Safety and Risk Management of Large LNG Spills Over Water

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The increasing demand for natural gas in the U.S. could significantly increase the number and frequency of marine LNG (Liquefied Natural Gas) imports. While many studies have been conducted to assess the consequences and risks of potential LNG spills, 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.

While standard procedures and techniques exist for the analysis of the potential hazards from an LNG spill over land, no equivalent set of standards currently exists for LNG spills over water. This is due in part to the lack of large-scale data of LNG spills onto water, as well as the much more complicated physical and dispersion phenomena that occur when a very cold liquid such as LNG is spilled onto water. For that reason, the U.S. Department of Energy (DOE) requested that Sandia National Laboratories (Sandia) develop guidance on a risk-based analysis approach to assess and quantify potential threats to an LNG ship, the potential hazards and consequences of a large spill from an LNG ship, and review prevention and mitigation strategies that could be implemented to help reduce the possibility and risks to people and property of an LNG spill over water.

To support this effort, Sandia worked with the DOE, the U.S. Coast Guard, LNG industry and ship management agencies, LNG shipping consultants, and government intelligence agencies to collect background information on ship and LNG cargo tank designs, accident and threat scenarios, and standard LNG ship safety and risk management operations. Sandia developed a report, “Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water”, SAND2004-6258, that provides communities and agencies dealing with the marine import of LNG on the general scale of safety, security, and hazard issues of a large spill and how to focus risk prevention and risk management efforts[Hightower 2004].

The information and results presented in the Sandia LNG safety and risk analysis report are intended to be used as guidance for conducting site-specific hazard and risk analyses. The results are not intended to be used prescriptively, but rather as a guide for using performance-based approaches to analyze and responsibly manage risks to the public and property from potential LNG spills over water. This paper provides an overview of the guidance presented in the Sandia report and how it can be used to assess and manage site-specific hazards and risks from marine LNG imports.

Factors that Influence an LNG Spill

Figure 1 provides an artists rendering of the various factors or events that can occur during an LNG spill over water. First, an LNG cargo tank must be breached, either from an accidental event such as a collision or grounding or possibly from a malevolent or intentional event. Quantifying the likelihood and results of such events are very important because they influence the size and location of a possible breach, the potential volume of a spill, and the associated hazards. Many site-specific, and system-specific variables must be considered including; the LNG vessel size and design type, cargo tank geometry and construction materials, potential ignition sources, site-specific environmental factors such as waves, wind, and terrain, safety and security measures and operations, and emergency response plans and initiatives.

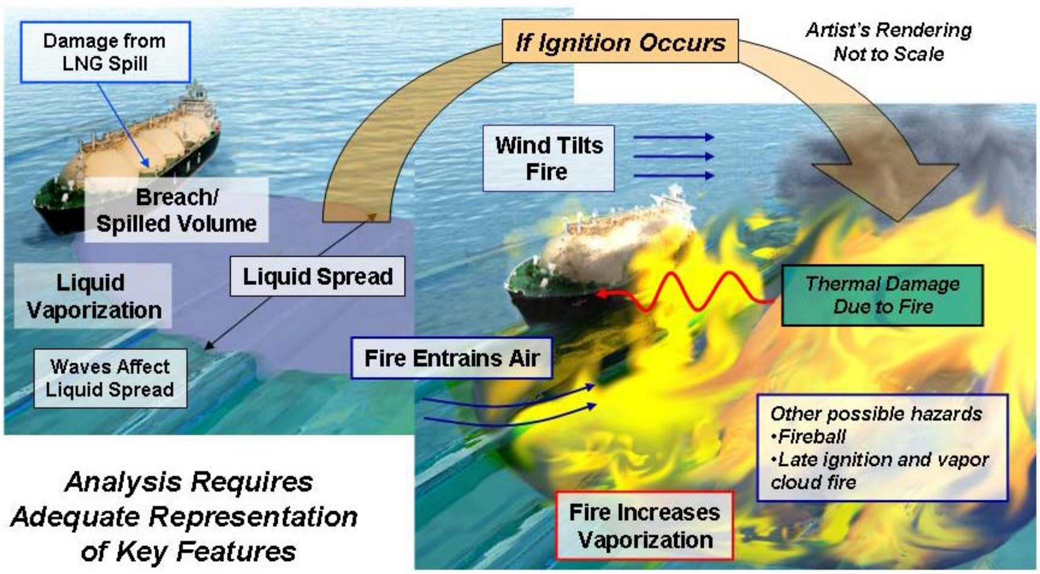

Figure 1. Key factors that influence an LNG vessel spill over water.

