Breach and Safety Analysis of Spills Over Water from Large Liquefied Natural Gas Carriers

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Abstract

In 2004, at the request of the Department of Energy, Sandia National Laboratories (Sandia) prepared a report, "Guidance on the Risk and Safety Analysis of Large Liquefied Natural Gas (LNG) Spills Over Water". That report provided a framework for assessing hazards and identifying approaches to minimize the consequences to people and property from an LNG spill over water. The report also presented the general scale of possible hazards from a spill from 125,000 m^3 to 150,000 m^3 class LNG carriers, at the time the most common LNG carrier capacity.

Because of the increasing size and capacity of many new LNG carriers, the Department of Energy requested that Sandia assess the general scale of possible hazards for a breach and spill from newer LNG carriers with capacities up to 265,000 m^3. Building on the research and analyses presented in the 2004 report, Sandia reassessed emerging accidental and intentional threats and then conducted detailed breach analyses for the new large LNG carrier designs. Based on the estimated breach sizes, breach locations, and LNG carrier configurations, we estimated LNG spill rates and volumes and conducted thermal hazard and vapor dispersion analyses. This report summarizes the different analyses conducted, the expected range of potential hazards from a large LNG carrier spill over water, and risk management approaches to minimize consequences to people and property from such a spill.

ACKNOWLEDGEMENTS

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CFD	Computational fluid dynamics
CTH	Hydrodynamics Code 3-D
DOE	Department of Energy
DWP	Deep Water Ports
GAO	Government Accountability Office
FERC	Federal Energy Regulatory Commission
kW/m^2	kilowatts per square meter
km	kilometer – 1000 meter
Knts	Knots – 0.514 m/s
L/D	Height to diameter ratio
LFL	Lower flammability limit
LNG	Liquefied natural gas
LNGC	LNG Carrier
m	meters
m^2	square meter (area)
m^3	cubic meter (volume)
m/s	meters per second
psi	pounds per square inch
RLNGC	Regasification LNG Carrier
SRV	Storage and Regasification Vessel
USCG	United States Coast Guard
°C	degrees Celsius
°F	degrees Fahrenheit
°K	degrees Kelvin

1. EXECUTIVE SUMMARY

The demand for natural gas in the U.S. could significantly increase the number and frequency of marine liquefied natural gas (LNG) imports [EIA, 2003]. Because of the increased demand for natural gas, many LNG import terminals around the world are being designed to handle and operate with larger capacity LNG carriers. While studies have been conducted to assess the consequences and risks of potential spills from the current size and capacity of LNG carriers, no hazard studies have been conducted for the emerging larger capacity LNG carriers. Most current LNG carriers transport 125,000 m^3 - 145,000 m^3 of LNG in either four or five cargo tanks. Many new LNG carriers are being designed to carry up to 265,000 m^3 of LNG.

The increasing importance of LNG imports suggests that consistent methods and approaches be used to identify the hazards and protect the public and property from a potential LNG spill. For that reason, the U.S. Department of Energy (DOE), Office of Fossil Energy, requested that Sandia National Laboratories (Sandia) assess and quantify the potential hazards and consequences of a large spill from these emerging larger capacity LNG carriers. The effort undertaken for these larger LNG carriers was similar to that presented in the 2004 Sandia report "Guidance on Risk and Safety Assessment of Large Liquefied Natural Gas (LNG) Spills Over Water" [Hightower, et.al., 2004]. For this new effort, DOE specifically requested that Sandia:

- Reassess current threat considerations and recommendations from intelligence agencies for marine energy imports,

- Evaluate the potential breaching sizes and LNG spill rates and volumes for the larger capacity LNG carriers for both near-shore and offshore operations, and

- Assess the range of potential hazards from a spill from these larger capacity LNG carriers, and risk management considerations needed to improve public safety.

To support these efforts, Sandia worked with the U.S. DOE, the U.S. Coast Guard (USCG), LNG industry representatives, and government intelligence agencies to collect background information on ship and LNG cargo tank designs and the most recent credible breach scenarios. The information gathered was used to conduct detailed three-dimensional, dynamic, structural analyses of cargo tank breaching for various scenarios. These results were then used to calculate possible spill rates and volumes, and to model the associated hazards and consequences of the potential spills.

While a discussion of the specific threats and expected consequences is beyond the scope of this report, we do discuss the range of breaches that were calculated for these events. A detailed summary of the structural modeling conducted to calculate the potential breaches from various intentional events is presented in an associated report [Luketa, et al., 2008].

The hazard results developed were based on a range of nominal, or most likely, spill conditions and are not site-specific. Site-specific hazard distances will change depending upon the location of the facility, number, size, and type of LNG carriers or regasification vessels used, as well as environmental conditions. Therefore, the hazard results presented are intended to convey the scale of possible hazard distances for a large spill over water from emerging large capacity LNG carriers. While the major hazards expected from an LNG spill for the intentional events

considered are thermal hazards from a fire, vapor dispersion distances for potential spills were also calculated. Dispersion is significantly influenced by environmental conditions and potential ignition sources, and the information presented should again be used for identifying the scale of hazards, not necessarily be used for defining hazard distances for a specific site.

As noted in the 2004 Sandia LNG report, scenarios could include breaching of more than one LNG cargo tank during intentional events and was considered in these evaluations. Also, cascading damage to an adjacent LNG cargo tank from initial damage to one LNG cargo tank may be possible, based on current experimental data and modeling evaluations, and was considered. As discussed in the 2004 Sandia LNG report, while not considered the most likely LNG spill events, consideration of up to three tanks spilling at any one time is expected to provide a conservative analysis of possible cascading damage concerns and associated hazards.

Near-shore Operations
Based on these detailed analyses for emerging LNG tanker designs up to 265,000 m^3, the range of breach sizes calculated for credible intentional scenarios appropriate for near-shore operations, where there is waterway surveillance, monitoring and control, ranged between 2 – 12 m^2. Our analysis suggests that in these near-shore operations, the most likely or nominal intentional events would result in an LNG cargo tank breach of approximately 5 m^2. For this size breach in the larger LNG carriers, the spill rates and spill volumes increase slightly and therefore the thermal hazard distances are approximately 7–8% greater than the previous results presented in the 2004 Sandia LNG study for similar event considerations. This is due to the greater amount of LNG above the waterline, or hydrostatic head, and the larger LNG volumes per cargo tank for the larger LNG carriers. Even with the increase in thermal hazard distances from pool fires for the larger ships, the most significant impacts to public safety and property are still within approximately 500 m of a spill, with lower public health and safety impacts at distances beyond approximately 1600 m for near-shore operations.

Offshore Operations
For offshore operations, where there is less control and surveillance of ship operations, credible intentional scenarios can be larger and the calculated breach sizes can range from 5 – 16 m^2, with the most likely or nominal intentional breaching scenario resulting in an LNG cargo tank breach of approximately 12 m^2. For offshore LNG facilities where consideration of a breach size of 12 m^2 is appropriate, the most significant impacts to public safety and property are within approximately 700 m of a spill, with lower public health and safety impacts at distances beyond approximately 2000 m. Given the location of many proposed offshore facilities, these hazard distances suggest the potential for minimal impact to public safety or property from even a large spill from these larger capacity LNG carriers.

2. BACKGROUND

The increasing demand for natural gas in the U.S. could significantly increase the number and frequency of marine LNG imports. Net imports of natural gas into the U.S. are expected to grow from 0.5 trillion cubic feet in 2006 to 2.9 trillion cubic feet in 2030 [EIA, 2008]. Currently there are five operational LNG marine terminals. Four to eight new LNG terminals are expected to be constructed in the next four to five years and more than 40 new terminal sites are under consideration and investigation. A factor in the siting of LNG receiving terminals is the proximity to market. Therefore, terminals are being considered in areas with high natural gas demands, which include locations on all three U.S. coasts. Most are being planned to handle one to two LNG tanker shipments per week. A fleet of over 250 specially designed LNG ships is currently being used to transport natural gas around the globe. Worldwide, there are over 20 LNG export (liquefaction) terminals and over 50 import (re-gasification) terminals. This commercial network handles approximately 120 million tons of LNG every year. LNG carriers often travel through areas of dense traffic. In 2000, for example, Tokyo Bay averaged one LNG cargo every 20 hours and one cargo per week entered Boston harbor. Estimates are that world wide LNG trade will increase 35% by 2020. The major areas for increased LNG imports are Europe, North America, and Asia [EIA, 2008].

