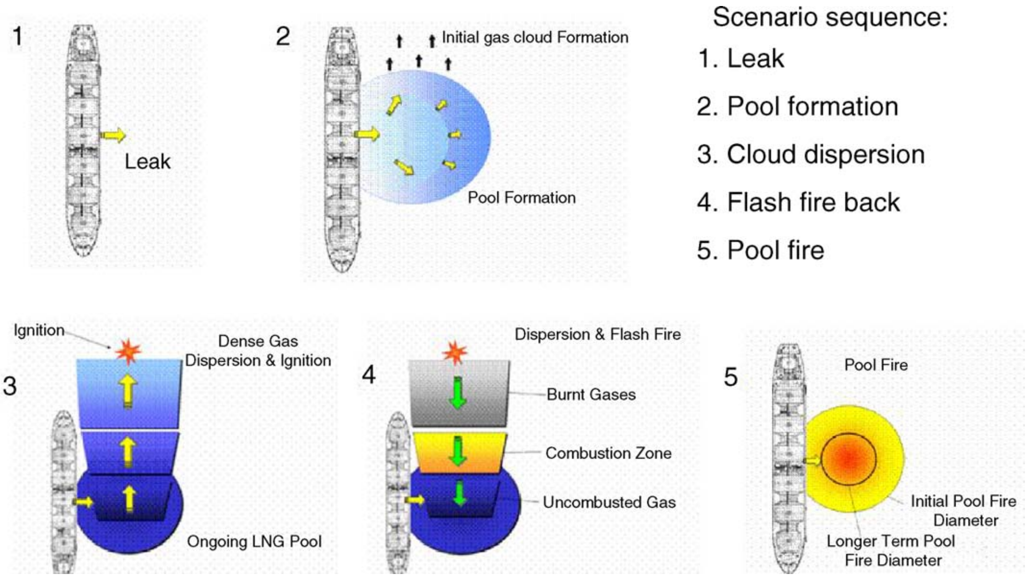

Fig. 1. LNG hazard scenarios for modelling.

Fire results were all generally similar for smaller events 0.75–1.0 m holes, with thermal radiation zones mostly in the range 440–690 m. There was a bigger divergence on larger events with PHAST and Fay similar for 1.5 m holes, but thereafter Fay and ABS differ significantly to CANARY. More recent work by Cornwell and Johnson [16] indicates that typical wave heights could reduce LNG pool diameters dramatically compared to flat surface assumptions. They do not predict the effect on dispersion or fire thermal hazard range from this revision.

Table 4
Comparison of model results for various cases of LNG release

Case	Model (results calculated by the authors here unless indicated otherwise)				
	PHAST	DEGADIS	HGSYSTEM	SLAB	CANARY (Cornwell 2001)
Dispersion results D stability 5 m/s weather					
10,000 m^3/h	790 m	1380 m	1250 m	1635 m	
0.75 m hole	920 m	1765 m	1740 m	2205 m	
1.0 m		2000 m ABS [5] D3			1000 m
1.5 m	2000 m	3150 m	3440 m	4500 m	
5.0 m					4080 m
Dispersion results F stability 2 m/s weather					
10,000 m^3/h	1600 m	2420 m	1690 m	4500 m	
0.75 m hole	1400 m	3250 m DNV	2460 m	7180 m	
1.0 m		3300–3400 m ABS [5]			780 m
1.5 m	3100 m	6700 m	4265 m	7910 m	
5.0 m		4100 m ABS [5]			3730 m

Case	PHAST	[2]	[5]	[3]	CANARY (Cornwell 2001 to 4.7 kW/m^2)
Pool fire results to 5 kW/m^2					
500 m^3 spill				500 m^3 + pool radius (7kW/m^2)	
0.75 m hole	440 m				
1.0 m			580–690 m		430 m
1.5 m	750 m	850 m			
3.4 m		1900 m (Fay)			
5.0 m			1500 m		540 m

