SANDIA REPORT

SAND2004-6258
Unlimited Release
Printed December 2004

Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water

Mike Hightower, Louis Gritzo, Anay Luketa-Hanlin, John Covan, Sheldon Tieszen, Gerry Wellman, Mike Irwin, Mike Kaneshige, Brian Melof, Charles Morrow, Don Ragland

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Abstract

While recognized standards exist for the systematic safety analysis of potential spills or releases from LNG (Liquefied Natural Gas) storage terminals and facilities on land, no equivalent set of standards or guidance exists for the evaluation of the safety or consequences from LNG spills over water. Heightened security awareness and energy surety issues have increased industry's and the public's attention to these activities. The report reviews several existing studies of LNG spills with respect to their assumptions, inputs, models, and experimental data. Based on this review and further analysis, the report provides guidance on the appropriateness of models, assumptions, and risk management to address public safety and property relative to a potential LNG spill over water.

ACKNOWLEDGEMENT

The authors received technical, programmatic, and editorial support on this project from a number of individuals and organizations both inside and outside Sandia National Laboratories. We would particularly like to express our thanks for their support and guidance in the technical evaluations and development of this report.

The U.S. Department of Energy was instrumental in providing coordination, management, and technical direction. Special thanks go to DOE personnel in the Office of Oil and Natural Gas, DOE Office of Fossil Energy, for their help in supporting the modeling, analysis, technical evaluations, and risk guidance efforts.

To support the technical analysis required for this project, the authors worked with many organizations, including maritime agencies, LNG industry and ship management agencies, LNG shipping consultants, and government intelligence agencies to collect the background information on ship and LNG cargo tank designs, accident and threat scenarios, and LNG ship safety and risk management operations needed to assess LNG spill safety and risk implications.

The following individuals were especially helpful in supporting our efforts, providing information, coordinating contacts, and reviewing technical evaluations.

Capt. Dave Scott – U.S. Coast Guard
Dr. Robin Pitblado – Det Norske Veritas
Eric Linsner – PRONAV Ship Management
Mike Edens – Office of Naval Intelligence
Richard Hoffmann – Federal Energy Regulatory Commission
Chris Zerby – Federal Energy Regulatory Commission

To help in technically reviewing this report, the DOE commissioned an External Peer Review Panel to evaluate the analyses, conclusions, and recommendations presented. The Peer Review Panel consisted of experts in LNG spill testing and modeling, fire modeling, fire protection, and fire safety and risk management. The panel's comments and suggestions were extremely valuable in improving the technical presentation and organization of the report. The authors would like to thank the following members of the External Peer Review Panel for their valuable comments, suggestions, and directions.

Dr. Paul Croce – Vice President and Manager of Research, FM Global
Dr. Carlos Fernandez-Pello – Professor of Fire Sciences, University of California Berkeley
Dr. Ron Koopman – Consultant on LNG spills and modeling
Dr. Fred Mowrer – Associate Professor of Fire Protection Engineering, University of Maryland

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SYMBOLS AND ACRONYMS

<	less than
>	greater than
/	per
^{o}C	degrees Celsius
^{o}F	degrees Fahrenheit
^{o}K	degrees Kelvin
g	gram
k	kilo- (multiplied 1000 times; e.g. 5 kW = 5000 watts)
knot	nautical mile per hour (1 knot = 1.15 miles per hour)
m	meter (1 m = 39.37 inches)
m^2	meter squared (an area measuring one meter on each side)
m (as a prefix)	milli- (1/1000; e.g., 1 mm = 1/1000 of a meter)
s	second
Tcf	Trillion cubic feet
W	Watt
(CFD) Computational Fluid Dynamics	a modern analysis technique using computer technology to numerically solve the complete nonlinear partial differential equations governing complex fluid flows
Credible event	a group (or groups) could have the general means and technical skill to accomplish successfully an intentional breach.
(LFL) Lower Flammability Limit	lowest concentration of a fuel by volume mixed with air that is flammable
(LNG) Liquefied Natural Gas	natural gas that has been cooled to a temperature such that the natural gas becomes a liquid
Nominal Case	expected outcomes of a potential breach and associated thermal hazards based on an assessment of identified credible threats and the use of best available data to select model input parameters
(RPT) Rapid Phase Transitions	the rapid evaporation of a liquid resulting from contact with another liquid that is at a temperature significantly above the boiling temperature of the evaporating liquid
(UFL) Upper Flammability Limit	highest concentration of a fuel by volume mixed with air that is flammable
Validation	comparison of analytical results from a model with experimental data to ensure that the physical bases and assumptions of the model are appropriate and produce accurate results

FOREWORD

The Energy Information Administration (EIA) estimates that domestic natural gas production is expected to increase more slowly than consumption, rising to 20.5 trillion cubic feet (Tcf) in 2010 and 21.9 Tcf in 2025. Domestic gas production is relatively flat, while the marginal costs of domestic production are increasing, which has caused a fundamental shift in long-term gas prices. At the same time, gas demand is rising sharply, particularly for electric power generation. The National Petroleum Council (NPC) states in its recent report, "*Balancing Natural Gas Policy – Fueling the Demands of a Growing Economy,*" that "traditional North American producing areas will provide 75% of long-term U.S. gas needs, but will be unable to meet projected demand," and that … "New, large-scale resources such as LNG and Arctic gas are available and could meet 20%-25% of demand, but are higher-cost and have long lead times."

The combination of higher natural gas prices, rising natural gas demand, and lower liquefied natural gas (LNG) production costs, is setting the stage for increased LNG trade in the years ahead. Estimates are that worldwide LNG trade will increase 35 percent by 2020. In the United States, EIA projects that natural gas imports will more than double over the next 20 years. Nearly all the projected increase is expected to come from LNG, requiring an almost 28-fold increase in LNG imports over 2002 levels.

The United States currently has four marine LNG import terminals: Lake Charles, Louisiana; Everett, Massachusetts; Elba Island, Georgia; and Cove Point, Maryland. EIA projects that three new LNG terminals could be constructed in the U.S. in the next 4 to 5 years, and others have estimated that as many as eight could be constructed within this time frame. More than 40 new marine LNG terminal sites are under consideration and investigation. A major factor in the siting of LNG import terminals is their proximity to a market, enabling natural gas to be easily supplied to areas where there is a high demand, but limited domestic supplies. For this reason, marine LNG import terminals are being proposed or considered near major population centers on all three U.S. coasts.

For more information on North American natural gas supply and demand, please refer to the latest *Annual Energy Outlook* of the Energy Information Administration (EIA). The EIA (www.eia.doe.gov) is the statistical agency of the Department of Energy. It provides policy-independent data, forecasts, and analyses to promote sound policy-making, efficient markets, and public understanding regarding energy and its interaction with the economy and environment. Also useful is the National Petroleum Council (NPC) report, *Balancing Natural Gas Policy – Fueling the Demands of a Growing Economy* (www.npc.org). This multi-volume report was prepared in response to a request from the Secretary of Energy for a new study on natural gas markets in the 21st century, to update the NPC's 1992 and 1999 reports on the subject. It provides insights on energy market dynamics, as well as advice on actions that can be taken by industry and Government to ensure adequate and reliable supplies of energy for customers.

1 EXECUTIVE SUMMARY

The increasing demand for natural gas in the U.S. could significantly increase the number and frequency of marine LNG 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.

For that reason, the U.S. Department of Energy (DOE), Office of Fossil Energy, 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 reduce both the potential for and the risks of an LNG spill over water. Specifically, DOE requested:

- An in-depth literature search of the experimental and technical studies associated with evaluating the safety and hazards of an LNG spill from an LNG cargo tank ship;
- A detailed review of four recent spill modeling studies related to the safety implications of a large-scale LNG spill over water;
- Evaluation of the potential for breaching an LNG ship cargo tank, both accidentally and intentionally, identification of the potential for such breaches and the potential size of an LNG spill for each breach scenario, and an assessment of the potential range of hazards involved in an LNG spill; and
- Development of guidance on a risk-based approach to analyze and manage the threats, hazards, and consequences of an LNG spill over water to reduce the overall risks of an LNG spill to levels that are protective of public safety and property.

To support this effort, Sandia worked with the U.S. 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. The information gathered was used to develop accidental and intentional LNG cargo tank breach scenarios, for modeling of potential spill hazards, and as the basis for analysis to determine the extent and severity of LNG spill consequences. Based on analysis of the modeling results, three consequence-based hazard zones were identified plus. In addition, risk reduction and mitigation techniques were identified to reduce impacts on public safety and property.

Several conclusions and recommendations were developed based on these results. The key conclusions are listed below.