As LNG imports have increased in the U.S., safety and security concerns have been raised. In response to these concerns, background information on LNG properties, siting processes, and safety and security operations have been developed [FERC, 2004; DOE, 2005; USCG, 2005; Parfomak, 2003 and 2007]. While many studies have been conducted to assess the consequences and risks of potential LNG spills for the current class of LNG carrier, none has been conducted for the newer and larger capacity LNG carriers. Many of the current LNG carriers are designed to carry approximately 125,000 m^3 - 145,000 m^3 of LNG in either four or five cargo tanks. Because of the increased demand for LNG, many LNG import terminals around the world are being designed to handle and operate with LNG carriers with capacities up to 265,000 m^3.

The increasing importance of LNG imports suggests that consistent methods and approaches be identified and implemented to help ensure protection of public safety and property from a potential LNG spill. For that reason, the U.S. Department of Energy (DOE), Office of Fossil Energy, requested that Sandia National Laboratories (Sandia) assess and quantify the potential hazards and consequences of a large spill from these larger LNG carrier designs. The effort was similar to what was presented in the 2004 Sandia report "Guidance on Risk and Safety Assessment of Large Liquefied Natural Gas (LNG) Spills Over Water", for the current class of LNG carriers [Hightower et.al, 2004]. Specifically, DOE requested:

- An assessment of the current threat recommendations from intelligence agencies for marine energy imports,

- An evaluation of the potential breaching sizes for controlling intentional events against emerging large LNG carriers and potential spill rates and volumes, and

- An assessment of the potential range of hazards from an LNG spill over water from these larger capacity LNG carrier designs and potential risk management needs and considerations.

To support this effort, Sandia worked with the U.S. DOE, the U.S. Coast Guard, LNG industry groups, and government intelligence agencies to collect background information on ship and LNG cargo tank designs and breach scenarios. The information gathered was used to model potential breach sizes, associated spill rates and volumes, and the extent and severity of hazards to the public and property.

2.1 Overview of LNG Carriers

Specially designed ships are used to transport LNG to U.S. import terminals. Some of the special features of LNG ships include:

- Construction of specialized materials and equipped with systems designed to safely store LNG at temperatures of -260°F (-162.2°C).
- Constructed with double hulls. This construction method not only increases the integrity of the hull system but also provides additional protection for the cargo tanks in the event of accidents.
- Coast Guard regulations and the "International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk" (International Gas Carrier Code) require that LNG ships meet a Type IIG standard, which is an intermediate-level safety design standard for hazardous cargoes that includes requirements on double-hull designs and materials, subdivision, damage stability, and cargo tank location.

In general, LNG ships are classified according to the type of system that contains the LNG, either a Moss system or a membrane/prismatic system shown in Figure 1.

(a)   (b)
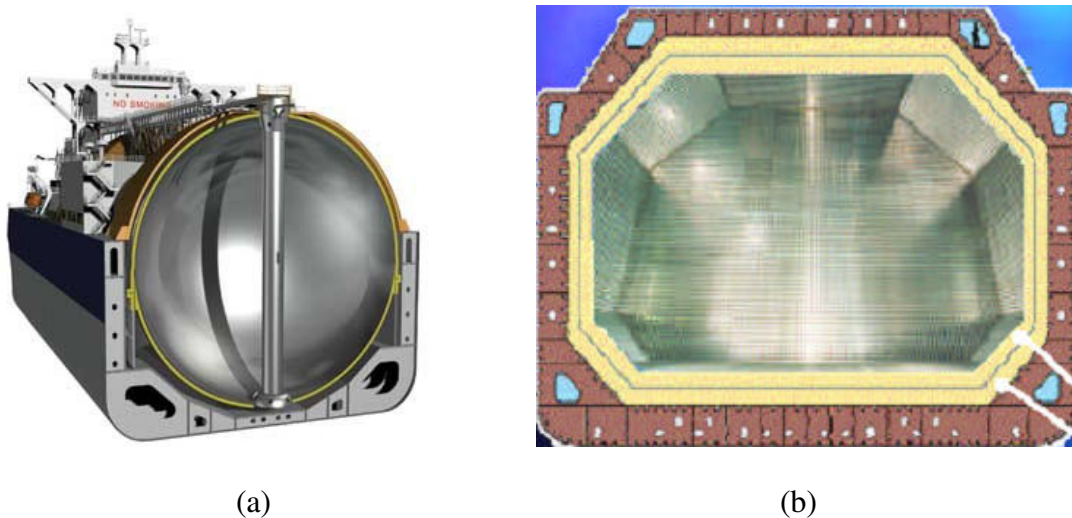
Figure 1. Typical Containment Systems for LNG Carriers

(a) Moss Spherical Design (b) Membrane/Prismatic Design

The difference between the two designs is that the Moss system use spheres built from aluminum that contain the LNG and have a structural integrity independent of the ship. For the membrane systems, the LNG is contained within thin, stainless steel membranes directly supported by the hull structure.

2.2 Size and Capacity of Emerging LNG Carrier Designs

Many new LNG carriers are being designed to carry as much as 265,000 m^3 of LNG. The new 215,000 m^3 membrane carriers are often referred to as Q-flex designs, and the 265,000 m^3 membrane carriers are often referred to as Q-max designs. Table 1 provides an overview of the general size and dimensions of current and emerging LNG carriers for both membrane and Moss-type cargo tank configurations.

Table 1. Emerging LNG Carrier Size and Capacity
(Poten and Partners, 2006)

CLASS	MEMBRANE DESIGNS			
	145,000 m^3	155,000 m^3	215,000 m^3	265,000 m^3
Tanks	4	4	5	5
Length (m)	283	288	315	345
Width (m)	44	44	50	55
Draft (m)	11.4	11.5	12	12
CLASS	MOSS DESIGNS			
	138,000 m^3	145,000 m^3	200,000 m^3	255,000 m^3
Tanks	5	4	5	5
Length (m)	287	290	315	345
Width (m)	46	49	50	55
Draft (m)	11	11.4	12	12.5

From the data presented in Table 1, a couple of key points should be noted. One is that the new larger LNG carrier designs are becoming longer and wider, not necessarily deeper. Because of channel depth limitations in many ports, the new ships are designed to have similar drafts as current LNG carriers. The overall heights are slightly greater with the tank height above the waterline about 20 m versus 15 m for current LNG carriers. Another point is that the volume of LNG per cargo tank is increasing from nominally 30,000 – 40,000 m^3 for the current fleet of carriers to as much as 53,000 m^3 for the larger LNG carriers. This means that spill rates and the spill volumes from the new large capacity LNG carriers could be larger.

There are several variations of the new larger capacity LNG carriers being developed. For example, several new LNG carriers are being designed to include regasification capabilities. With the advent of flexible pipeline and unloading buoy systems, gasification of LNG on the LNG carrier can now be conducted offshore and the natural gas pumped through a flexible riser system down to a sea floor natural gas pipeline and then onto shore. This enables LNG unloading to occur many miles offshore. In some cases this can provide alternatives to on-shore import terminals, which are being considered by the U.S. Coast Guard in several LNG DeepWater Port (DWP) applications.