Depending on the size and location of an LNG cargo tank breach, LNG could spill onto or into the LNG ship, flow from the breach onto the water surface, or both. Depending on whether there is early or late ignition, LNG dispersion will occur through volatilization of the LNG from contact with water and be transported as a vapor cloud in the air or as a liquid on the water surface. The timing of a potential ignition will determine whether the LNG will disperse without a fire, burn as a pool fire, or burn as a vapor fire.

These factors can each significantly influence the estimates of the hazard distances and hazard levels for an LNG spill and each should be carefully assessed for each site. For example, an evaluation of several recent LNG spill studies showed significant differences in thermal hazard estimates due to differences in assumptions and modeling approaches used in each analysis [Lehr and Simecek-Beatty 2003][Fay 2003][Quest 2003][Vallejo 2003][Pitblado 2004].

Example of Potential Hazards from Large LNG Spills over Water

To provide the general scale of the potential hazards of a large LNG spill over water, existing experimental data were evaluated and analysis and modeling were used by Sandia to assess several potential spill hazards including; asphyxiation, cryogenic burns and cryogenic damage to the ship from the very cold LNG, dispersion, fires, and explosions. Available accidental and intentional threat information was used to identify possible breaching scenarios. Based on this review, the most likely hazards to people and property are thermal hazards from an LNG fire. Cryogenic and fire damage to an LNG ship were also identified as concerns that could cause additional damage to LNG cargo tanks following an initial cargo tank breach.

To help the public get a feel of the expected scale and range of the hazards from a large LNG spill over water, the hazard distances for several possible accidental and intentional breach scenarios of a standard LNG vessel, holding 125,000 – 140,000 m^3 of LNG, for generally stable atmospheric conditions were evaluated by Sandia and are presented in the guidance report. The results consider spill volumes of one-half the contents of a standard LNG cargo tank, approximately 12,500 m^3, for each LNG cargo tank breached. The range of the results, based on different assumptions and various spill parameters, are presented in Table 1 for thermal fire hazards. Most intentional events are expected to provide an ignition source such that a pool fire occurs and the likelihood of a large unignited release of LNG is unlikely. Table 2 though, provides information on possible hazard distances for a spill with a significant delay in ignition of the LNG. The 37.5 kW/m^2 and 5 kW/m^2 values shown in Table 1 are thermal flux values commonly recognized for defining hazard distances for LNG [NFPA 2001]. The 37.5 kW/m^2 is a level suggesting severe structural damage and major injuries if expected for over 10 minutes. The 5 kW/m^2 is a level suggesting second-degree skin burns on exposed skin if expected for periods of over about 20 seconds, and is the value suggested as the protection standard for people in open spaces. The distances shown in Table 2 are to the lower flammability limit (LFL) the lowest level at which LNG will burn. The LFL value is commonly used as the maximum hazard distance for a vapor dispersion fire.

Table 1: Potential Thermal Hazard Distances for Possible Breaching Events of a Standard LNG Vessel

HOLE SIZE (m^2)	TANKS BREACHED	DISCHARGE COEFFICIENT	BURN RATE (m/s)	SURFACE EMISSIVE POWER (kW/m^2)	POOL DIAMETER (m)	BURN TIME (min)	DISTANCE TO 37.5 kW/m^2 (m)	DISTANCE TO 5 kW/m^2 (m
ACCIDENTAL EVENTS								
1	1	.6	$3X10^{-4}$	220	148	40	177	554
2	1	.6	$3X10^{-4}$	220	209	20	250	784
INTENTIONAL EVENTS								
5	3	.6	3×10^{-4}	220	572	8.1	630	2118
5*	1	.6	3×10^{-4}	220	330	8.1	391	1305
5	1	.9	3×10^{-4}	220	405	5.4	478	1579
5	1	.6	8×10^{-4}	220	202	8.1	253	810
12	1	.6	3×10^{-4}	220	512	3.4	602	1920

* nominal case considered

Table 2: Potential Lower Flammability Limit (LFL) Distances for Possible Vapor Dispersions

HOLE SIZE (m^2)	TANKS BREACHED	POOL DIAMETER (m)	SPILL DURATION (min)	DISTANCE TO LFL (m)
Accidental Events				
1	1	181	40	1536
2	1	256	20	1710
Intentional Events				
5	1	405	8.1	2450
5	3	701	8.1	3614

While these results show the general range of hazards for spills from common LNG vessels, larger vessels are being considered for offshore ports, and larger spills could occur. Examples of hazard distances for spills from larger vessels are presented in a Sandia report [Hightower 2006]. The results show the scale of the concerns, but actual hazard distances will vary based on site-specific environmental conditions, fire dynamics, terrain, ship sizes, and safety and emergency response measures in place.