Key Conclusions

1. The system-level, risk-based guidance developed in this report, though general in nature (non site-specific), can be applied as a baseline process for evaluating LNG operations where there is the potential for LNG spills over water.
2. A review of four recent LNG studies showed a broad range of results, due to variations in models, approaches, and assumptions. The four studies are not consistent and focus only on consequences rather than both risks and consequences. While consequence studies are important, they should be used to support comprehensive, risk-based management and planning approaches for identifying, preventing, and mitigating hazards to public safety and property from potential LNG spills.
3. Risks from accidental LNG spills, such as from collisions and groundings, are small and manageable with current safety policies and practices.
4. Risks from intentional events, such as terrorist acts, can be significantly reduced with appropriate security, planning, prevention, and mitigation.
5. This report includes a general analysis for a range of intentional attacks. The consequences from an intentional breach can be more severe than those from accidental breaches. Multiple techniques exist to enhance LNG spill safety and security management and to reduce the potential of a large LNG spill due to intentional threats. If effectively implemented, these techniques could significantly reduce the potential for an intentional LNG spill.
6. Management approaches to reduce risks to public safety and property from LNG spills include operation and safety management, improved modeling and analysis, improvements in ship and security system inspections, establishment and maintenance of safety zones , and advances in future LNG off-loading technologies. If effectively implemented, these elements could reduce significantly the potential risks from an LNG spill.
7. 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, available intelligence, threat assessments, safety and security operations, and available resources.
8. While there are limitations in existing data and current modeling capabilities for analyzing LNG spills over water, existing tools, if applied as identified in the guidance sections of this report, can be used to identify and mitigate hazards to protect both public safety and property. Factors that should be considered in applying appropriate models to a specific problem include: model documentation and support, assumptions and limitations, comparison with data, change control and upgrade information, user support, appropriate modeling of the physics of a spill, modeling of the influence of environmental conditions, spill and fire dynamics, and peer review of models used for various applications. As more LNG spill testing data are obtained and modeling capabilities are improved, those advancements can be incorporated into future risk analyses.
9. Where analysis reveals that potential impacts on public safety and property could be high and where interactions with terrain or structures can occur, modern, validated computational fluid dynamics (CFD) models can be used to improve analysis of site-specific hazards, consequences, and risks.

10. LNG cargo tank hole sizes for most credible threats range from two to twelve square meters; expected sizes for intentional threats are nominally five square meters.
11. The most significant impacts to public safety and property exist within approximately 500 m of a spill, due to thermal hazards from fires, with lower public health and safety impacts at distances beyond approximately 1600 m.
12. Large, unignited LNG vapor releases are unlikely. If they do not ignite, vapor clouds could spread over distances greater than 1600 m from a spill. For nominal accidental spills, the resulting hazard ranges could extend up to 1700 m. For a nominal intentional spill, the hazard range could extend to 2500 m. The actual hazard distances will depend on breach and spill size, site-specific conditions, and environmental conditions.
13. Cascading damage (multiple cargo tank failures) due to brittle fracture from exposure to cryogenic liquid or fire-induced damage to foam insulation was considered. Such releases were evaluated and, while possible under certain conditions, are not likely to involve more than two or three cargo tanks for any single incident. Cascading events were analyzed and are not expected to greatly increase (not more than 20%-30%) the overall fire size or hazard ranges noted in Conclusion 11 above, but will increase the expected fire duration.

1.1 Safety Analysis and Risk Management of Large LNG Spills over Water

In modern risk analysis approaches, the risks associated with an event are commonly defined as a function of the following four elements:

- The probability of the event — such as an LNG cargo tank breach and spill;
- The hazards associated with the event — such as thermal radiation from a fire due to an LNG spill;
- The consequences of the event — such as the thermal damage from a fire, and
- The effectiveness of systems for preventing the event or mitigating hazards and consequences — such as any safety/security systems.

1.1.1 LNG Spill Prevention and Mitigation

Risks from a potential LNG spill over water could be reduced through a combination of 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. In addition, since September 11, 2001, further 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 and special security sweeps, and positive control of an LNG ship during port transit.

Proactive risk management approaches can reduce both the potential for and hazards of such events. These are discussed in Section 6 of this report, and include:

- Improvements in ship and terminal safety/security systems,
- Modifications and improvements in LNG tanker escorts, vessel movement control zones, and safety operations near ports and terminals,
- Improved surveillance and searches,
- Redundant or offshore mooring and offloading systems, and
- Improved emergency response coordination and communications.

Risk prevention and mitigation techniques can be 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. However, what might be applicable for effective risk reduction in one location might not be appropriate at another. The options identified in Table 1 provide examples of how implementation of different strategies, alone or in combination, can be used to reduce certain threats, mitigate consequences of a spill, or reduce hazard analysis uncertainties.

Table 1: Representative Options for LNG Spill Risk Reduction

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

To help reduce the risks to public safety and property from both accidental and intentional events, this report provides guidance on risk-based approaches for analyzing and managing the threats, hazards, and consequences of an LNG spill over water. The guidance is summarized in the remainder of the Executive Summary and presented in detail in Sections 3 – 6 of this report and in technical discussions in Appendices A – D.

1.1.2 LNG Breach, Spill, and Hazard Analyses

Currently, the potential for an LNG cargo tank breach, whether accidental or intentional, the dynamics and dispersion of a large spill, and the hazards of such a spill, are not fully understood, for two primary reasons. First, the combination of current LNG ship designs and safety management practices for LNG transportation have reduced LNG accidents to the extent that

there is little historical or empirical information on the consequences of breaches or large spills. Second, existing experimental data on LNG spill dynamics and its dispersion over water address spill sizes that are more than a factor of one hundred smaller than spill sizes currently being postulated for some intentional events. Variations in site conditions, LNG ship designs, and environmental conditions further complicate hazard predictions.

The lack of large-scale experimental data forces analysts to make many assumptions and simplifications in calculating the breach of an LNG cargo tank, the resulting spill dispersion, and associated thermal hazards. For example, an evaluation of four recent LNG spill studies (Appendix A) showed significant differences in thermal hazard estimates due to the differences in assumptions and modeling approaches used in each analysis.

Although existing spill assessment and modeling techniques and validation of models against large-scale LNG spill data have limitations, the guidance provided in this report is applicable to performance-based hazard and risk management approaches. Such approaches can be used in conjunction with existing spill and hazard analysis techniques, and safety and security methods, to assess and reduce the risks to both public safety and property caused by an LNG spill over water. Guidance is provided on the use of existing analysis techniques applied to site-specific conditions for increasing confidence in the management of hazards and risks. As additional LNG spill data are obtained and hazard analysis models are improved, they can be incorporated into future risk analysis guidance.

LNG Cargo Tank Breach Analysis

Based on available information, a range of historically credible and potential accidental and intentional events was identified that could cause an LNG cargo tank breach and spill. Modern finite element modeling and explosive shock physics modeling were used to estimate a range of breach sizes for credible accidental and intentional LNG spill events, respectively. The results are discussed in Sections 4 and 5 and detailed in Appendix B.

From these analyses, the sizes of LNG cargo tank breaches for accidents were estimated to be less than 2 m^2. For intentional events, the size of the hole depends on its location on the ship and the source of the threat. Intentional breaches were estimated at 2 to approx. 12 m^2, with nominal sizes of about 5 – 7 m^2. These sizes are smaller than those used in many recent studies. Although smaller, the breach sizes estimated can still lead to large LNG spills.

Using structural fracture mechanics analyses, the potential for cryogenic damage to the LNG ship and other LNG cargo tanks was also evaluated, as discussed in Sections 4 and 5 and Appendix D. Based on these analyses, the potential for cryogenic damage to the ship cannot be ruled out, especially for large spills. The degree and severity of damage depends on the size and location of the breach. Sandia considered cryogenic damage to the ship's structure and concluded that releases from no more than two or three tanks would be involved in a spill that occurs due to any single incident. This cascading release of LNG was analyzed and is not expected to increase significantly the overall fire size or hazard ranges, but the expected fire duration will increase. Hazard analysis and risk prevention and mitigation strategies should consider this in assessing public safety and damage to property.

Spill and Dispersion Analysis

The variability in existing LNG spill and dispersion/thermal hazard modeling approaches is due to physical limitations in the models and the lack of validation with large-scale spill data. Obtaining experimental data for large LNG spills over water would provide needed validation and help reduce modeling uncertainty. Because extrapolation of existing models will be necessary for analysis of potentially large spills, models should be used that invoke as much fundamental physics as possible. Based on the evaluations presented in Sections 4 and 5 and Appendices C and D, several types of models currently exist to assess hazards. Models should be used only where they are appropriate and understood to ensure that the results increase confidence in the analysis of the hazards and risks to public safety and property.

In higher hazard zones, where analysis reveals that potential impacts on public safety and property could be high and where interactions with terrain or structures can occur, modern, CFD models, as listed in Table 2, can be used to improve analysis of site-specific hazards, consequences, and risks. Use of these models is suggested because many of the simpler models have limitations that can cause greater uncertainties in calculating liquid spread, vapor dispersion, and fire hazards. CFD models have their own limitations and should be validated prior to use. Further refinement of CFD models will continue to improve the degree of accuracy and reliability for consequence modeling.

Table 2: Models for Improved Analysis of an LNG Spill in High Hazard Areas

APPLICATION	IMPROVED MODELING APPROACHES
Breach Analysis	Finite element codes for modeling accidental ship collisions & shock physics codes for modeling intentional breaches.
Tank Emptying	Modified orifice model that includes the potential for LNG leakage between hulls.
Structural Damage Modeling	Coupled spill leakage, fluid flow, and fracture mechanics codes for modeling ship structural damage & damage to LNG cargo tanks.
Spreading	CFD codes for modeling spread of cryogenic liquids on water.
Dispersion	CFD codes for modeling dispersion of dense gases.
Fire	CFD codes for modeling fire phenomena, including combustion, soot formation, and radiative heat transfer.

While these studies provide insight into appropriate models to use, additional factors should be considered in applying models to a specific problem. These include model documentation and support, assumptions and limitations, comparison and validation with data, change control and upgrade information, user support, appropriate modeling of the physics of a spill, modeling of the influence of environmental conditions, spill and fire dynamics, and model peer review.

Hazards Analysis and Public Safety Impacts

Current LNG spill and dispersion modeling and analysis techniques have limitations. In addition, variations exist in location-specific conditions that influence dispersion, such as terrain, weather conditions, waves, currents, and the presence of obstacles. Therefore, it is sensible to provide guidance on the general range of hazards for potential spills rather than suggest a specific, maximum hazard guideline.