The regasification configured carriers are commonly referred to as Regasification LNG Carriers (RLNGCs). Figure 2 provides a drawing of a planned 205,000 m^3 LNG regasification carrier. The main difference between an RLNG carrier and an LNG carrier is that the front cargo storage tanks are often reduced in size to accommodate regasification equipment in the bow, which reduces overall LNG storage capacity. This change in the size of the forward cargo tank can be

seen in Figure 2. The regasification equipment and buoy docking system reduce the average LNG cargo capacity by about 10,000 m^3 for both the 215,000 m^3 and the 265,000 m^3 membrane carriers. While an RLNG carrier contains less LNG, the overall structural design, size, and dimensions are very similar to the emerging large capacity LNG carrier designs, especially the membrane carriers noted in Table 1. Therefore, the results presented in this report are applicable to many of the large regasification LNG carriers being considered and proposed for use at many locations.
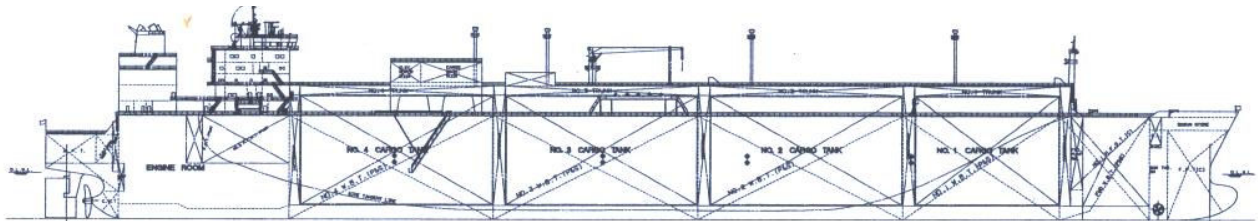
Figure 2. Example of a 205,000 m^3 Membrane Regasification LNG Carrier

A second variation of emerging, large-capacity LNG carriers are vessels commonly called Storage and Regasification Vessels or SRV's. These vessels often are designed to remain offshore and act as a floating LNG terminal. They are connected through a buoy and riser system, similar to the RLNGC system discussed above, to a sea floor natural gas pipeline that goes onto shore. The SRV's store LNG supplied and transferred from smaller LNG carriers, regasify the LNG on-board, and then pump the natural gas through the buoy and flexible riser system down to a sea floor natural gas pipeline. While many proposed SRV designs are similar to the emerging large capacity LNG carrier designs that were evaluated, some SRV's have unique designs, configurations, and operational characteristics developed for specific sites and needs. Therefore, while the results presented in this report may be applicable and representative of some SRV designs and configurations, they may not be applicable to others and site-specific assessments will be required to determine if the results presented in this report would be applicable to a specific SRV.

3. THREAT AND BREACH ANALYSES

The LNG shipping industry has an exemplary safety record, with only eight accidents over the past 40 years. None of these accidents have led to a loss of life or a breach of the vessel's cargo containment system. Even with this excellent safety record, consideration should be given to what might be a potential LNG cargo tank breach based on a possible accidental collision with another ship, grounding, or ramming. Based on the previous work on breach sizes for accidental events in the 2004 Sandia LNG study, it is clear that accidental events in near-shore LNG operations are smaller and much easier to mitigate through operational safety improvements than spills caused by intentional events. Therefore, for this report, DOE requested that Sandia focus on assessing the potential breach sizes, spills, and associated hazard distances for credible intentional events against emerging larger capacity LNG carriers carrying up to 265,000 m^3 of LNG.

3.1 Analysis of Intentional Threat Scenarios for Large LNG Carriers

For the 2004 Sandia LNG report, Sandia worked with intelligence groups and agencies and used historical data to establish a range of potential intentional LNG cargo tank breaches that could be considered credible and possible. This included evaluating information on insider and hijacking attacks on ships, as well as information on external attacks on ships. The level of knowledge, materials, and planning needed to create these types of intentional breaching events was also considered.

For this report, Sandia again contacted intelligence agencies and reviewed recent threat information in order to identify the most current estimate by the intelligence agencies of the credible intentional threats to consider in modeling breaching events against the larger capacity LNG carriers. The threats identified and considered included attacks with hand held munitions, attacks with explosives by a team of hijackers or attackers, attacks by boats and airplanes with and without explosives, underwater mines and explosives, as well as consideration of more sophisticated techniques. Additionally, with the development of LNG deepwater ports, threats against both near-shore and offshore operations and facilities were considered.

3.2 Analysis of Intentional Breaching of Large LNG Carriers

Based on the credible intentional threats identified, a series of scoping evaluations were conducted to identify the controlling threat scenarios that provide the highest spill rates and largest spill volumes and therefore create the largest hazard zones. For those scenarios and events identified, a series of very detailed, three-dimensional, shock physics-based analyses were conducted. Structural drawings of the large capacity LNG carriers obtained through LNG industry contacts were used to develop detailed three-dimensional models of the LNG carriers. The structural models included all major vessel structural elements including the inner and outer hull thicknesses and materials, all stiffeners and their dimensions and materials, and the frame and web dimensions, spacing, and materials. Figure 3 shows the type of structural elements included in the breach analyses.
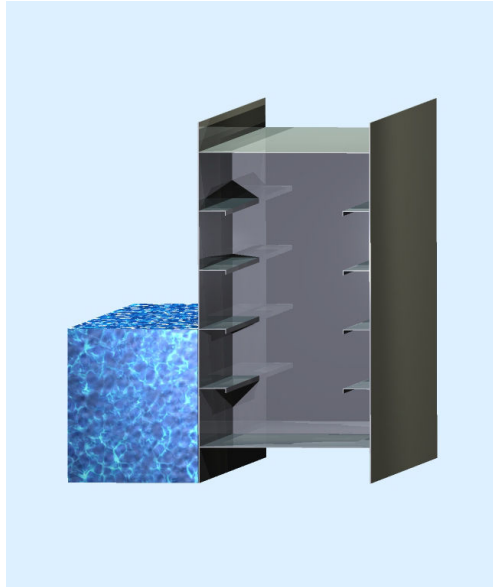
Figure 3. Example of Large Capacity LNG Carrier Structural Elements Modeled

Also included in the analytical model along with the inner and outer hull structural elements were the LNG cargo tanks, insulation, the LNG, and the sea water next to the outer hull. The breach analyses were conducted using a three-dimension shock physics code developed at Sandia called CTH. This computer code is capable of modeling multi-dimensional, multi-material, strong shock-wave controlled physics problems. This type of analysis approach is necessary to accurately model large-scale structural deformations and material responses under the very high strain rates that occur during many intentional threats such as high velocity penetration or explosion scenarios. The detailed three-dimensional breach analyses conducted required a massively parallel computing platform using 920 processors. Each analysis required approximately 2 to 3 weeks of computational time.

A number of different threats and threat locations were analyzed based on the controlling threat scenarios identified from the scoping studies. A summary of the detailed structural models and specific analysis results for each of the threat scenarios evaluated is presented in an associated report [Luketa et al, 2008].

Near-shore Operations Breaching Analysis Summary
Based on these detailed analyses for the emerging large capacity LNG tanker designs, the range of hole sizes calculated for credible intentional threats appropriate for near-shore operations, where there is waterway surveillance and control, ranged from $2 - 12$ m^2. Our analysis suggests that in these near-shore operations, the most likely or nominal intentional breaching scenarios would result in an LNG cargo tank breach of approximately 5 m^2. The overall results obtained were not significantly different from the breach results identified in the 2004 Sandia LNG report. This is for two reasons. First, the controlling intentional threats since 2004 have not increased significantly, and the general design of the larger LNG carriers are similar to current LNG carrier designs. While there are differences in the general size, dimensions, and thicknesses of many of the structural elements in the larger capacity LNG carriers, these structural differences only have

a minor impact on the breach size of the inner hull, which controls the rate of the LNG spilling onto the water.

Offshore Operations Breaching Analysis Summary
For offshore operations, where there is less waterway control and surveillance of ship operations, credible intentional threats can be larger and the calculated breach sizes can range from 5 – 16 m^2, with a most likely or nominal intentional breaching scenario resulting in an LNG cargo tank breach of approximately 12 m^2. This range of breach sizes should be considered for facilities or operations about 5 or more miles offshore, where surveillance, control, and risk management of both intentional and accidental events can be much more difficult.