Notes: Cases defined by hole size release ultimately around 70% of the cargo from a single 25,000 m^3 tank. All dispersion results for models calculated to LFL concentration except PHAST to 0.85 LFL (based on validation runs achieving a zero bias). PHAST, DEGADIS, HGSYSTEM, SLAB all run with same parameters and source terms, surface roughness 0.3 mm (as per the validation run specifications). Pool radius calculated based on the boiling rate of 0.085 kg/m^2 s for DEGADIS, HGSYSTEM and SLAB runs. The boiling rate is given by the analysis of the Shell Maplin Sands LNG release experiments [17]. ABS Update reports ABS calculated results for DEGADIS with their source term calculated separately, and surface roughness 10 mm CANARY F stability results reported for F1.5 m/s rather than F 2m/s Fay Fire result reported at 3.4 m diameter, calculated from his paper for 1.5 m.

Table 5
Proposed baseline cases for models used in LNG marine assessments

Validation scale: use Burro 3,7,8,9, Coyote 5,6 and Maplin Sands 27, 29, 34, 35, run models for dispersion only

Large Scale: use an amalgam of current cases reported by many current LNG workers, run these models for dispersion and pool fire results
a) Puncture case—leading to near instantaneous release of 500 m^3 LNG
b) Maximum credible event case (accidental release)—750 mm hole above waterline releasing all the cargo that can flow from the single largest tank
c) Maximum credible event case (terrorism)—1500 mm hole above waterline releasing all the cargo that can flow from the single largest tank
d) Maximum credible event case (jettison)—10,000 m^3/h for 60 min
e) Worst case event (single tank)—5000 mm hole above waterline releasing all the cargo that can flow from the single largest tank

Material—pure liquid methane
Weathers—cases should be run for D 5 m/s and F 2 m/s
Surface roughness—use 0.3 mm and 10 mm
Relative humidity −70%
Temperature −20 °C air and water
LFL—base on latest data from AIChE DIPPR = 4.4 vol%

Outcome:
Source term—discharge rate duration and total amount, pool diameter and thickness (maximum and event average), boil-off rate (maximum and event average)
Dispersion—distance to LFL
Fire—sustainable pool diameter for pool fire (maximum and event average), duration, and distance to thermal radiation predicted of 5 kW/m^2

6. Proposed benchmark cases for marine accidents

Given the importance of LNG terminal developments and uncertainties with large scale releases, many times greater than validation trials, it will be necessary to carry out larger scale trials rather urgently. However, such trials can take 2–3 years to organize, define the program, select the location, execute the program, analyze the results, and verify these with peer review. The authors do not believe that all development should halt until better data is collected. Many decisions on hazardous developments today are taken on less well established information, operational track record and operator/regulator toxic controls than applies to LNG developments. Examples include common toxic and pressurized gases and health risks (e.g. BSE).

The authors believe a way forward is to nominate specific cases to model (both trial scale and large scale) and any assessment using any model should run that model for the base cases, regardless of the specific cases in the assessment. This will allow those assessing the results to come to a view as to the likely bias (if any) in the results for the real cases selected for analysis. Given the difference in modeling results possible with a specific model (e.g. DEGADIS) the case specification should be sufficiently detailed to reduce as much as possible modeler discretion from the base cases. As models improve, and that must be an important objective, modeler discretion is necessary as extra information will be necessary to include (e.g. wave height, rapid phase transition effects, ice formation, transient effects, etc.) to initialize the better modeling. The authors propose the following cases (see Table 5).

7. Conclusions on decision making

There are many different models currently available and used for LNG assessments. These give varying results and those assessing LNG hazards should be aware of the differences.

ABS [4] and Pitblado et al. [8] list example areas of LNG uncertainties that will probably require large scale experimental trials to resolve. These will need to involve both the LNG vessel itself and its response to mechanical damages, and to the physical consequences of large LNG spills onto water. Some key issues with modeling currently include:

- Failure cases selected need careful consideration and justification
- Models are variable in results
- Some models are supported technically, others are not

Given the modeling challenges associated with LNG it would not be prudent to regulate a single model as this might inhibit innovation either in existing models or in possible CFD codes. Instead the authors propose a protocol of baseline cases, both at the trial validation scale and at realistic major event scale, which should be run for any model being used in LNG assessments. This will permit the users of such results to be able to benchmark the particular model used with other alternatives.

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