To assess the general magnitude of expected hazard levels, a limited sensitivity analysis was performed using simplified models for a range of spill volumes. The spill volumes were based on potential breaches from credible accidental and intentional threats. These analyses are

summarized in Sections 4 and 5 of this report. While not conducted for a specific site, the analyses provide examples of general considerations for hazards and risks. From the assessment conducted, thermal hazards will occur predominantly within 1600 m of an LNG ship spill, with the highest hazards generally in the near field (approximately 250 - 500 m of a spill). While thermal hazards can exist beyond 1600 m, they are generally lower in most cases.

The general hazard zones and safety guidance identified from this assessment are as follows:

- The pool sizes for the credible spills estimated could range from generally 150 m in diameter for a small, accidental spill to several hundred meters for a large, intentional spill. Therefore, high thermal hazards from a fire are expected to occur within approximately 250 – 500 m from the origin of the spill, depending on the size of the spill. Major injuries and significant structural damage are possible in this zone. The extent of the hazards will depend on the spill size and dispersion from wind, waves, and currents. People, major commercial/industrial areas or other critical infrastructure elements, such as chemical plants, refineries, bridges or tunnels, or national icons located within portions of this zone could be seriously affected.
- Hazards and thermal impacts transition to lower levels with increasing distance from the origin of the spill. Some potential for injuries and property damage can still occur in portions of this zone; but this will vary based on spill size, distance from the spill, and site-specific conditions. For small spills, the hazards transition quickly to lower hazard levels.
- Beyond approximately 750 m for small accidental spills and 1600 m for large spills, the impacts on public safety should generally be low for most potential spills. Hazards will vary; but minor injuries and minor property damage are most likely at these distances. Increased injuries and property damage would be possible if vapor dispersion occurred and a vapor cloud was not ignited until after reaching this distance.

Table 3 summarizes the results on expected hazard levels for several types of accidental and intentional spills. While the analyses included evaluations of the size and number of breaches, spill rate and discharge coefficient, burn rate, surface emissive power, and transmissivity, site-specific environmental conditions such as wind speed, direction, waves, and currents, were not specifically considered. Therefore, the distances to each of the different hazard zones are provided as guidance and will vary depending on site-specific conditions and location.

The upper part of Table 3 identifies the estimated hazard zones in terms of public safety from potential accidents, where spills are generally much smaller. The lower part of Table 3 identifies the estimated hazard zones in terms of public safety from examples of intentional LNG spills, which can be larger.

Table 3: Guidance for Impacts on Public Safety from LNG Breaches and Spills

EVENT	POTENTIAL SHIP DAMAGE AND SPILL	POTENTIAL HAZARD	POTENTIAL IMPACT ON PUBLIC SAFETY*		
			High	Medium	Low
Collisions: Low speed	Minor ship damage, no spill	Minor ship damage	None	None	None
Collisions: High Speed	LNG cargo tank breach and small - medium spill	Damage to ship and small fire	~ 250 m	~ 250 – 750 m	> 750 m
Grounding: <3 m high object	Minor ship damage, no breach	Minor ship damage	None	None	None
Intentional Breach	Intentional breach and medium to large spill	Damage to ship and large fire	~ 500 m	~ 500 m – 1600 m	> 1600 m
	Intentional, large release of LNG	▪ Damage to ship and large fire ▪ Vapor cloud dispersion with late ignition	~ 500m ~ 500 m	~ 500 m – 1600 m > 1600 m	> 1600 m > 2000 m

[a] Distance to spill origin, varies according to site
Low – minor injuries and minor property damage
Medium – potential for injuries and property damage
High – major injuries and significant damage to property

Many of the hazard zones identified in Table 3 are based on thermal hazards from a pool fire, because many of the events will provide ignition sources such that a fire is likely to occur immediately. In some cases, the potential exists for a vapor cloud to be created without being ignited. As noted in Sections 4 and 5 and Appendices C and D, a vapor cloud from an LNG spill could extend to 2,500 m, if an ignition source is not available. The potential thermal hazards within a vapor cloud could be high. Because vapor cloud dispersion is highly influenced by atmospheric conditions, hazards from this type of event will be very site-specific.

In addition, latent or indirect effects, such as additional damage that could be caused by a damaged infrastructure (e.g. a refinery or power plant), were not directly assessed. These types of issues and concerns are site-specific and should be included as part of the overall risk management process.

1.2 Safety Analysis Conclusions

The potential for damage to LNG containment systems that could result from accidents or intentional events was evaluated. While hazard distances and levels will vary based on site-specific conditions, a summary of the safety analysis conclusions is presented below.

1.2.1 General Conclusions

1. The most significant impacts to public safety and property exist within approximately 500 m of a spill, with much lower impacts at distances beyond 1600 m, even for very large spills.
2. Under certain conditions, it is possible that multiple LNG cargo tanks could be breached as a result of the breaching event itself, as a consequence of LNG-induced cryogenic damage to nearby tanks, or from fire-induced structural damage to the vessel.
3. Multiple breach and cascading LNG cargo tank damage scenarios were analyzed, as discussed in Sections 4 and 5. While possible under certain conditions, they are likely to involve no more than two to three cargo tanks at any one time. These conditions will not greatly change the hazard ranges noted in General Conclusion Number 1, but will increase expected fire duration.

1.2.2 Accidental Breach Scenario Conclusions

1. Accidental LNG cargo tank damage scenarios exist that could potentially cause an effective breach area of 0.5 to 1.5 m^2.
2. Due to existing design and equipment requirements for LNG carriers, and the implementation of navigational safety measures such as traffic management schemes and safety zones, the risk from accidents is generally low.
3. The most significant impacts to public safety and property from an accidental spill exist within approximately 250 m of a spill, with lower impacts at distances beyond approximately 750 m from a spill.

1.2.3 Intentional Breach Scenario Conclusions

1. Several credible, intentional LNG cargo tank damage scenarios were identified that could initiate a breach of between 2 m^2 to approximately 12 m^2, with a probable nominal size of 5 – 7 m^2.
2. Most of the intentional damage scenarios identified produce an ignition source and an LNG fire is very likely to occur.
3. Some intentional damage scenarios could result in vapor cloud dispersion, with delayed ignition and a fire.
4. Several intentional damage scenarios could affect the structural integrity of the vessel or other LNG cargo tanks due to ignition of LNG vapor trapped within the vessel. While possible under certain conditions, these scenarios are likely to involve no more than two to three cargo tanks at any one time, as discussed in Sections 4 and 5.
5. Rapid phase transitions (RPT) are possible for large spills. Effects will be localized near the spill source and should not cause extensive structural damage.
6. The potential damage from spills to critical infrastructure elements such as bridges, tunnels, industrial/commercial centers, LNG unloading terminals and platforms, harbors, or populated areas can be significant in high hazard zones.

7. In general, the most significant impacts on public safety and property from an intentional spill exist within approximately 500 m of a spill, with lower impacts at distances beyond approximately 1600 m from a spill, even for very large spills.

1.3 Guidance on Risk Management for LNG Operations over Water

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, available intelligence, threat assessments, safety and security operations, and available resources. This approach should be performance-based and include identification of hazards and risks, protection required for public safety and property, and risk prevention and mitigation strategies.

The following guidance is provided to assist risk management professionals, emergency management and public safety officials, port security officials and other appropriate stakeholders in developing and implementing risk management strategies and processes. For both accidental and intentional spills, the following is recommended:

- Use effective security and protection operations that include enhanced interdiction, detection, delay procedures, risk management procedures, and coordinated emergency response measures, which can reduce the risks from a 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 would often be sufficient in areas where the impacts of a spill are low.
- Where analysis reveals that potential impacts on public safety and property could be high and where interactions with terrain or structures can occur, modern, validated computational fluid dynamics (CFD) models can be used to improve analysis of site-specific hazards.

1.3.1 Guidance on Risk Management for Accidental LNG Spills

Zone 1

These are areas in which LNG shipments transit narrow harbors or channels, pass under major bridges or over tunnels, or come within approximately 250 meters of people and major infrastructure elements, such as military facilities, population and commercial centers, or national icons. Within this zone, the risk and consequences of an accidental LNG spill could be significant and have severe negative impacts. Thermal radiation poses a severe public safety and property hazard, and can damage or significantly disrupt critical infrastructure located in this area.

Risk management strategies for LNG operations should address both vapor dispersion and fire hazards. Therefore, the most rigorous deterrent measures, such as vessel security zones, waterway traffic management, and establishment of positive control over vessels are options to be considered as elements of the risk management process. Coordination among all port security stakeholders is essential. Incident management and emergency response measures should be

carefully evaluated to ensure adequate resources (i.e., firefighting, salvage, etc.) are available for consequence and risk mitigation.

Zone 2

These are areas in which LNG shipments and deliveries occur in broader channels or large outer harbors, or within approximately 250 m – 750 m of major critical infrastructure elements like population or commercial centers. Thermal radiation transitions to less severe hazard levels to public safety and property. Within Zone 2, the consequences of an accidental LNG spill are reduced and risk reduction and mitigation approaches and strategies can be less extensive.

Within Zone 2, the consequences of an accidental LNG spill are reduced and risk reduction and mitigation approaches and strategies can be less extensive. In this zone, risk management strategies for LNG operations should focus on approaches dealing with both vapor dispersion and fire hazards. The strategies should include incident management and emergency response measures such as ensuring areas of refuge (e.g. enclosed areas, buildings) are available, development of community warning signals, and community education programs to ensure persons know what precautions to take.

Zone 3

This zone covers LNG shipments and deliveries that occur more than approximately 750 m from major infrastructures, population/commercial centers, or in large bays or open water, where the risks and consequences to people and property of an accidental LNG spill over water are minimal. Thermal radiation poses minimal risks to public safety and property.