Cascading Damage Spill Considerations
As noted in the 2004 Sandia LNG report, threats could include breaching of more than one LNG cargo tank during intentional events, and these types of multiple events were considered and the impact of the hazard results discussed in the following chapter. Damage to an adjacent LNG cargo tank from the initial damage to one LNG cargo tank could be possible, based on current experimental data and modeling evaluations, and was considered in our analyses. As discussed in the 2004 Sandia LNG report, multiple tank spills are not considered the most likely or nominal LNG spill event, but should be a consideration in developing risk management and mitigation approaches to LNG spills and associated hazards. Consideration of up to three tanks spilling at any one time is expected to provide a conservative analysis of possible multi-tank damage concerns and associated hazards.

4. LNG SPILL HAZARD EVALUATIONS AND RISK REDUCTION

The intent of the fire and dispersion analyses is to provide an understanding of the general scale of possible public safety hazards from larger capacity LNG carrier spills. It should be understood that this is not a site-specific analysis which takes into account environmental and surrounding conditions for a particular site. Thus, the results presented are not to be used prescriptively, that is, applied generally to any given site. For a given facility, an analysis which incorporates the particular environmental and facility conditions for that site should be performed as recommended in the 2004 Sandia report. The following discussions provide a general description of the models and assumptions used for the fire and dispersion hazard calculations presented in this report. A more detailed description of the models and approaches can be found in the 2004 Sandia LNG report.

Note that the experimental data for several parameters used in these analyses vary considerably. Due to the complexity of the physics involved and the lack of experimental data for an LNG spill and subsequent fire or dispersion event for the large spills expected, a parametric analysis of the sensitivity of different values over the range of applicable experimental data was considered. The various factors that contribute to the variation in LNG hazard analyses has been previously discussed [Hightower, et al., 2004, Luketa, 2006]. As additional experimental data is obtained, the conservatism in the approach used in this report could be reduced. The parametric approach and associated analyses though are useful in providing the scale and range of possible public safety hazards from spills from larger capacity LNG carriers. The analysis results presented can be used by government officials to identify the scale of potential hazards for LNG marine import operations.

4.1 Pool Fire Hazard Analyses

As discussed in the 2004 Sandia LNG report, a pool fire is the most likely outcome from the breach of an LNG tanker due to the high probability of immediate ignition of the LNG during the event. The extent of thermal damage to populations and structures from the radiated heat from a pool fire is a function of the total amount of energy received, which depends not only on the magnitude of the heat flux, but also on the area and the orientation of the receiving object relative to the fire, exposure duration, and material properties of the object. Thus, an assessment of the thermal hazards from a pool fire requires evaluating heat flux levels in terms of energy per unit time per unit area (or power per unit area) as a function of distance away from the fire and the fire's duration and the exposed surface area of a receiving object and its properties. The consideration of these quantities will allow for assessment of the total energy received and hence the extent of thermal damage.

For this analysis a solid flame model was used to predict thermal hazard distances at levels that would severely impact populations. A solid flame model represents the surface of the flame with a simple, usually cylindrical geometry. The thermal radiation is uniformly emitted from this surface and the average radiant surface emissive power is based upon empirical correlations with pool diameter. The geometric view factor is modeled, which is the fraction of radiant energy that is received by an object's field of view. The attenuation of the thermal radiation by water vapor and carbon dioxide in the atmosphere is included in the analysis.

The disadvantage of solid flame models is their inability to model more complex flame shapes such as those arising from irregular shaped pools or object interaction with the flame. Therefore, solid flame models are most appropriately used for sites where pool formation is not restricted, such as in wide or open waterways, harbors, bays, or open water. For sites where there are nearby shorelines or structures that can alter the nature of the pool spread and fire, such as modifying pool geometry or through fire interaction with structures, these models have diminished capability to predict hazards.

In contrast to an open waterway, the numerous structures comprising an urban environment can affect the distribution of thermal energy or radiated to people and structures. In some cases increased shielding can occur, thereby reducing the thermal energy received, or 'hot spots' from recirculation zones or reflecting surfaces can occur, thereby increasing the amount of thermal energy received. Additionally, the presence of obstacles can affect overall thermal hazards by providing additional fuel for latent fire propagation. For those cases where solid flame models are not appropriate for use, many computational fluid dynamics (CFD) based codes have the ability to model irregular pool geometries as well as fire and smoke propagation. However, to be used accurately, a CFD model should be validated for use in the specific application proposed.

It should also be noted that thermal damage is only one aspect of assessing the hazards arising from a LNG pool fire, especially in an urban environment. Smoke propagation can become a visibility hazard or a hazard when drafted in through ventilation systems of buildings. Human behavior during fire evacuations can influence the number of casualties/injuries and hence risks to the public since large populations and complicated pathways for exit can restrict effective evacuation efforts. All these factors are considerations in understanding the overall risks from an LNG pool fire in an urban environment, and therefore risk analysis and risk management should be coordinated with local public safety and emergency response organizations to reduce overall risks to the public and property for specific sites.

To determine the size of a pool fire, the amount of LNG draining over time from a breached tank, as well as the spreading of LNG on water must be calculated. The spilling and spreading of LNG onto water can be classified as a multi-phase, multi-component problem. In the event of a breach not only will there be LNG flowing out, but there can also be water entering the tank, the degree to which will depend upon the breach size and location. It is expected that any water entering the tank would be turned to ice and in the process would cause the LNG to vaporize. The amount of LNG spilled between the hulls will depend upon the breach size and location, as well as the framing design. The ability of the tank to maintain atmospheric pressure above the height of the LNG is also a consideration. Below we summarize our approach for analyzing each of these different elements of a spill and an associated sensitivity analysis to identify the scale and range of the potential hazards.

Most simplified models for the draining of LNG from a tank apply the Bernoulli's equation which neglects the effect of viscosity. Bernoulli's equation is a good approximation for large ratios of tank cross sectional to orifice areas (~100 or greater) since viscous effects will be negligible. There are free surface CFD-based codes that can model, using simplifying assumptions, the spilling and spreading of LNG onto water. However the Bernoulli's equation which was used for this analysis can provide a reasonable approximation for the rate of LNG

flowing out of a tank that is in accord with the intent of providing the general scale of the range of hazards from these events.

Once spilled onto the water, the shape and size of a spreading LNG pool can be affected by several factors: wind, waves, currents, confinement, composition, rapid phase transitions, and object interaction. Despite these complexities, in order to obtain an estimate of pool size, a steady mass balance can be utilized in which the mass flux of LNG flowing into the pool is balanced by the mass flux being evaporated. The results presented in this analysis used such an approximation. The pool will grow and then eventually shrink and break up after reaching a maximum diameter. The results presented pertain to the maximum pool diameter during spreading assuming an average flow rate from the tank.

It should be noted that the hydrostatic head and cargo tank volumes differ between the current and emerging larger LNG carriers. While the nominal LNG level in the cargo tanks extends approximately 15 m above the waterline for current LNG carriers, the LNG level for the larger LNG carriers is approximately 20 m above the waterline. Spill volumes for the larger LNG carriers are about 41,000 m^3. These result in slightly higher spill rates and larger spill volumes, which result in estimated pool diameters and associated hazards for the larger LNG carriers that are slightly larger than for the current class of LNG carriers.

As was done in the 2004 Sandia LNG report, nominal fire modeling parameters along with variations around the nominal case were used to calculate the thermal hazards. The justification for the range of values used can be found in the Appendix. Due to the non-site specific nature of the analysis, the affect of wind tilting the flame was not included. It should be noted that a minor modification to the calculation procedure from the 2004 Sandia LNG report has been made by way of incorporating an average among several flame height correlations instead of using a single flame height correlation. This approach was used because of the lack of large-scale data to identify the best correlation and results in about a 2% decrease in the average thermal hazard distance relative to past analyses. The flame height correlations considered and the approach is presented in the Appendix.

Tables 2 and 3 provide the results for thermal hazards from a pool fire for near-shore breach events and for offshore breach events respectively. The analyses present hazard distances for heat flux levels of 37.5 kW/m^2 and 5 kW/m^2. The 37.5 kW/m^2 value is a level at which process equipment is damaged after 10 minutes of exposure, and is currently considered to represent the extent of hazards to structures and equipment. The 5 kW/m^2 value is a level at which second-degree burns occur on bare skin after 30 seconds of exposure, and is currently considered to represent the extent of hazards to people in an open area.