Risk Management for LNG Operations over Water

While it is important to assess the possible hazards from a large LNG spill over water, it should be noted that the risks and hazards from a potential LNG spill can be reduced in many cases through a combination of safety and risk mitigation approaches, including 1) reducing the potential for a spill, 2) reducing the consequences of a spill, or 3) improving LNG transportation safety equipment, security, or operations to prevent or mitigate a spill.

For example, a number of international and U.S. safety and design standards have been developed for LNG ships to prevent or mitigate an accidental LNG spill over water. These standards are designed to prevent groundings, collisions, and steering or propulsion failures. They include traffic control, safety zones around the vessel while in transit within a port, escort by Coast Guard vessels, and coordination with local law enforcement and public safety agencies. These efforts have been exemplary, and in over 40 years of LNG marine transport operations there have been no major accidents or safety problems either in port or on the high seas [Pitblado 2004]. In addition, since September 11, 2001, additional security measures have been implemented to reduce the potential for intentional LNG spills over water. They include earlier notice of a ship's arrival (from 24 hours to 96 hours), investigation of crew backgrounds, at-sea boardings of LNG ships, special security sweeps, and positive control of an LNG ship during port transit.

Risk prevention and mitigation techniques are important tools in reducing both the potential for and the hazards of a spill, especially in zones where the potential impact on public safety and property can be high. The general risk management process recommended is discussed in detail in the Sandia report and a flow chart of the process is presented in Figure 2.

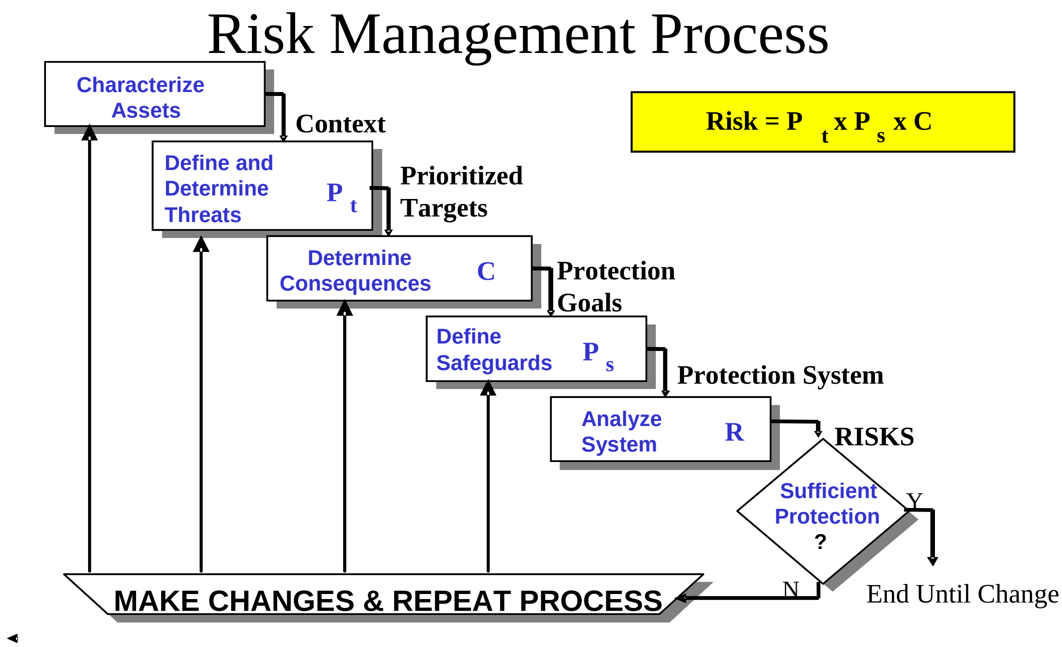

Figure 2. Risk Analysis and Risk Management Process Approach

The risk analysis process helps support a program for managing risks to the public of marine LNG imports. The process steps as shown in Figure 2 include:

- Evaluating the potential for an event that could cause a breach or loss of LNG from a ship;
- Establishing the potential damage to a cargo tank or other system from these events and the potential spills that could occur;
- Estimating the volume and rate of a potential LNG spill based on the dimensions and location of the breach, properties and characteristics of the LNG, ship construction and design, and environmental conditions (e.g., wind, waves, currents, etc.);
- Estimating the dispersion, volatilization, and potential hazards of a spill based on site-specific physical and environmental conditions; and
- Identifying prevention and mitigation approaches and strategies to meet identified protection goals and risk management goals.