Within Zone 3, risk reduction and mitigation strategies can be significantly less complicated or extensive. Risk management strategies should concentrate on incident management and emergency response measures that are focused on dealing with vapor cloud dispersion. Measures should ensure areas of refuge are available, and community education programs should be implemented to ensure that persons know what to do in the unlikely event of a vapor cloud.

1.3.2 Guidance on Risk Management for Intentional LNG Spills

Zone 1

These are areas in which LNG shipments occur in narrow harbors or channels, pass under major bridges or over tunnels, or come within approximately 500 meters of major infrastructure elements, such as military facilities, population and commercial centers, or national icons. Within this zone, the risk and consequences of a large LNG spill could be significant and have severe negative impacts. Thermal radiation poses a severe public safety and property hazard, and can damage or significantly disrupt critical infrastructure located in this area.

Risk management strategies for LNG operations should address vapor dispersion and fire hazards. The most rigorous deterrent measures, such as vessel security zones, waterway traffic management, and establishment of positive control over vessels are elements of the risk management process. Coordination among all port security stakeholders is essential. Incident management and emergency response measures should be carefully evaluated to ensure adequate resources (i.e., firefighting, salvage) are available for consequence and risk mitigation.

Zone 2

These are areas in which LNG shipments and deliveries occur in broader channels or large outer harbors, within approximately 500 m – 1.6 km of major critical infrastructure elements, such as population or commercial centers. Within Zone 2, the consequences of even a large LNG spill are reduced. Thermal radiation transitions to less severe hazard levels to public safety and property.

Risk management strategies for LNG operations that occur in this zone should focus on vapor dispersion and fire hazards. The strategies should include incident management and emergency response measures that ensure areas of refuge (enclosed areas, buildings) are available, the development of community warning procedures, and education programs to ensure that communities are aware of precautionary measures.

Zone 3

This zone covers LNG shipments and deliveries that occur more than approximately 1.6 km from major infrastructures, population/commercial centers, or in large bays or open water, where the risks and consequences to people and property of a large LNG spill over water are minimal. Thermal radiation poses minimal risks to public safety and property.

Risk reduction and mitigation strategies can be significantly less complicated or extensive than Zones 1 and 2. Risk management strategies should concentrate on incident management and emergency response measures for dealing with vapor cloud dispersion. Measures should ensure that areas of refuge are available, and community education programs should be implemented to ensure that persons know what to do in the unlikely event of a vapor cloud.

2 BACKGROUND

Many studies have been conducted to assess the consequences and risks of LNG spills from both storage terminals and LNG tankers. However, while recognized standards exist for the systematic safety analysis of potential spills or releases from LNG storage terminals and facilities on land, no equivalent set of standards exists for the evaluation of the safety or consequences from LNG tanker spills over water. Since the incidents surrounding September 11, 2001, much larger spill scenarios and their potential consequences are being evaluated for many types of flammable cargo transportation, including LNG tankers.

Due to limited experience and experimental testing associated with large-scale spills over water, most studies use simplifying assumptions to calculate and predict the hazards of a large LNG spill. The range of assumptions and estimates for many complicated spill scenarios can lead to significant variability in estimating the probability, hazards, consequences, and overall risks of large LNG spills over water.

To address these issues, DOE requested that Sandia help to quantify potential credible threats to an LNG ship, assess the potential hazards and consequences from an LNG spill, and identify potential prevention and mitigation strategies that could be implemented to reduce the risks of a potentially large LNG spill over water. These efforts included:

- An in-depth literature search of the experimental and technical studies associated with evaluating the safety and hazards of LNG following a major spill from an LNG ship;
- A detailed review of four recent LNG spill modeling studies related to the safety implications of a large-scale LNG spill over water;
- Evaluation of potential scenarios for breaching an LNG cargo tank, both accidentally and intentionally, identification of the potential size of an LNG spill for those scenarios, and an assessment of the potential range of hazards and consequences from the spills; and
- Development of a risk analysis approach to quantify threats, assess hazards, and identify operational, safety, and security procedures and techniques to reduce to acceptable levels the probability, risks, and hazards of a large LNG spill over water.

To support its efforts, Sandia worked with the U.S. DOE, the U.S. Coast Guard, LNG industry and ship management agencies, LNG shipping consultants, and government intelligence agencies to collect background information on LNG ship and cargo tank designs, accident and threat scenarios, and standard LNG ship safety and risk management operations. The information gathered was used to develop accidental and intentional LNG cargo tank breach scenarios, for modeling of potential spill hazards, and as the basis for analysis to determine the extent and severity of LNG spill consequences. Based on analysis of the modeling results, three consequence-based hazard zones were identified and risk reduction and mitigation techniques were identified to reduce impacts on public safety and property.

The results of these evaluations are summarized in Sections 3 – 6 and detailed analyses are presented in Appendices A – D.

2.1 History and Description of LNG

Natural gas liquefaction dates back to the 19th century, when British chemist and physicist Michael Faraday experimented with liquefying different types of gases, including natural gas. A prototype LNG plant was first built in West Virginia in 1912, and the first commercial liquefaction plant was built in Cleveland, Ohio, in 1941. The Cleveland plant liquefied natural gas and stored the LNG in tanks, which was vaporized later for use during heavy demand periods. Natural gas continues to be liquefied and stored for use during peak demands, with almost 100 LNG peaking facilities in the U.S. [EIA 2002].

2.1.1 Growth of International LNG Transportation

In January 1959, the world's first LNG tanker, *The Methane Pioneer,* a converted World War II liberty freighter, carried an LNG cargo from Lake Charles, Louisiana to the United Kingdom. The U.S. began exporting LNG to Asia in 1969, when Phillips Petroleum built a liquefaction facility on the Kenai Peninsula, about 100 miles south of Anchorage, Alaska. The Phillips plant continues to operate and is one of the oldest continuously operated LNG plants in the world.

A fleet of about 150 specially designed LNG ships is currently being used to transport natural gas around the globe. Worldwide, there are 17 LNG export (liquefaction) terminals and 40 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 [Kaplan and Marshal 2003] [DOE 2003].

Four LNG marine terminals were built in the United States between 1971 and 1980: Lake Charles, Louisiana; Everett, Massachusetts; Elba Island, Georgia; and Cove Point, Maryland. After reaching a peak receipt volume of four million tons in 1979, LNG imports declined when de-control of natural gas prices produced an economic supply of natural gas within U.S. borders. The Elba Island and Cove Point receiving terminals were mothballed in 1980. Due to the recent growth in natural gas demand, both of these terminals have undergone refurbishment and reactivation, and both are currently receiving LNG shipments. The Lake Charles and Everett terminals, which have operated below design capacity for many years, have also recently increased receipt of LNG.

Import of natural gas into the U.S. is expected to double over the next 20 years [DOE 2003]. 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 includes locations on all three U.S. coasts. Most are being planned to handle one to two LNG tanker shipments per week.

2.1.2 LNG Transportation by Ship

Specially designed ships are used to transport LNG to U.S. import terminals [Harper 2002] [OTA 1977]. Many LNG tankers currently in service use Moss spherical tanks, as illustrated in Figure 1. Moss tankers sometimes use nitrogen to purge some below-decks spaces to aid in preventing fires. Moss ship holds are designed to collect spilled LNG and the vessels contain equipment required to recover it [Glasfeld 1980]. In addition to Moss tankers, other LNG ships are designed with prismatic, membrane-lined cargo tanks.

Figure 1. Moss-Spherical LNG Tanker Ship

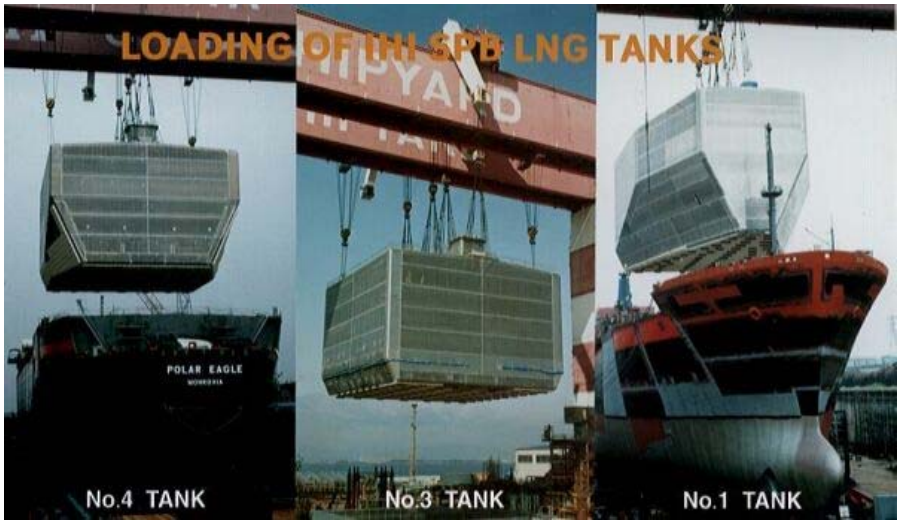


Figure 2. Prismatic Tanker Ship

Prismatic tanks are designed to conform to the shape of the ship's hull, thus occupying much of the internal area of the ship, which minimizes areas into which LNG from a tank rupture or spill can be diverted.

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).
- All LNG ships are 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 an accidental collision.
- 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 direction on double-hull designs and materials, subdivision, damage stability, and cargo tank location.

During the past 40 years, more than 80,000 LNG carrier voyages have taken place, covering more than 100 million miles, without major accidents or safety problems, either in port or on the high seas [Pitblado 2004]. Over the life of the industry, eight marine incidents worldwide have resulted in LNG spills, with some damage; but no cargo fires have occurred. Seven incidents have been reported with ship structural damage, two from groundings; but no spills were recorded. No LNG shipboard fatalities from spills have occurred [Beard 1982] [SIGTTO 2003].