The time and length scales for cascading cryogenic or thermal damage to additional LNG cargo tanks is unknown at this time because rapid multi-tank failures involve very complex physical process that will be an area of ongoing research for some time to come. In order to address the potential for cascading damage and possible hazard distances, an analysis of the breach and spill from three LNG cargo tanks at one time was conducted. Each tank breach assumes a similar hole-size with simple orifice flow. The assumption is that all tanks could possibly fail, which would affect the fire duration, but in the short timescales that it takes to reach a maximum fire

size from a large spill, only three tanks were considered to be contributing to the maximum size of the pool fire.

Near-shore Operations Pool Fire Hazard Analysis Results
For near-shore operations, the intentional breach cases considered for the emerging larger capacity LNG carriers are presented in Table 2. The average thermal hazard distance for the nominal or most likely breach size of 5 m^2 for a 41,000 m^3 spill is about 450 m for the 37.5 kW/m^2 level and 1400 m for the 5 kW/m^2 level. For comparison, the nominal hazard distance results presented in the 2004 Sandia LNG report for the smaller size LNG carriers for similar breach sizes at the 5 kW/m^2 level was about 1300 m. Thus, the increase in hydrostatic head and tank volumes for the larger capacity LNG carriers results in an approximately 7 – 8 % increase in the thermal hazard distances, and increased fire durations.

The results though indicate that the thermal hazard distances for the 37.5 kW/m^2 and 5 kW/m^2 heat flux levels for the larger LNG ships for near-shore locations are still expected to be within the 500 m and 1600 m hazard zones suggested in the 2004 Sandia LNG report. In Tables 2 and 3, "τ" is the atmospheric transmissivity, which is discussed in the Appendix.

Table 2. Thermal hazard distances from a pool fire for near-shore operations

HOLE SIZE (m^2)	TANKS BREACHED	DISCHARGE COEFFICIENT	BURN RATE (m/s)	SURFACE EMISSIVE POWER (kW/m^2)	τ	POOL DIAMETER (m)	BURN TIME (min)	DISTANCE TO 37.5 kW/m^2 (m)	DISTANCE TO 5 kW/m^2 (m)
INTENTIONAL EVENTS									
2	3	0.6	3×10^{-4}	220	0.8	225	57	282	881
5	3	0.6	3×10^{-4}	220	0.8	615	23	774	2197
5*	1	0.6	3×10^{-4}	220	0.8	355	23	446	1344
5	1	0.3	3×10^{-4}	220	0.8	251	46	315	975
5	1	0.6	2×10^{-4}	220	0.8	435	23	547	1487
5	1	0.6	8×10^{-4}	220	0.8	217	23	273	1042
5	1	0.6	3×10^{-4}	220	0.5	355	23	305	1050
5	1	0.6	3×10^{-4}	175	0.8	355	23	373	1188
5	1	0.6	3×10^{-4}	350	0.8	355	23	617	1683
12	1	0.6	3×10^{-4}	220	0.8	550	10	692	1981

*nominal case

Offshore Operations Pool Fire Hazard Analysis Results
For offshore operations, generally 5 of more miles offshore, intentional threats can be larger and as noted in Section 3 result in a larger nominal or most likely breach size of 12 m^2. The hazard distance results calculated for a 41,000 m^3 spill and a range of possible breach sizes for offshore operations for the larger LNG carriers are shown in Table 3. The results suggest that for offshore operations and associated breach events, the thermal hazard distance at the 37.5 kW/m^2 and 5 kW/m^2 heat flux levels are approximately 700 m and 2000 m, respectively.

Table 3. Thermal hazard distances from a pool fire for offshore operations

HOLE SIZE (m²)	TANKS BREACHED	DISCHARGE COEFFICIENT	BURN RATE (m/s)	SURFACE EMISSIVE POWER (kW/m²)	τ	POOL DIAMETER (m)	BURN TIME (min)	DISTANCE TO 37.5 kW/m² (m)	DISTANCE TO 5 kW/m² (m)
INTENTIONAL EVENTS									
5	3	0.6	3×10^{-4}	220	0.8	615	23	774	2196
12	3	0.6	3×10^{-4}	220	0.8	953	9.6	1090	3168
12*	1	0.6	3×10^{-4}	220	0.8	550	9.6	692	1980
12	1	0.3	3×10^{-4}	220	0.8	389	19	466	1429
12	1	0.6	2×10^{-4}	220	0.8	674	9.6	786	2335
12	1	0.6	8×10^{-4}	220	0.8	337	9.6	407	1261
12	1	0.6	3×10^{-4}	220	0.5	550	9.6	462	1539
12	1	0.6	3×10^{-4}	175	0.8	550	9.6	553	1738
12	1	0.6	3×10^{-4}	350	0.8	550	9.6	864	2452
16	1	0.6	3×10^{-4}	220	0.8	635	7.2	741	2202

*nominal case

4.2 Vapor Dispersion Analyses

For the controlling intentional breach events identified in this study, which cause the biggest breaches and largest spills, there is a high expectation that the events will provide secondary ignition sources that will provide ignition of any spilled LNG. Additionally, if a dispersion event does occur, the vapor cloud could ignite from ignition sources on the ship itself. Thus, the probability of a natural gas cloud fully extending, especially in a near-shore populated area where many ignition sources exist, and then igniting is very low. The cloud will most likely ignite when it comes in contact with the first available ignition source.

Since the possibility of a dispersion event though cannot be ruled out, dispersion calculations were performed to determine the distance to the lower flammability limit (LFL) for a vapor cloud from an un-ignited LNG spill from these emerging larger capacity LNG carriers. The LFL for natural gas can change slightly depending on the experimental conditions and measurement techniques used. For this analysis it is defined as a 5% concentration of methane in air by volume for ambient conditions [Liao, et al, 2005]. These calculations were performed using Vulcan [Nicolette, 1996, Holen, et al, 1990], a computational fluid dynamics (CFD) based code.

It should also be realized that the hazard zone area is elongated in the downwind direction from the spill point, rather than spread over a uniform circle, for a dispersion event. Therefore, dispersion distances and associated hazards are significantly influenced by site-specific environmental and operational conditions. For the analyses and information presented in this report, nominal environmental and atmospheric conditions were assumed. Therefore, the information presented should be used to identify the scale of possible dispersion hazards from a potential spill from the larger capacity LNG carriers, not necessarily for defining hazard distances for a specific site. For a site where dispersion issues may be a concern, a site-specific dispersion calculation should be conducted using wind, topography, and environmental conditions for that location to assess potential impacts on public safety and property. Guidance

on performing vapor dispersion calculations using CFD codes have been discussed by Luketa, et al., 2007.

Near-shore Operations Vapor Dispersion Analysis Results

The information presented is based on calculations performed for stable atmospheric conditions with a wind speed of 2.33 m/s for the near-shore intentional events that nominally cause a 5 m^2 breach of 1 tank spilling 41,000 m^3 of LNG, or approximately 70% of its contents. Dispersion analyses are more appropriate for the nominal single tank spill events. Multiple tank spills and large vapor dispersions are more unlikely due to the multiple ignition sources available for these events and the fact that cascading multiple tank spill scenarios are often from fire damage, such that an ignition source for most cascading spill scenarios is present. For the given spill volume and head, an LNG pool will be created that lasts for about 1380 seconds. The vapor generation and vapor flow conditions from the LNG pool were calculated using a liquid density of 450 kg/m^3 and a vapor density of 1.74 kg/m^3. Two values for evaporative mass flux were evaluated that span the range of experimental values reported in the literature, which vary by an order of magnitude. Table 4 indicates that the distance to the LFL ranges from 2800 to 3300 m with an average of 3050 m.

