

4 ACCIDENTAL LNG BREACH, SPILL, AND HAZARD ANALYSES

Currently, the potential for an accidental LNG cargo tank breach, the dynamics and dispersion of a spill, and the hazards of such a spill, are only generally understood because the combination of LNG ship designs and current safety management practices for LNG transportation have reduced LNG accidents to a level such that there is little historical or empirical information on breaches or spills.

This lack of information forces analysts to make many assumptions and simplifications when calculating the size, dispersion, and thermal hazards of a spill, as discussed in Section 3 and detailed in Appendix A for four recent LNG spill studies. Therefore, it should be understood that while many existing models and techniques can be used to provide adequate guidance on the hazards of an LNG spill, a level of variability can exist in estimating the potentiality and size of a breach and the extent of the hazards from an associated spill.

This section summarizes the modeling and analyses conducted to assess the potential for an accidental breach of an LNG cargo tank, the probable size of a potential accidental breach, and the associated spill size and hazards to people and property from a resulting spill. The detailed results of these analyses are presented in Appendices B – D.

4.1 Analysis of Accidental Breach Scenarios of an LNG Cargo Tank

As noted in Section 2 of this report, the LNG industry has an exemplary safety record, with only eight accidents over the past 40 years. None of these accidents led to a loss of life. Even with this excellent safety record, consideration should be given to what might be a likely LNG cargo tank breach based on a potential accidental collision with another ship, grounding, or ramming. The severity of a breach based on these events depends on the location, vessel design, relative vessel speeds and collision alignment, and mitigation or prevention systems in place to limit potential damage.

Using previously conducted finite element modeling of collisions of a series of ships with a double-hulled oil tanker similar in overall size, mass, and design to an LNG vessel, we were able to estimate the level of damage and hole sizes expected for several different accident scenarios [Ammerman 2002]. These analyses were conducted using PRONTO-3D, a transient dynamic, explicitly integrated, Eulerian finite volume code. The analysis tracked the progressive failure of the struck ship as the striking ship penetrated and the results are discussed and presented in detail in Appendix B. The results show that breaching of the inner hull does not occur until impact velocities exceed approximately 5 – 6 knots for large vessels. For small vessels, such as pleasure craft, the kinetic energy is generally insufficient to penetrate the inner hull of a double-hulled vessel such as an LNG ship. This analysis also calculated that penetration into a double-hulled tanker must be approximately three meters before a hole occurs in the inner hull, which can be used to estimate the minimum size of a penetration to cause a spill in a grounding event.

Because of the additional insulation and third level of containment in many LNG vessels, it is expected that a deeper penetration would be required to rupture the primary LNG cargo tank. Therefore, because of its general design and construction, collision velocities for equivalent hole sizes could be expected to be one to two knots higher for an LNG vessel. This would suggest that the required velocity to cause a breach of an LNG cargo tank during a 90 deg collision with a large vessel could be six to seven knots.

After a collision with an LNG tanker in which LNG is pouring out, the striking ship would probably back out, unless it could not move. In many collisions between two ships, the ships can remain joined for several hours, if significant penetration of one ship occurs. The analysis by Ammerman discussed in Appendix B suggests that as little as 5% – 10% of the generated breach size would be available for the release of LNG. Therefore, the collision of a large ship with an LNG carrier at even 10 knots is expected to produce an effective hole size of no more than approximately one square meter for an LNG spill.

The size and location of potential breaches were used as a basis for analysis of the potential for cryogenic damage to the structural steel of an LNG ship from a spill. Contact of steel with cryogenic fluids is known to cause embrittlement, which can significantly reduce the strength of steel [Vaudolon 2000]. A detailed structural analysis was beyond the scope of this review; but structural integrity embrittlement scoping analyses were conducted to assess the potential damage to an LNG ship from small and large LNG spills based on available fracture mechanics data and models. These analyses were guided by available information on LNG ship and tank designs, construction, and structural steel material property data [Linsner 2004] [Shell 2002] [Wellman 1983] and are discussed in detail in Appendix D.