2.1.3 LNG Properties

Typical properties of LNG:

- LNG is simply natural gas that has been cooled to its liquid state at atmospheric pressure: -260°F (-162.2°C) and 14.7 psia. Currently, imported LNG is commonly 95% – 97% methane, with the remainder a combination of ethane, propane, and other heavier gases.
- LNG is transported at ambient pressures.
- Liquefying natural gas vapor, which reduces the gas into a practical size for transportation and storage, reduces the volume that the gas occupies more than 600 times.
- LNG is considered a flammable liquid.
- LNG vapor is colorless, odorless, and non-toxic.
- LNG vapor typically appears as a visible white cloud, because its cold temperature condenses water vapor present in the atmosphere.
- The lower and upper flammability limits of methane are 5.5% and 14% by volume at a temperature of 25°C.

Table 4 lists the flammability limits for several compounds.

Table 4: Flammability Limits for Selected Fuel Compounds at 25°C

FUEL	LOWER FLAMMABILITY LIMIT (LFL) % by volume in air	UPPER FLAMMABILITY LIMIT (UFL) % by volume in air
Methane	5.5	14.0
Butane	1.6	8.4
Propane	2.1	9.6
Ethanol	3.3	19.0
Gasoline (100 Octane)	1.4	7.8
Isopropyl alcohol	2.0	12.7
Ethyl ether	1.9	36.0
Xylene	0.9	7.0
Toluene	1.0	7.1
Hydrogen	4.0	75.0
Acetylene	2.5	85.0

2.2 Growing Interest in LNG Safety and Security

The increasing demand for natural gas will significantly increase the number and frequency of LNG tanker deliveries to ports across the U.S. Because of the increasing number of shipments, concerns about the potential for an accidental spill or release of LNG have increased. In addition, since the incidents surrounding September 11, 2001, concerns have increased over the impact that an attack on hazardous or flammable cargoes, such as those carried by LNG ships, could have on public safety and property.

The risks and hazards from an LNG spill will vary depending on the size of the spill, environmental conditions, and the site at which the spill occurs. Hazards can include cryogenic burns to the ship's crew and people nearby or potential damage to the LNG ship from contact with the cryogenic LNG. Vaporization of the liquid LNG can occur once a spill occurs and subsequent ignition of the vapor cloud could cause fires and overpressures that could injure people or cause damage to the tanker's structure, other LNG tanks, or nearby structures.

With the growing dependence on imported LNG to meet increasing U.S. natural gas demands, damage or disruption from a spill to an LNG import terminal or harbor facilities could curtail LNG deliveries and impact natural gas supplies. Therefore, methods to ensure the safety, security, and reliability of current or future LNG terminals and LNG shipments are important from both public safety and property perspectives, as well as from a regional, energy reliability standpoint. Methods to reduce the risks and hazards from a potential LNG spill must be considered on a site-specific basis and will vary, depending on factors such as location, geography, operational considerations, and weather conditions. The next section discusses the process used to assess LNG tanker safety and security from accidental and intentional events, improve overall protection, and reduce impacts on public safety and property.

3 RISK ASSESSMENT OF LNG SPILLS OVER WATER

High consequence operations such as the transportation, off-loading, and storage of LNG imply potential risks to people and property. Risk is defined as the potential for suffering harm or loss and is often quantified as the product of the probability of occurrence of a threatening event times the system vulnerability to that event and the consequences of that event. Thus,

Risk = $\mathbf{P_t}$ (threat occurring) x $\mathbf{P_s}$ (system failure/threat) x **Consequences**;
Where: $\mathbf{P_t}$ = the probability of an accidental or intentional threat,
$\mathbf{P_s}$ = the probability that preventive or mitigating measures fail, and
Consequences = usually expressed in fatalities or costs.

Effectively evaluating the risks of a large LNG spill over water requires that the potential hazards (results of events that are harmful to the public and/or property) and consequences be considered in conjunction with the probability of an event, plus the effectiveness of physical and operational measures of LNG transportation to prevent or mitigate a threatening event. For example, safety equipment, operational considerations and requirements, and risk management planning can work together to reduce the risks of an LNG spill by reducing both the probability of an event that could breach the LNG tanker and by reducing the consequences of a spill.

Because of the difficulty in assessing the effectiveness of ship safety measures and operational safety and security strategies, many studies assume the probability of an event and a ship's vulnerability to be one; therefore, the concentration is on calculating expected consequences. This often provides worst-case results with low probability and very high uncertainty, which can inappropriately drive operational decisions and system designs. Therefore, for high consequence and low probability events, a performance-based approach is often used for developing risk management strategies that will reduce the hazards and risks to both public safety and property.

3.1 Risk Analysis Elements of a Potential LNG Spill

The risk analysis approach of a potential LNG spill should include:

1. **Uncertainty:** Assessment of the accuracy of the assumptions used and the probable ranges.
2. **Comprehensiveness:** Do the failure modes considered account for all major avenues of loss? Understanding the full range of consequences associated with a catastrophe can require considerable effort. Completeness is important to properly support risk assessment and risk management.

   Two important variables are 'directness of effect' and 'latency.' For example, if an explosion breaches an LNG cargo tank on a ship, that is a direct effect. Conversely, if a resulting explosion damages an LNG terminal—hampering future LNG deliveries for extended periods—that is an indirect or latent effect. Latency refers to when the effects are felt. Immediate effects occur simultaneously with the threat; whereas latent effects occur after an interval, the length of which might vary from system to system. It should be emphasized that indirect/latent effects sometimes dominate other consequences.

3. **Evaluation of risk reduction measures:** One way to reduce risk is to remove or block the threat; i.e., prevent the disaster from occurring in the first place. For example, reinforce ships against collisions or reduce ship speeds in a harbor to reduce the chance of a spill.
4. **Threat as a moving target:** Many avenues to failure — mechanical, environmental insult, operator error — are amenable to analysis and can be confidently predicted to occur with some probability in the future. Other types of threats can be constantly changing and difficult to assess accurately, requiring more robust approaches for prevention or mitigation and frequent re-evaluations of new threats.

3.2 LNG Spill Risk Assessment and Management Process

A general performance-based risk assessment and risk management process is shown schematically in Figure 3. The risk analysis, in turn, helps support a program for managing risks of LNG deliveries to terminals for site-specific locations and conditions. The risk assessment and management process includes:

- 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 physical and environmental conditions; and
- When necessary, identifying prevention and mitigation approaches and strategies to meet risk management goals.

As illustrated in Figure 3, if risks, costs, or operational impacts are deemed to be too high, the overall process cycles back through the evaluation to identify alternative approaches for improving system performance. Safeguards could include a range of risk management options: improvements in ship protection, modification of existing operational and safety and security management procedures, improvements in emergency response coordination, or changes in support operations or services. The risks are then re-evaluated according to the new approaches to determine if they meet identified risk management goals. If not, then the evaluations can be repeated with additional provisions or changes until the risk management goals are reached. The potential alternatives, changes, and/or upgrades can be compared through the process to identify appropriate and effective approaches for improving overall system safety and security.

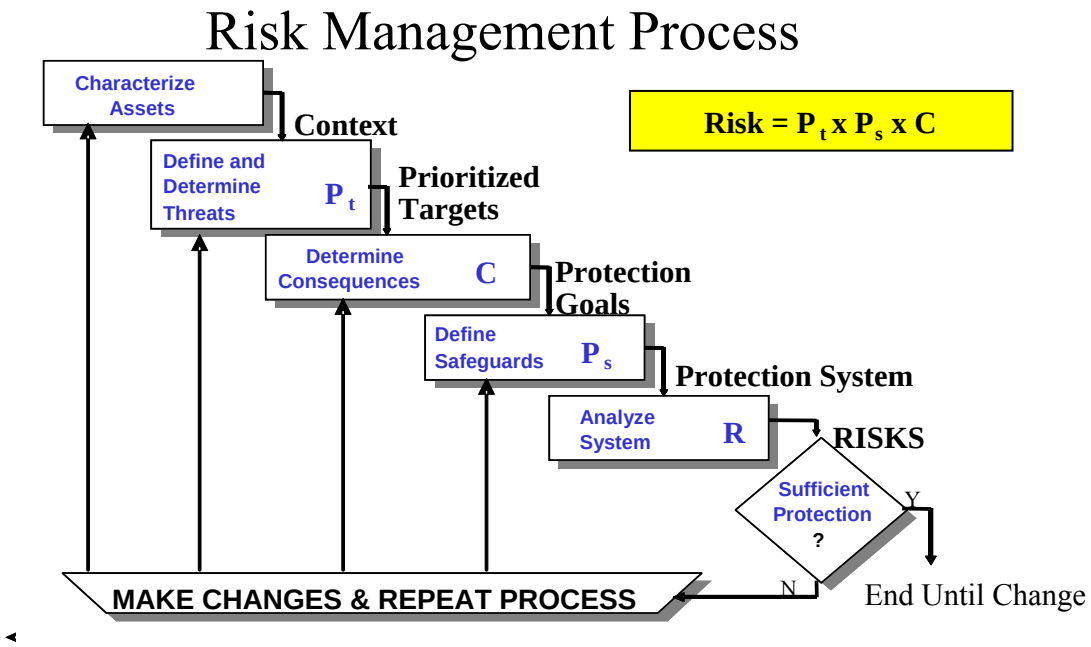


Figure 3. Risk Assessment and Risk Management Approach

Deciding on the sufficiency of protection measures to meet risk management goals is often aided by a benefit-cost evaluation. In most locations and most operations, some level of risk is common and, therefore, a "residual" risk often remains. For example, certain levels of safety equipment are standard features in automobiles, such as seat belts, air bags, and antilock brakes. While they might be effective safety measures, they do not provide total protection in all automobile accident scenarios. Therefore, the public does have some level of risk associated with driving.