As illustrated in Figure 2, if risks, costs, or operational impacts are deemed to be too high such that sufficient protection can not be provided to meet defined protection goals for the site, the overall process cycles back through the evaluation to identify alternative approaches for improving system performance and protection. Proactive risk management approaches can help reduce both the potential for and hazards of such events and include:

- Improvements in ship and terminal safety/security systems – including improved surveillance, tank and insulation upgrades, tanker standoff protection systems,

- Modifications and improvements in LNG tanker escorts, extension of vessel movement control zones, and safety operations near ports and terminals,
- Improved surveillance and searches of tugs, ship crews, and vessels,
- Redundant or offshore mooring and offloading systems, and
- Improved emergency response systems to reduce fire and dispersion hazards and improved emergency response coordination and communication.

The risks can be re-evaluated according to the new approaches to determine if they meet the identified protection and risk goals. If not, then the evaluations are repeated with additional provisions or changes until the protection and risk goals are reached. The potential alternatives, changes, and/or upgrades can be compared through the process to identify the most appropriate and cost-effective approaches for improving overall system safety and security. Deciding on the sufficiency of protection measures to meet risk management goals is often aided by a benefit-cost evaluation, with measures matched to risk levels as shown in Table 3. For most locations and operations, some level of risk is common and, therefore, a "residual" risk often remains.

Table 3: Representative Examples of LNG Spill Risk Reduction Options

IMPACT ON PUBLIC SAFETY	REDUCTION IN EVENT POTENTIAL (Prevention)	IMPROVE SYSTEM SECURITY AND SAFETY (Mitigation)	IMPROVED HAZARD ANALYSIS (Reduce Analytical Uncertainties)	RESULTANT RISK REDUCTION
High and Medium	▪ Early off-shore interdiction ▪ Ship inspection ▪ Control of ship, tug and other vessel escorts ▪ Vessel movement control zones (safety/security zones) ▪ One-way traffic ▪ LNG offloading system security interlocks	▪ Harbor pilots ▪ Ship and terminal safety and security upgrades ▪ Expanded emergency response and fire fighting to address fires, vapor clouds, and damaged vessels	▪ Use of validated CFD models for LNG spill and thermal consequence analysis for site specific conditions ▪ Use of CFD and structural dynamic models for spill/structure interactions	Combination of approaches to reduce risks to acceptable levels
Low	Use of existing best risk management practices on traffic control, monitoring & safety zones	Use of existing best risk mitigation practices to ensure risks remain low	Use of appropriate models to ensure hazards are low for site-specific conditions	Combination of approaches to ensure risks are maintained at acceptable levels

The risk management approach presented is performance-based and should include identification of site-specific hazards and risks and site-specific public and property protection goals. What might be applicable for effective risk reduction in one location might not be appropriate in another. Therefore, risk management must be balanced between public protection goals, emergency management capabilities and other resources, and overall hazards relative to other local industrial operations and activities. For this reason, risk identification and risk management processes should be conducted in cooperation with appropriate stakeholders, including public safety officials and elected public officials. Considerations should include site-specific conditions and needs, available intelligence, threat assessments, safety and security operations, and available resources.

Summary of Guidance on Risk Management for Marine LNG Transport

Based on public safety issues and risk mitigation and prevention considerations, Sandia developed guidance to assist risk management professionals, emergency management and public safety officials, port security officials and other appropriate stakeholders in developing and implementing appropriate safety and risk management strategies and processes for marine LNG import operations. In summary, the guidance recommends for accidental and intentional spills:

- Use effective security and protection operations that include enhanced interdiction, detection, delay procedures, risk management procedures, and coordinated emergency response measures, to reduce the risks from a possible breaching event;
- Implement risk management strategies based on site-specific conditions and the expected impact of a spill on public safety and property. Less intensive strategies could often be sufficient in areas where the impacts of a spill are low.
- Where analysis reveals that impacts to public safety and property could be high and where a spill could interact with terrain or structures - modern, validated Computational Fluid Dynamics models - can be used to improve hazard analyses.

Although current spill assessment and modeling techniques and validation of models against large-scale LNG spill data have limitations, the guidance provides a performance-based hazard and risk management approach. As additional LNG spill data are obtained, they can be incorporated into future risk analyses. The risk assessment and management process can be used in conjunction with existing spill and hazard analysis techniques, and safety and security methods, to assess and help reduce the risks to both the public and property from a potential large LNG spill over water for any size vessel or location.

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