Table 4. Distance to the LFL for vapor dispersion for near-shore operations

POOL DIAMETER (m)	HOLE SIZE (m^2)	NUMBER OF TANKS	MASS FLUX (m/s)	DISTANCE TO LFL (m)*
290	5	1	4.5 x 10^{-4}	2800
917	5	1	4.5 x 10^{-5}	3300

*Assumes no Ignition source along path

Offshore Operations Vapor Dispersion Analysis Results

The information presented is based on calculations performed for stable atmospheric conditions with a wind speed of 2.33 m/s for the offshore intentional threat scenarios that nominally cause a 12 m^2 breach of 1 tank spilling 41,000 m^3 of LNG. Again, dispersion analyses are more appropriate to consider for the nominal single tank events. The larger spill rate will create a larger LNG pool but will last for only about 576 seconds. Again, the vapor generation and flow conditions from the LNG pool were based on a liquid density of 450 kg/m^3 and a vapor density of 1.74 kg/m^3, and two values of evaporative mass flux were used that span the range of experimental values noted above. Table 5 indicates that the distance to the LFL ranges from 4000 to 5200 m with an average of 4600 m. As noted, this distance will change depending upon the offshore facility design, operations, environmental conditions, and the number of ships that might be involved in an event. The analyses presented should be used as a guide on the scale of potential hazards, but site-specific analyses may have to be considered for many offshore operations because of the variability in operational scenarios.

Table 5. Distance to the LFL for vapor dispersion for offshore operations

POOL DIAMETER (m)	HOLE SIZE (m^2)	NUMBER OF TANKS	MASS FLUX (m/s)	DISTANCE TO LFL (m)*
450	12	1	4.5 x 10^{-4}	4000
1420	12	1	4.5 x 10^{-5}	5200

*Assumes no Ignition source along path

4.3 Hazard and Risk Reduction Considerations

Risk prevention and mitigation techniques can be important tools in reducing both the potential for a spill and the hazards from a spill, especially in zones where the potential impact on public safety and property can be high. However, what might be applicable for cost-effective risk reduction in one location might not be appropriate at another. Therefore, coordination of risk prevention and management approaches with local and regional emergency response and public safety officials is important in providing a comprehensive, efficient, and cost-effective approach to protecting public safety and property at a specific site.

Near-shore Operations
The analyses presented suggest that for near-shore operations, a nominal intentional event would result in an LNG cargo tank breach of approximately 5 m^2. For this size breach in the larger capacity LNG carriers, the spill rates and spill volumes increase slightly and therefore the thermal hazard distances are approximately 7–8% greater than the results presented in the 2004 Sandia LNG study for current LNG carrier designs. With this modest increase in thermal hazard distances, the most significant impacts to public safety and property for near-shore operations are still approximately 500 m of a spill, with lower public health and safety impacts at distances beyond approximately 1600 m. Also, potential vapor dispersion distances for near-shore operations are similar to those suggested in the 2004 Sandia report.

As such, the risk mitigation and risk management approaches suggested in the 2004 report are still appropriate for use with the larger capacity ships. Proactive risk management approaches can reduce both the potential and the hazards of such events. The approaches could include:
- Improvements in ship and terminal safety/security systems,
- Modifications to improve effectiveness of LNG tanker escorts, vessel movement control zones, and safety operations near ports and terminals,
- Improved surveillance and searches, and
- Improved emergency response coordination and communications with first responders and public safety officials.

Offshore Operations
For offshore operations, where there might be less surveillance or control, credible intentional threats could be larger, with a nominal breach size of about 12 m^2. From the analyses presented, the most significant impacts to public safety and property from an LNG spill and fire are within approximately 700 m of a spill, with lower public health and safety impacts at distances beyond approximately 2000 m. Vapor dispersion distances for a spill for these offshore operations for the larger capacity LNG carriers or regasification carriers could extend up to nominally 5000 m. Given the location of many of these proposed offshore facilities, the hazard distances suggest that there might be minimal impact to public safety or property from even a large spill. As such, risk management might best be directed at providing approaches, measures, or systems to ensure that the offshore facilities and operations are maintained sufficiently offshore such that they do not inadvertently or inappropriately impact near-shore public safety and property.

5. CONCLUSIONS

Because of the increasing size and capacity of many new LNG carriers, the Department of Energy requested that Sandia assess the general scale of possible hazards for a breach and spill from newer LNG carriers with capacities ranging up to 265,000 m³.   Building on the research and analyses presented in Sandia's 2004 LNG report, we reassessed emerging accidental and intentional threats and then conducted detailed three-dimensional breach analyses for several new large capacity (up to 265,000 m³) LNG carrier designs. Based on the estimated breach sizes, breach locations, and LNG carrier configurations, we estimated LNG spill rates and volumes and conducted thermal hazard and vapor dispersion analyses.

The results include analysis of the hazards of potential LNG spills at both near-shore and offshore facilities and operations, which should help improve the understanding of the range of hazards for different marine LNG import options. The results can be summarized as follows:

Near-shore Operations
- For the identified breach scenarios for near-shore LNG marine import operations, the calculated breach sizes to the inner hull range between 2 – 12 m². Our analysis suggests that intentional breaching scenarios would result in a nominal tank breach of 5 m².
- The estimated thermal hazard distances from a pool fire for the larger capacity LNG carriers are approximately 7–8% greater than the distances presented in the 2004 Sandia LNG study for near-shore operations. This is due to the greater amount of LNG above the waterline, or hydrostatic head, for the larger capacity LNG carriers versus current LNG carrier designs.
- Even with the increase in thermal hazard distances from pool fires for the larger ships, the most significant impacts to public safety and property are still within approximately 500 m of a spill, with lower public health and safety impacts at distances beyond approximately 1600 m.
- Based on current threats, it is possible that more than one LNG cargo tank could be breached. This includes cascading failure to adjacent cargo tanks from the initial damage. This type of damage is possible and should be considered as a variation of the nominal case in site-specific evaluations.
- While the most likely outcome of a large spill from an intentional event is expected to be a pool fire, a vapor dispersion analysis was conducted. The average distance to the vapor dispersion LFL from an LNG spill over water for a nominal 5 m² breach would be about 3,050 m. This result was obtained from the range of 2800 m - 3300 m obtained when considering a range of mass flux values.
- The likelihood of a natural gas cloud fully extending, especially in a near-shore urban area, and then igniting is very low. The cloud will most likely ignite from the first available ignition source and progress to a pool fire. For a dispersion event, the hazard zone area is elongated in the downwind direction from the spill point, rather than spread over a uniform circle.
- Pool fire and vapor dispersion hazard distances are significantly influenced by site-specific environmental, topographical, and operational conditions. The results presented use nominal environmental and operational conditions and can be used to identify the general

scale of possible hazards from a potential spill, but should not be used to define hazard distances for a specific site.

- For near-shore operations, risk prevention and risk management should be considered as ways to reduce the hazards to public safety and property, especially for near-shore operations.

Offshore Operations

- For the identified breach scenarios for offshore LNG marine import operations, the calculated breach sizes to the inner hull range between 5-16 m^2. Our analysis suggests that intentional breaching scenarios would results in a nominal tank breach of 12 m^2.
- The most significant impacts to public safety and property from pool fires are within approximately 700 m of a spill, with lower public health and safety impacts at distances beyond approximately 2000 m. The 2004 Sandia LNG study did not conduct threat, breach, and hazard analyses for offshore facilities, such as LNG deepwater ports or other offshore facilities, since these facilities were not in operation at that time.
- Based on current threats, it is possible that more than one LNG cargo tank could be breached. This includes cascading failure to adjacent cargo tanks from the initial damage. This type of damage is possible and should be considered as a variation of the nominal case in site-specific evaluations.
- While the most likely outcome of a potential LNG spill would be a pool fire, a vapor dispersion analysis was conducted. The average distance to vapor dispersion LFL from an LNG spill over water for a nominal 12 m^2 breach would be about 4,600 m. This result was obtained from the range of 4000 m - 5200 m obtained when considering a range of mass flux values.
- As noted above, the hazard zone area for a vapor dispersion event is elongated in the downwind direction from the spill point, rather than spread over a uniform circle and will likely ignite when it encounters the first ignition source. For offshore operations, there may be fewer ignition sources relative to near-shore operations.
- Pool fire and vapor dispersion hazard distances are significantly influenced by site-specific environmental and operational conditions. The results presented use nominal environmental and operational conditions and can be used to identify the general scale of possible hazards from a potential spill, but the wide variety of offshore facility designs, operations, and number of LNG ships and designs being considered suggest that the results presented should not be used to define hazard distances for a specific offshore facility.
- For offshore operations, risk prevention and risk management may have a different focus than near-shore operations, since many spills and associated hazards might not impact the on-shore public and property.