How might risk management considerations apply to LNG transportation and off-loading? Table 5 illustrates some examples of potential LNG transportation safeguards and associated impacts on overall effectiveness, cost, operations, and residual risks.

Table 5: Examples of Potential LNG Transportation Safeguards and Impacts

SAFEGUARD ACTION	RISK REDUCTION	RESIDUAL RISKS	CONSEQUENCE IMPROVEMENT	COST OF SAFEGUARD APPROACH	OPERATIONAL IMPACTS
Smaller LNG tankers	Potential smaller fire size and shorter fire duration	Thermal hazards from small fire, higher accident potential with increased shipments	potential reduction in hazard zone and reduced impacts on public safety and property	Increased shipping costs, increased energy costs	Increased number of shipments, additional port disruption
Evacuation during LNG shipments	Reduce hazards to people from potential spill	Hazards to property from a fire, accidents during evacuation	Reduce injuries and deaths from potential fire	Labor intensive, increased costs for emergency services	Disruption of evacuees
Remote terminal and pipeline	Reduce impacts on public safety and property from potential fire	Impact on public safety and property from potential pipeline leaks	potential reduction in hazards from large-scale or catastrophic fire	potential high capital costs, increased energy costs	Pipeline vulnerability issues

While many potential safeguards might be identified for a given location, the level of risk reduction and risk management required to be protective of public safety and property for LNG transportation will vary based on site-specific conditions. The risk management goals for a given location should be determined in cooperation with all stakeholders. Stakeholders include the general public, public safety officials and elected officials, facility operators, port and transportation safety and security officials, underwriters, utility representatives, regulatory agencies, and ship management companies.

3.3 The Elements of an LNG Spill over Water

The detailed flowchart ('event tree') in Figure 4 illustrates an overview of event sequences that might ensue following a breach of an LNG cargo tank and /or a spill. The purpose of the flowchart is to provide a basis for a comprehensive risk analysis. In the event tree, time progresses roughly from left to right, beginning with a potential breach or damage of an LNG cargo tank or LNG handling system; progressing to an LNG spill, dispersion, and energy release; ending with an analysis of impacts on people and property. The event tree approach helps ensure that all credible events are considered systematically and helps identify critical elements in the event sequence. This aids in focusing risk management efforts on the most important elements, and improving both public safety and security more efficiently and cost-effectively. As shown in the event tree, the hazards and consequences from potential spills can vary.

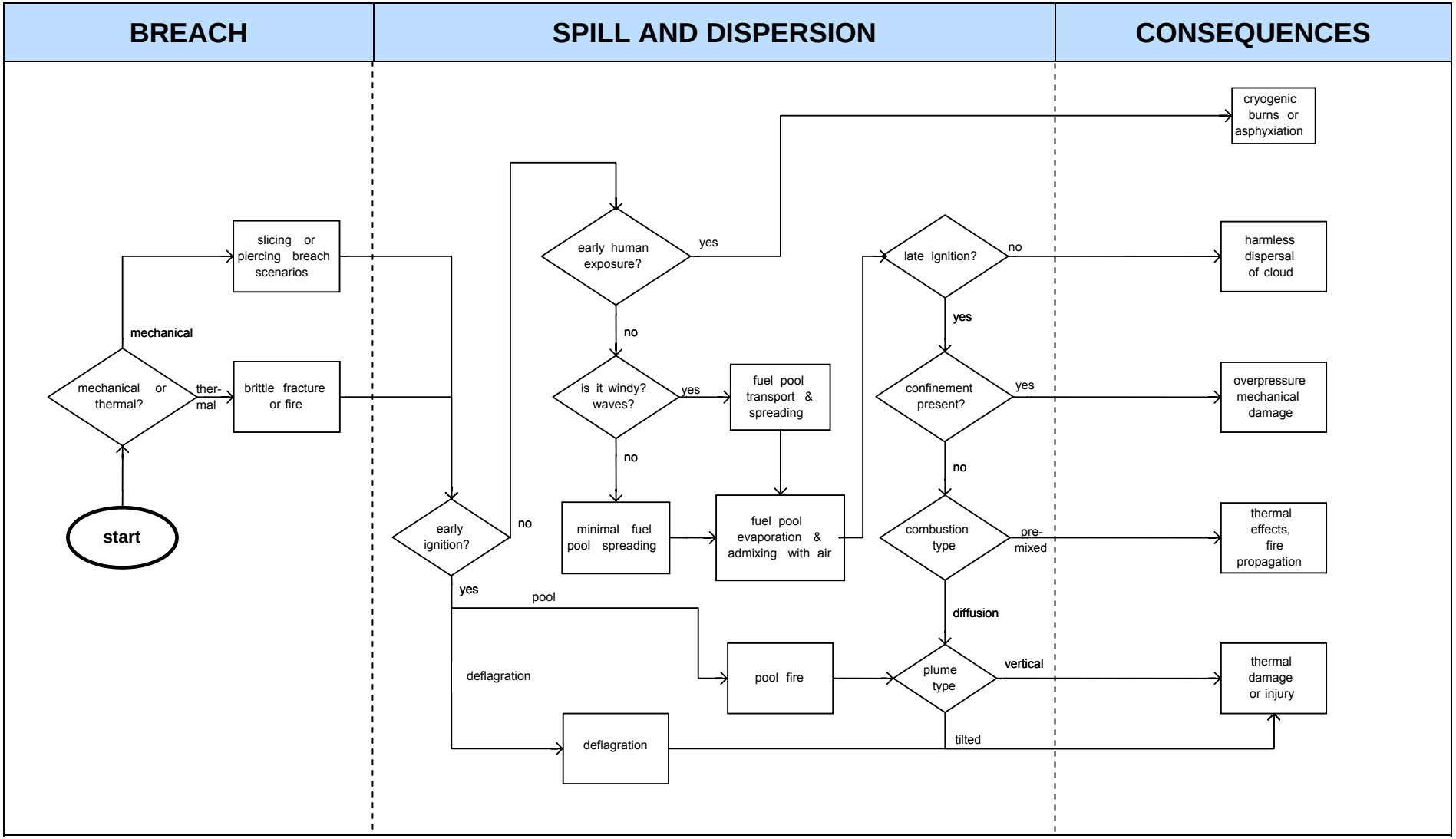


Figure 4. Potential Sequences of Events Following a Breach of an LNG cargo tank

3.3.1 LNG Cargo Tank Breaches

The variables that influence an LNG cargo tank breach include:

- Type and location of the breach and the energy involved,
- The vessel's geometry, its construction and materials, hold spaces, distance between hulls, tonnage, and event mitigation systems;
- LNG cargo tank construction and size; and
- The fluid mechanics and thermodynamic characteristics of LNG.

Figure 5 illustrates a breach and subsequent spill involving a Moss tanker. If the cargo tank is punctured, LNG driven only by weight of the fluid itself will traverse the ship's below-decks spaces plus the ballast space between the two hulls, which are empty when a full cargo is on board [Kaplan and Marshall 2003]. The speed at which an LNG spill will progress will depend on the size and location of the breach in the LNG cargo tank.

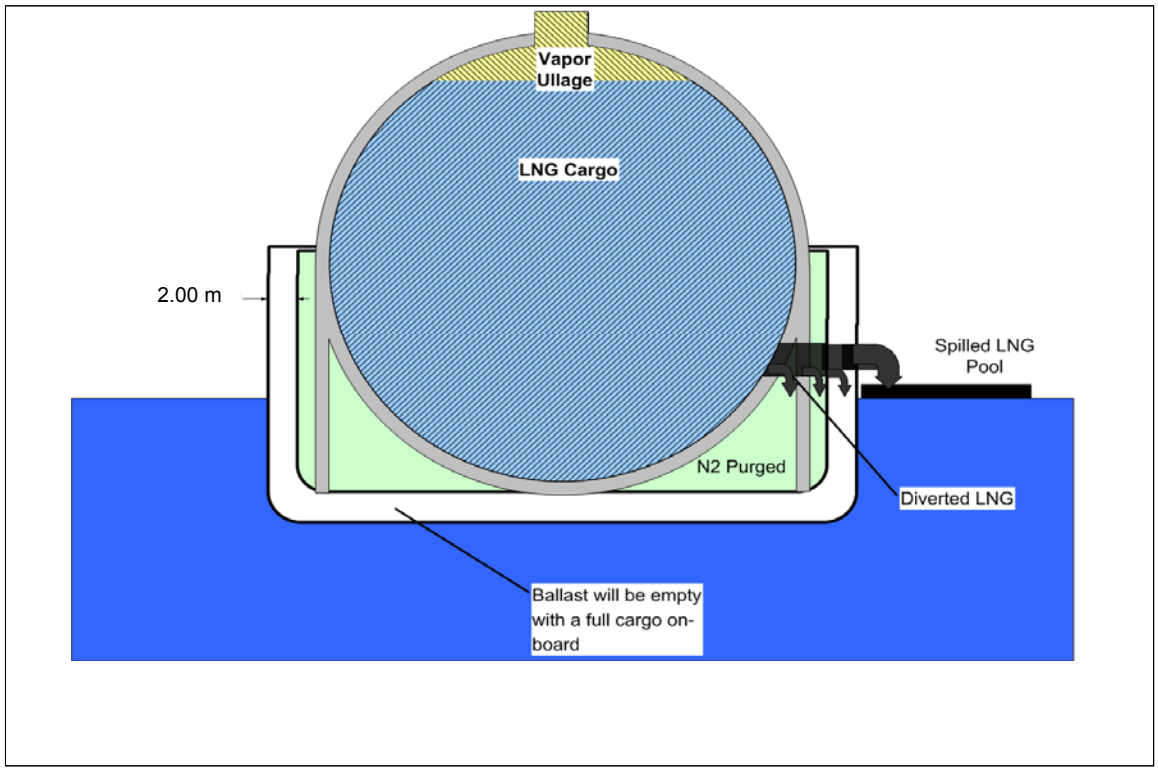


Figure 5. Anatomy of an LNG Spill on Water

For LNG cargo tank designs, a realistic estimate of tanker losses (i.e., the fraction of the spill that reaches the water) must be reduced to account for LNG diverted to the ballast space or, for the Moss spherical design, vacant hold areas. Spill damage to the ship from contact with the cryogenic LNG and/or from fire damage to the ship or its other LNG cargo tanks are consequences that were considered during this study. Based on the analyses, the potential for damage to the ship cannot be ruled out, especially for large spills. However, it was concluded that releases from no more than two or three tanks would be involved in a spill at

any one time. This cascading release is not expected to increase significantly the overall fire size or hazard ranges, but the expected fire duration would increase.