In general, the results suggest that the critical flaw size for cryogenic damage of common LNG ship steels is less than one-tenth of an inch. It is common to see flaws of this size in typical, welded construction or around corrosion areas. Therefore, it is expected that some cryogenic damage of the LNG vessel, even for some accidental spills, would be likely. The extent and impact of the damage will depend on the breach and spill size and location and effectiveness of risk prevention and mitigation strategies and should be considered relative to overall ship integrity and LNG cargo tank support integrity.

A summary of the potential breach size and potential ship damage from several different accident scenarios is presented in Table 9, based on the detailed analyses presented in Appendices B and D.

Table 9: Estimated LNG Cargo Tank Breach Sizes for Accidental Scenarios

ACCIDENTAL BREACHES			
Type	Breach Size	Tanks Breached	Ship Damage
Accidental collision with small vessel	None	None	Minor ^b
Accidental collision with large vessel	5 - 10m ² (Spill area 0.5 – 1m ²) ^a	1	Moderate ^c
Accidental Grounding	None	None	Minor

Notes: a - Assumes vessels remain joined during spill event and breach is mostly plugged
b - Minor suggests ship can be moved and unloaded safely
c - Moderate suggests damage that might impact vessel and cargo integrity

The potential breaching of an LNG cargo tank due to an accident, such as a collision or grounding, appears to be minimal. Such a breach can be easily reduced through a number of operational mechanisms, including managing ship traffic, coordinating ship speeds, and by active ship control in inner and outer harbors where the consequences of a potential LNG spill might be most severe. These methods are all currently used by the Coast Guard. Therefore, the safety and hazard issues that can lead to an accidental breach appear manageable with current safety policies and practices.

4.2 Spill and Hazard Analysis of an Accidental Breach of a Cargo Tank

After developing an assessment of the potential sizes of LNG cargo tank breaches, the relative size of various spills and potential hazards and impacts on public safety and property were assessed. These results are discussed in detail in Appendix C for evaluation of spill dispersion and volatilization and thermal impacts; and in Appendix D for evaluation of asphyxiation, LNG ship structural damage, and structural damage to critical infrastructure elements.

4.2.1 Fire Hazard Evaluation of an Accidental LNG Spill

In most of the scenarios identified, the thermal hazards from an accidental spill are expected to manifest as a pool fire, based on the high probability that an ignition source will be available from most of the events identified. Based on a detailed review of the existing experimental literature presented in Appendix C, nominal fire modeling parameters were used to calculate the expected thermal hazards from a fire for the accidental breach scenarios developed.

For example, a solid flame model that accounts for view factors and transmissivity and the Moorhouse correlation for flame height to diameter was used. A low wind condition was assumed; therefore, flame tilt and drag were not required. A surface emissive power of 220 kW/m², a transmissivity value of 0.8, and a burn rate of 3×10^{-4} were also used. The volume of the spill assumed for each breached LNG cargo tanks was approximately 12,500 m³ or about half the contents of the average LNG cargo tank. The fire duration was based on the hole size, associated spill rate and the assumed burn rate.

Several significant fire parameters have a range of values, thus a parameter variation was performed to ascertain the result on thermal hazard distance. By grouping these parameters to result in extremes of hazard distances, it can be shown that the ranges can vary by factors of five to ten. Such groupings are not probable; therefore, it is more reasonable to choose a nominal case and conservatively vary different factors individually to bounding values to obtain hazard distances. This general approach is presented in Appendix D and a summary of the results calculated using that approach for potential accidental spills is shown in Table 10, where the distance to 37.5 kW/m² and 5 kW/m² is from the center of the pool.

Table 10: Effect of Parameter Combinations on Pool Diameter in an Accidental Breach

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)
1	1	.6	3X10 ⁻⁴	220	148	40	177	554
2	1	.6	3X10 ⁻⁴	220	209	20	250	784
2	3	.6	3X10 ⁻⁴	220	362	20	398	1358

The results presented in Table 10 show that thermal hazards of 37.5 kW/m² from a potential accidental breach of an LNG cargo tank and potential fire are expected to exist within approximately 150 - 250 m of the spill, depending on site-specific conditions. Thermal hazards of 5 kW/m² are expected to exist out to 500 and 750 m from the spill.