Overall, the results obtained from the more detailed analyses conducted and presented in this report for the emerging larger capacity LNG carriers are similar to the previous conclusions, recommendations, and guidance presented in the 2004 Sandia LNG report concerning the general scale of hazards to the public and property from a large LNG spill over water and approaches to reduce those risks and consequences.

APPENDIX

The following provides a discussion of the parameter values used to predict the thermal hazard distances from a large-scale LNG pool fire on water. It is recommended that the range of parameter values provided be incorporated into site specific analyses that use a solid flame model.

A1. Surface Emissive Power

The surface emissive power has been shown to initially increase with increasing pool diameter as indicated by the Montoir experiments on land for pool fires up to 35 m [Nedelka,1989; British Gas, 1988; Tucker, 1988]. There is indication that the surface emissive power asymptotes to a maximum value somewhere between 257 – 273 kW/m^2 when plotted as a function of pool diameter. The limit appeared to be reached near a pool diameter of 35 m, and thus the surface emissive power would not be expected to significantly increase for larger diameters. Beyond this maximum value, the surface emissive power would expect to decrease with increasing diameter due to greater smoke production. Smoke is made up of a mixture of gases, vapors, and particulate matter from a fire. Carbon particulates, or soot, is included as a particulate matter of smoke and is responsible for the luminosity of the fire. Smoke will absorb a significant portion of the radiation to result in much lower emission to the surroundings. Soot and smoke is a result of incomplete combustion which is affected by radiative losses and limited oxygen supply.

In the Montoir experiments, smoke shielding was observed in the upper half of the 35 m diameter LNG fires, while the lower half was highly emissive and essentially smoke free. This behavior is observed with heavier hydrocarbon fuels, but with smoke shielding occurring much closer to the fuel surface in an equivalent sized fire. The emissive power of black smoke is approximately 20 kW/m^2. Periodically the flame will break through the smoke, revealing areas of higher surface emissive power around 120 kW/m^2. Thus, for heavier hydrocarbons the time-averaged, area-weighted surface emissive power asymptotes to a value of about 40 kW/m^2. Thus, it would be expected that LNG, at some pool diameter, would display similar behavior, but the diameter at which this occurs is unknown due to lack of data at very large scales and cannot be predicted analytically based upon existing data sets.

Although it's expected that the average surface emissive power will drop below 200 kW/m^2 for pool diameters 100 m and greater, it is unknown by how much it will decrease. It is recommended that until additional data is obtained, due to safety considerations, a conservative value for surface emissive power should be used when applying a solid flame model by the range of values of ±50 kW/m^2 around 220 kW/m^2 based on existing data for LNG pool fires on water [Raj, 1979]. The maximum value of 350 kW/m^2 obtained from narrow-angle radiometer measurements from the Montoir tests could also be included as a data point for uncertainty analysis.

A2. Fuel Volatilization Rate

The fuel volatilization rate, herein called the burn rate, will affect the size of pool, with higher burn rates resulting in smaller pools. Higher burn rates also increase flame height, hence there is

a trade-off in the effect that burn rate has on thermal hazard distances. While a decrease in pool area will tend to reduce hazard distances, the increase in flame height will tend to increase hazard distances. However, the overall affect will be to decrease thermal hazard distances for increasing burn rates.

The only experiment able to obtain burn rate data for LNG pool fires on water are the tests funded by the USCG which reported calculated burn rates ranging from 4×10^{-4} to 11×10^{-4} m/s [Raj, 1979]. The calculations use the total quantity spilled divided by the approximate pool area and time of 'intense' burning to derive the burn rate. The volume spilled during steady state burning was less than the total volume of LNG spilled. By using the total volume of LNG spilled rather than the volume spilled during steady burning, higher burn rates are calculated. If burn rates are calculated based upon dividing the reported values for spill rate by the pool area, then burn rates vary from 2.6×10^{-4} to 9×10^{-4} m/s.

Since the burn rate is a function of the heat transfer from the flame and from the water, the range of burn rates for LNG pool fires on water can be estimated by combining data from pool fire experiments on land and un-ignited spill tests on water. The Montoir tests report an average mass burn rate of 0.14 kg/m^{2}s performed in wind speeds that ranged from about 3 – 10 m/s. The mass burn rate was calculated from dip tube measurements assuming a liquid density of 500 kg/m^3. This indicates a burn rate of 2.8×10^{-4} m/s for an LNG pool fire on land. It should be noted that uncertainties in the burn rate measurements were not provided. The range of values for mass flux derived from un-ignited LNG pools on water range from 0.64×10^{-4} to 4.3×10^{-4} m/s with no uncertainty values reported [Boyle, 1973; Burgess, 1970; Feldbaur, 1972; Koopman, 1978]. If these values are added to the Montoir data, the range of burn rate values for pool fires on water would be 3.4×10^{-4} to 7.1×10^{-4} m/s. The higher values in this range, above what was calculated from the LNG pool fire tests on water, could be due to inadequate measurements, differences in LNG composition, and different wind conditions. Pool fire tests conducted at China Lake and Sandia National Laboratories have indicated that wind speeds can significantly affect burn rate as shown in Figure A-1 [Blanchat, 2006 and 2002]. Thus, there is significant uncertainty concerning current burn rate data for LNG, and it is unknown what burn rates would result for pool diameters 100 m or greater.
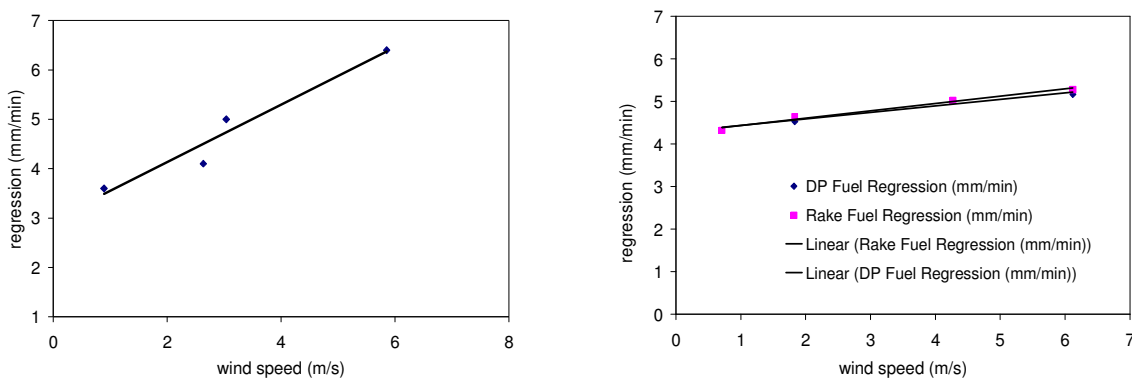
Figure A-1: Regression rates as a function of wind speed for (a) 18.9 m JP-8 pool fire, 4000 gallons, China Lake [Blanchat, 2006] and (b) 7.9 m JP-8 pool fire, 2200 gallons, Sandi[Blanchat, 2002].