The potential size and impact from several breaching scenarios from both accidental and intentional events were evaluated and are summarized in Sections 4 and 5 and discussed in detail in Appendix B – *Threat Analysis and Spill Probabilit*y.

3.3.2 LNG Spill Dispersion after a Breach

Quantifying the size and likelihood of spills from different events drives the *Spill and Dispersion* part of the event tree. Following a tank breach or other spill event, depending on the size and location, LNG can be expected to spill onto or into the LNG ship itself, escape through a breach onto the water surface, or both. Depending on whether there is early or late ignition, LNG dispersion can occur through either volatilization of the LNG into the air and transport as a vapor cloud or transport as a liquid on the surface of the water.

Several variables must be addressed in developing an assessment of an LNG spill and its general dispersion, including potential ignition sources and ignition times. These factors determine whether the LNG disperses without a fire, burns as a pool fire, or burns as a vapor fire. Assumptions made in addressing or analyzing these variables can have a significant impact on estimates of the potential hazards associated with an LNG spill. The experimental results from a wide range of spill and dispersion testing were evaluated and the expected impacts of large-scale spills over water were evaluated. They are summarized in Sections 4 and 5 and discussed in detail in Appendix C – *LNG Spill and Dispersion Analysis*.

3.3.3 Potential Consequences from an LNG Spill over Water

The consequences or hazards from an LNG spill include a wide range of potential events, as illustrated in the event tree. The sections below discuss the analyses that should be considered in a study attempting to assess the consequences and hazards of an LNG spill for a specific site. The potential hazards and their results were reviewed and evaluated and are summarized in Sections 4 and 5, and discussed in detail in Appendix C – *LNG Spill and Dispersion Analysis* and Appendix D – *Spill Consequence Analysis*.

Asphyxiation

Methane is considered a simple asphyxiant, but has low toxicity to humans. In a large-scale LNG release, the cryogenically cooled liquid LNG would begin to vaporize upon release from the breach of an LNG cargo tank. If the vaporizing LNG does not ignite, the potential exists that the LNG vapor concentrations in the air might be high enough to present an asphyxiation hazard to the ship crew, pilot boat crews, emergency response personnel, or others that might be exposed to an expanding LNG vaporization plume. Although oxygen deficiency from vaporization of an LNG spill should be considered in evaluating potential consequences, this should not be a major issue because flammability limits and fire concerns will probably be the dominant effects in most locations.

Cryogenic Burns and Structural Damage

The very low temperature of LNG suggests that a breach of an LNG cargo tank that could cause the loss of a large volume of liquid LNG might have negative impacts on people and property near the spill, including crewmembers or emergency personnel. If LNG liquid contacts the skin, it can cause cryogenic burns.

Potential degradation of the structural integrity of an LNG ship could occur, because LNG can have a very damaging impact on the integrity of many steels and common ship structural connections, such as welds. Both the ship itself and other LNG cargo tanks could be damaged from a large spill.

Combustion and Thermal Damage

In general, combustion resulting from industrial incidents such as an LNG spill can result in thermal and/or pressure loading. Thermal loads are very dependent on the rate of energy conversion ('heat release rate'). Pressure loads are very dependent on the power density; that is, the heat release rate per unit volume. Thus, how combustion occurs is as important to the consequences of a spill as is the energy available. Table 6 shows the general type of thermal radiation damage from a fire. These levels are often used to establish fire hazard areas.

Table 6: Common, Approximate Thermal Radiation Damage Levels

Incident Heat Flux (kW/m^2)*	Type of Damage
35 – 37.5	Damage to process equipment including steel tanks, chemical process equipment, or machinery
25	Minimum energy to ignite wood at indefinitely long exposure without a flame
18 – 20	Exposed plastic cable insulation degrades
12.5 – 15	Minimum energy to ignite wood with a flame; melts plastic tubing
5	Permissible level for emergency operations lasting several minutes with appropriate clothing

*Based on an average 10 minute exposure time
[Barry 2002]

For example, the National Fire Protection Association standard for the production, storage, and handling of Liquefied Natural Gas (Standard 59A) recommends that an incident heat flux value of 5 kW/m^2 be the design level that should not be exceeded at a property line or in areas where groups of more than 50 people might assemble [NFPA 2001]. Therefore, 5 kW/m^2 is a commonly used value for establishing fire protection distances for people. While structures might be able to withstand higher levels of incident heat flux, as shown in Table 6, heat flux levels approaching 35 kW/m^2 will cause significant damage to structures, equipment, and machinery.

Generally, combustion of LNG vapor is controlled by two limiting factors: 1) whether the LNG vapor does not have enough time to mix with the air (called non-pre-mixed combustion), and 2) whether the ignition occurs after the fuel has time to mix with the surrounding air (appropriately called 'pre-mixed combustion'). Therefore, ignition time is important in spill scenarios to assess appropriately the type and extent of thermal radiation

from an LNG spill and fire. As noted in Table 6, combustion and thermal damage from a fire can have severe consequences and should be carefully and thoroughly analyzed.

LNG/Fireballs

Two types of combustion modes might produce damaging pressure: 'deflagration' and 'detonation'. Deflagration is a rapid combustion that progresses through an unburned fuel-air mixture at subsonic velocities; whereas, detonation is an extremely rapid combustion that progresses through an unburned fuel-air mixture at supersonic velocities. For low reactivity fuels such as natural gas, combustion will usually progress at low velocities and will not generate significant overpressure under normal conditions. Ignition of a vapor cloud will cause the vapor to burn back to the spill source. This is generally referred to as a 'fireball', which, by its nature, generates relatively low pressures, thus having a low potential for pressure damage to structures.

LNG/Air Explosions

Certain conditions, however, might cause an increase in burn rate that does result in overpressure. If the fuel-air cloud is confined (e.g., trapped between ship hulls), is very turbulent as it progresses through or around obstacles, or encounters a high-pressure ignition source, a rapid acceleration in burn rate might occur [Benedick et al. 1987]. The potential for damaging overpressures from such events could occur under some limited spill and dispersion scenarios, specifically in confined areas. However, effects will be localized near the spill source and are not expected to cause extensive structural damage.

Rapid Phase Transitions (RPT)

Rapid Phase Transitions occur when the temperature difference between a hot liquid and a cold liquid is sufficient to drive the cold liquid rapidly to its superheat limit, resulting in spontaneous and explosive boiling of the cold liquid. When a cryogenic liquid such as LNG is suddenly heated by contacting a warm liquid such as water, explosive boiling of the LNG can occur, resulting in localized overpressure releases. Energy releases equivalent to several kilograms of high explosive have been observed. The impacts of this phenomenon will be localized near the spill source and should not cause extensive structural damage.

3.4 Evaluation of Four Recent LNG Spill Modeling Studies

Four recent LNG spill-modeling studies were evaluated to assess whether they provide a definitive determination of the lateral extent and thermal hazards of a large-scale release of LNG over water. The results of the comparisons are summarized below and detailed in Appendix A. The studies reviewed include:

- "Comparison of Hypothetical LNG and Fuel Oil Fires on Water." Report by the National Oceanic and Atmospheric Administration (NOAA), Office of Response and Restoration, Seattle, WA, 2003, DRAFT [Lehr and Simicek-Beatty 2003].
- "Model of spills and fires from LNG and oil tankers." Journal of Hazardous Materials, B96-2003, 171-188, 2003 [Fay 2003].
- "Modeling LNG Spills in Boston Harbor." Copyright© 2003 Quest Consultants, Inc., 908 26th Ave N.W., Norman, OK 73609; Letter from Quest Consultants to DOE

(October 2, 2001); Letter from Quest Consultants to DOE (October 3, 2001); and Letter from Quest Consultants to DOE (November 17, 2003) [Quest 2003].

- "Liquefied Natural Gas in Vallejo: Health and Safety Issues." LNG Health and Safety Committee of the Disaster Council of the City of Vallejo, CA, January 2003 [Vallejo 2003] [Koopman 2004].

An event tree of generic LNG spill scenarios was used to compare and contrast the analysis process in each study. Table 7 summarizes and illustrates the range of assumptions employed in each of the four studies for evaluating a potential LNG cargo tank breach plus an associated fuel spill, its spread and dispersion, and fuel ignition and burning. All the studies assumed ignition such that the fuel burns as a pool fire, with no explosions.