The multi-hole spill scenario presented considers the potential for a failure of three cargo tanks due to a long-duration fire that might occur in a smaller accidental spill. The impact of a fire on adjacent LNG cargo tanks is discussed in detail in Appendix D. Based on this analysis, depending on cargo tank design and fire duration, the potential for cascading damage to additional LNG tanks cannot be ruled out. A conservative estimate of the size of such a cascading fire and the thermal hazard distances from the fire were calculated assuming three simultaneous ruptures. In reality, the tank ruptures would more likely be sequential and, therefore, the hazard distances presented should be considered as conservative estimates.

4.2.2 Evaluation of Vapor Dispersion Hazard of Accidental LNG Spills

In most of the scenarios identified, the thermal hazards from an accidental spill are expected to manifest as a pool fire, based on the high probability that an ignition source will be available from most of the events identified. In some instances, an immediate ignition source might not be available and the spilled LNG could, therefore, disperse as a vapor cloud. Based on Sandia's review of data discussed in Appendix C, the vapor cloud for large spills could extend to beyond 1600 m, depending on spill location and site atmospheric conditions. In congested or highly populated areas, an ignition source would be likely; as opposed to remote areas, in which an ignition source might be less likely.

This suggests that LNG vapor dispersion analysis should be conducted using site-specific atmospheric conditions, location topography, and ship operations to assess adequately the potential areas and levels of hazards to public safety and property. Risk mitigation measures, such as development of procedures to quickly ignite a dispersion cloud and stem the leak, should be considered if conditions exist that the cloud would impact critical areas.

If ignited close to the spill, and early in the spill, the thermal loading from the vapor cloud ignition might not be significantly different from a pool fire, because the ignited vapor cloud would burn back to the source of liquid LNG and transition into a pool fire. If a large vapor cloud formed, the flame could propagate downwind, as well as back to the source. If the cloud is ignited at a significant distance from the spill, the thermal hazard zones can be extended significantly. The thermal radiation from the ignition of a vapor cloud can be very high within the ignited cloud and, therefore, particularly hazardous to people.

In order to obtain LNG dispersion distances to the lower flammability level (LFL) for accidental events, calculations were performed using VULCAN, a CFD code capable of simulating fire and non-fire conditions. The details of this modeling approach are discussed in detail in Appendix D. A low wind speed and highly stable atmospheric condition were chosen because this has shown to result in the greatest distances to LFL from experiment, and thus should be most conservative. A wind speed of 2.33 m/s at 10 m above ground and an F stability class were used for these simulations. The time it took for the LFL to be reached was approximately 20 minutes. As indicated in Table 11, dispersion distances to LFL for LNG spill vapor dispersion from an accidental spill might conservatively be approximately 1500 to 1700 m.

Table 11: Dispersion Distances to LFL for Accidental Spills

HOLE SIZE (m ²)	TANKS BREACHED	POOL DIAMETER (m)	SPILL DURATION (min)	DISTANCE TO LFL (m)
1	1	148	40	1536
2	1	209	20	1710

The results from the fire and vapor dispersion calculations suggest that high thermal hazards for accidental spills do not extend significantly from the spill location, but that some thermal hazards are possible to significant distances, especially if a vapor cloud occurs without early ignition and drifts into a critical area of facility. Table 12 summarizes the estimated results of the impact on public safety and property for an accidental LNG cargo tank breach and spill. In this table, high impact would include a thermal intensity in the range of 37.5 kW/m² and low values would correspond to thermal intensities in the range of 5 kW/m².

Table 12: Estimated Impact of Accidental LNG Breaches & Spills on Public Safety & Property

EVENT	POTENTIAL SHIP DAMAGE AND SPILL	POTENTIAL HAZARD	POTENTIAL IMPACT ON PUBLIC SAFETY*		
			~250 m	~250 – 750 m	>750 m
Collisions: Low speed	Minor ship damage, no breach	Minor ship damage	Low	Very Low	Very Low
Collisions: High Speed	LNG cargo tank breach from 0.5 to 1.5 m ² spill area	• Small fire	High	Medium	Low
		• Damage to ship	Medium	Low	Very Low
		• Vapor Cloud	High	High - Medium	Medium
Grounding: <3 m high object	Minor ship damage, no breach	Minor ship damage	Low	Very Low	Very Low

*Distance to spill origin, varies according to site

Very low – little or no property damage or injuries

Low – minor property damage and minor injuries

Medium – potential for injuries and property damage

High – major injuries and significant damage to structures