It is recommended that a range of burn rates be used when applying a solid flame model by considering the range of 2 x 10^{-4} to 8 x 10^{-4} m/s.
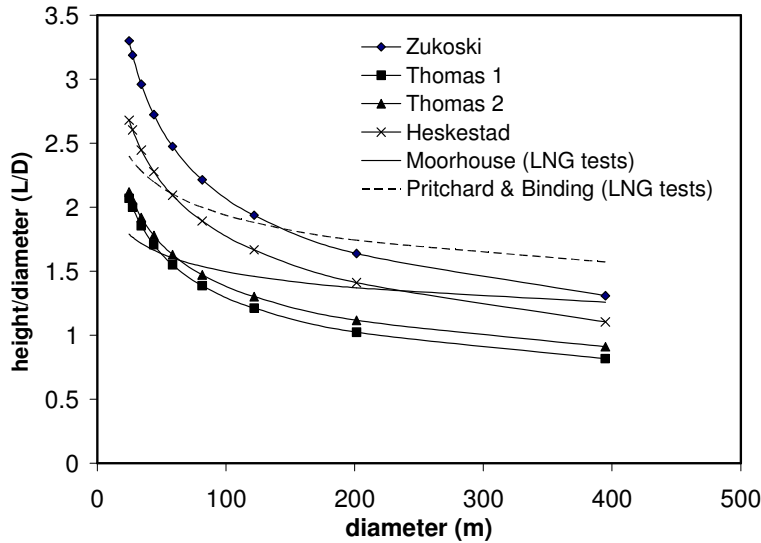
A3. Flame Height

There is great uncertainty in predicting flame height for large pool diameters for coherent fire plumes. Time-averaged flame height is usually defined as the height at which the intermittency reaches a value of 0.5, while maximum height is defined at an intermittency level of 0.05. Intermittency is defined as the fraction of time the flame is at a certain height. It has been demonstrated that the flame height of pool fires decreases for increasing pool diameters. It does become increasingly difficult to determine flame height for increasing pool diameters due to the obscuration of smoke and the periodic appearance of much higher temperature luminous zones.

Several flame height correlations based upon pool fires much smaller than the diameters presently considered have been developed. The majority of flame height correlations are based on a combination of flame height measurements and dimensional arguments such as the model by Thomas [Thomas, 1963], or experimental measurement combined with theoretical mathematical models such as the model by Steward [Steward, 1970]. Several correlations such as Moorhouse [Moorhouse, 1982] have based their correlation on Thomas's dimensional form. That is,

$$\frac{L}{D} = a \left[\frac{\dot{m}''}{\rho_a \sqrt{gD}} \right]^b \tag{1}$$

where L is flame height, D pool diameter, $\dot{m}''$ burn rate (kg/m^2 s), and ρ_a atmospheric air density.

The best fitting coefficients, a and b, for LNG fires from 29 tests ranging from 6.9 m to 15.4 m of equivalent pool diameters were identified by Moorhouse, while Thomas determined the coefficients with experimental data from wood crib fires up to 2 meters. It should be noted that LNG is very different than other hydrocarbons in its propensity to not produce as much smoke. Thus, correlations developed for hydrocarbons other than LNG may have significant error for predicted flame heights. In spite of similarities in fundamental approaches, a fascinating feature of these correlations is that they all predict different flame heights for any given hydrocarbon at a specified pool diameter. Predicted flame height to pool diameter ratios (L/D) for LNG can vary by a factor of 2 to 3 for a given pool diameter as shown in Figure A-2.

Figure A-2: Flame height correlations as a function of pool diameter for LNG.

There are at least twenty correlations, but only a few are plotted in Figure A-2 to indicate the range of disagreement. The variation among the correlations may be due to differences in the pool geometry tested and environmental conditions, as well as differences in the measurement technique and definition of flame height. It should also be noted that these correlations assume that the flame is characterized by a single temperature and gas composition regardless of the flame size or soot concentration in the flame. They also do not take into account fuel radiation properties, or turbulent mixing either from the mechanisms due to the fire or induced by the atmosphere. Thus, this justifies their classification of 'correlation' as well as their associated uncertainty.

Table A-1 shows a comparison among several flame height correlations and the largest LNG pool fire data sets. The burn rates reported from the experiments were used. From this comparison it would indicate that the correlation by Pritchard and Binding [Pritchard, 1992] is most appropriate for LNG, even at very large diameters, but caution should be used in coming to this conclusion since all of the correlations have been developed for a limited range of diameters and a large extrapolation could have significant error.

Table A-1: Comparison of several flame height predictions for LNG pool fire tests

Diameter (m)	Experiment (L/D)$_{AVERAGE}$	L/D predicted					
		Pritchard	Moorhouse	Thomas	Zukoski*	Steward*	Heskestad*
8.5 (test 1 china lake)	2.8	2.8	2.0	3.0	4.7	4.1	3.6
9 (test 4 china lake) (2.2 m/s)	2.8	2.6	1.9	2.5	3.9	3.7	3.1
20 (Mizner, Eyre - land) (6.2 m/s)	2.15	2.2	1.6	1.6	2.9	3.1	2.4
35 (Montoir) (9 m/s)	2.2	2.2	1.6	1.5	2.9	3.1	2.4

*no correction term for wind conditions

Since most correlations predict a flame height to diameter ratio between 1 and 2 for pool diameters 100 m and greater, it is recommended that when applying a solid flame model a range of L/D values of 1-2 be used. In this analysis, the correlations specified in Figure A-2 were used to obtain an average flame height as a function of pool diameter and burn rate.

A4. Flame Tilt and Drag

When pool fires are subject to wind they will tilt in the down wind direction and the base dimension of the flame will extend in the downwind dimension, also termed flame drag, while the upwind and crosswind dimensions remain unchanged. The affect of flame tilt and drag is to create an elliptical pool and increase the thermal hazard distances in the downwind direction.

Flame tilt and drag have been observed in both the Maplin Sands and Montoir LNG land tests, as well as the tests performed by Moorhouse [Moorhouse, 1982]. LNG pool fire land tests reported flame drag to be between 5 m and 10 m for a 20 m diameter pool in a wind speed of 6.16 m/s, with a flame tilt of 54 degree from vertical [Mizner, 1982]. The Montoir tests reported flame drag to be 10 m for a 35 m diameter pool in wind speed of 9-10 m/s, and 7 m for wind speeds of around 2 m/s [Nedelka, 1989;British Gas, 1988; Tucker, 1988]. The tilt decreased with increasing height, so that the tilt was about 50 degrees from vertical in the bottom portion of the flame (up to L/D ~ 0.5), and 35 degree from vertical for the remaining height. Thus, a single flame tilt value could not be used to describe the flame. From the China Lake tests on water, a flame tilt of 26.5 degrees from vertical was reported for test 4 in a 2.2 m/s wind [Raj, 1979]. For many tests the shape of the pool was observed to become elliptical. The correlations developed by American Gas Association [AGA, 1974], and Moorhouse [Moorhouse, 1982] to predict flame tilt and drag for integral models have been developed from LNG pool fire land tests.

It is recommended that an integral model include the flame drag and tilt for facility locations in which non-calm wind conditions exist. A variability of ± 30% of calculated values for flame tilt and drag should be included to account for the variability demonstrated from test data.

A5. Atmospheric Attenuation

The radiation that is emitted from a flame to the surroundings will be attenuated principally by absorption from CO_2 and H_2O in the atmosphere. Transmissivity is a measure of this attenuation and is a function of temperature and humidity since water vapor in the atmosphere depends upon temperature and relative humidity. It is very difficult to obtain accurate data on transmissivity because it depends upon knowledge of radiative spectral emission over the surface of the flame, as well as the absorption through the atmosphere to a receiving object. Thus, there is great uncertainty associated with transmissivity. Transmissivity curves are calculated based on LNG pool fires on water from the tests performed at China Lake and range from 0.4 to 0.9 for different humidity levels over a path length of 10,000 m [Raj, 1979]. The uncertainty associated with this calculation was not reported.

To account for experimental uncertainty, integral models should account for the variability of transmissivity by considering a range of values. Note that the transmissivity is a function of humidity and distance. Even though the level of uncertainty to incorporate is not known precisely, experiments conducted in outdoor environment will commonly have uncertainties

around ±30%. Thus, given a transmissivity function for a particular humidity level, a variability of ±30% should be considered. The upper bound value should not exceed the value of 1.

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