Table 7: Summary of Assumptions in the Four Studies Analyzed

STUDY	TIME TO EMPTY (Min)	VAPORIZES DURING SPREAD	EFFECT OF WAVES INCLUDED	POOL SHAPE	IGNITION TIME	FLAME MODEL	COMBUSTION MODE	IGNITION AT POOL; NOT IN VAPOR CLOUD
Lehr	Instantly	Yes	No	Circle	Instantly	Solid cylinder	Diffusion flame with no explosion	Yes
Fay	Varies with hole size	Yes	No	Semicircle	Instantly	Point source	Diffusion flame with no explosion	Yes
Quest	2	Yes	Yes	Circle	Instantly after spread	Solid cylinder that includes tilt for wind effects	Diffusion flame with no explosion	Yes
Vallejo	Varies with hole size	Yes	No	Circle	Instantly	Point source	Diffusion flame with no explosion	Yes

Table 8 presents a summary of the LNG spill and fire hazard predictions for each of the studies. The distances between the fuel fire and specific thermal hazards are shown in the columns labeled as "Skin Burn Distance" and "Paper Ignition Distance." A secondary indicator of thermal hazard is shown in the "Fire Duration" column.

Significant differences were observed among the studies in the thermal hazard distances calculated, due to each analyst's use of different fuel spill volumes and different approximations in the models for spill spreading, fuel burning, and heat transfer. The *Vallejo*, *Quest,* and *Fay* reports addressed comparable large spills; and the *Lehr* paper concentrated on spills that were twenty-five to fifty times smaller in volume.

Each of the studies differed in its use of models for fire and heat transfer. For example, if identical fuel spill areas and fire thermal emission levels are used as inputs, the heat transfer models used in the *Quest* and *Fay* studies predict thermal hazards that differ by 30%, due to the flame model and pool size assumptions noted in Table 7. Each of the studies assumed a source of ignition (required to start a fire), but excluded consideration of the timing of ignition relative to the release and spreading of the LNG.

Table 8: Summary of Results of Four Recent LNG Studies Analyzed

STUDY	FUEL SPILL VOLUME (m^3)	AREA OF FUEL SPILL (m^2)	"SKIN BURN" DISTANCE[a] (m)	"PAPER IGNITION" DISTANCE[b] (m)	FIRE DURATION (min)
Lehr	500 (hole area not specified)	not reported	500[c]	not reported	2-3
Fay[e]	14,300 ($20m^2$ hole area)	200,000	1900	930	3.3
Quest	12,500 ($20m^2$ hole area)	9503	490[d]	281[d]	28.6
Vallejo	14,300 ($20m^2$ hole area)	120,000	1290	660	9

[a]Thirty-second exposure to heat levels of 5 kW/m^2 causes second-degree skin burns (blisters) at this distance.
[b]Seventeen-second exposure to heat levels of 22 kW/m^2 causes newspaper to ignite at this distance. [SFPE Handbook of Fire Protection Engineering, 2nd ed., National Fire Protection Association, (1995)]
[c] Distance from edge of spill
[d]Assuming a wind speed of 9 m/s (20 mph).
[e] Considers a range of hole sizes. This size chosen for comparison.

The studies also differed in their use of meteorological conditions, such as waves for the locations considered. *Quest* is the only study that used an LNG spill dispersion model in which the impact of waves on the spill pool area was considered. Many of the assumptions and parameters used in the calculations and analyses were not specifically validated.

While existing analytical models and techniques can be used to provide general guidance on the potential hazards associated with a large LNG spill, the four studies do demonstrate how differences in the assumptions of spill size, fire modeling parameters, and environmental factors can have a significant impact on calculated hazard distances. Therefore, the studies show how important it is to use appropriate assumptions, data, and models in trying to develop an accurate assessment of hazards from an LNG spill. While each of the studies provides an example of the potential consequences of a large-scale LNG spill over water, none of the studies identified the probability of the postulated events and assumptions, nor did any discuss mechanisms or strategies that could be implemented to reduce the potential risks of such a spill. Therefore, they do not provide a characterization of how to manage the risks to people and property of a large-scale LNG spill over water

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/m^2, 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 m^3 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/m^2 and 5 kW/m^2 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/m^2 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/m^2 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/m^2 and low values would correspond to thermal intensities in the range of 5 kW/m^2.

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 ▪ Damage to ship ▪ Vapor Cloud	High Medium High	Medium Low High - Medium	Low Very Low 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

5 INTENTIONAL LNG BREACH, SPILL, AND HAZARD ANALYSES

Currently, the potential for an intentional LNG cargo tank breach, the dynamics and dispersion of a large spill, and the hazards of such a spill, are not fully understood, for two primary reasons. First, the combination of LNG ship designs and current safety management practices for LNG transportation have reduced LNG accidents, so that there is little historical or empirical information on large breaches or spills, as discussed in Section 4. Second, for an intentional event, existing experimental data on LNG spill dynamics, dispersion, and burning over water cover spill volumes that are more than two orders of magnitude less than the spill volumes being postulated in many recent studies.

This lack of information forces analysts to make many assumptions and simplifications when calculating the size, dispersion, and thermal hazards of a spill. This section summarizes the modeling and analyses conducted to assess the potential for an intentional LNG breach and the associated hazards to public safety and property from a resulting spill. The detailed results of these analyses are presented in Appendices B – D.

5.1 Analysis of Intentional Breach Scenarios of an LNG Cargo Tank

As in Section 4, available intelligence and historical data were also used to establish a range of potential intentional LNG cargo tank breaches that could be considered credible and possible. This included evaluation of information on insider and hijacking attacks on ships, and external attacks on ships. Again, the level of knowledge, materials, and planning needed to create intentional breaching events was evaluated. Based on this evaluation, explosive shock physics modeling and analysis were used to perform scoping calculations of potential breach sizes for a range of intentional attacks. Details of these evaluations and analyses are presented in Appendix B.

While a discussion of the specific threats and expected consequences is inappropriate for this report, it is appropriate to discuss the range of breaches that were calculated for a wide range of intentional events. A summary of the modeling and analysis efforts developed and conducted to calculate the potential breaches from various intentional scenarios is presented in an associated Classified report [Hightower 2004].

A computational shock physics code, CTH, and material data were used to calculate expected breach sizes for several different intentional scenarios. CTH is a Eulerian finite volume code and is required to estimate and analyze the large-scale deformations and material responses under very high strain rates that might be developed due to high velocity penetration or explosion scenarios.

Based on the scoping analyses for LNG tanker designs, the range of hole sizes calculated from most intentional breaches of an LNG cargo tank is between 2 – 12 m^2. Our analysis suggests that, in most cases, an intentional breaching scenario would not result in a nominal tank breach of more than 5 – 7 m^2. This range is a more appropriate value to use in

calculating potential hazards from spills. Based on the threat it is possible to breach more than one LNG cargo tank during an event.

For both LNG tanker designs, a breach could occur in LNG cargo tanks either above or below the water line. The location impacts the amount of LNG spilled onto the water surface and the amount of LNG that might be spilled into the internal ballast areas between the hulls and vacant hold areas. LNG spilled between the hulls could negatively impact the structural integrity of the tanker or the cargo tanks. Table 13 identifies the level of ship damage from each of the breaching events indicated.

Table 13: Estimated LNG Cargo Tank Breach Sizes for Intentional Scenarios

INTENTIONAL BREACHES		
Breach Size	**Tanks Breached**	**Ship Damage**
0.5 m^2	1	Minor
2 m^2	1	Minor
2 m^2	3	Moderate
12m^2	1	Severe
5 m^2	2	Severe
Premature offloading of LNG	None	Moderate-Severe

Note: *Severe* suggests significant structural damage. Ship might not be able to be moved without significant difficulty and includes potential for cascading damage to other tanks

The intentional breaches and spills shown above include several different events, including a range of potential attacks and insider threats. The large breach sizes calculated, while smaller than commonly assumed in many studies, still provide the potential for large LNG spills. Based on the ranges identified in this study, a nominal breach size of 5 – 7 m^2 was considered. Spill prevention or mitigation techniques should be considered where the consequences or hazards from such breach sizes are most severe.

Table 13 shows that, for many intentional breaching events, the cryogenic damage to the LNG vessel could be minor to moderate, or even severe. Severe structural damage could occur from some of the very large spills caused by intentional breaches. This result is because the volume and rate of the LNG spilled could significantly impact the ship's structural steel. A cascading failure that involves damage to adjacent cryogenic tanks on the ship from the initial damage to one of the LNG cargo tanks is a possibility that cannot be ruled out.

Determination of the potential or likelihood of such an event depends on the breach scenario, the spill location, and any implementation of prevention and mitigation strategies to prevent such an event. In areas where cascading failures might be a significant issue, the use of complex, coupled, thermal, fluid and structural analyses should be considered to improve the analysis of the potential for and extent of structural damage to the LNG ship and other LNG cargo tanks.

5.1.1 Evaluation of the Fire Hazard of an Intentional LNG Spill

In order to determine the general range of hazard levels and to provide a demonstration of how hazard zones can be delineated, the following analysis was performed, the details of which are described in Appendix D.

As stated in Section 4, in most of the scenarios identified, the thermal hazards from an intentional 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 intentional breach scenarios developed. The same modeling approach and assumptions as discussed in Section 4 were used for these analyses. While the details of the analyses are presented in Appendix D, a summary of these results is shown in Table 14, where the distances to 37.5 kW/m^2 and 5 kW/m^2 are from the center of the pool.

Table 14: Intentional Breach — Effect of Parameter Combinations on Pool Diameter

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)
2	3	.6	3×10^{-4}	220	209	20	250	784
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	2×10^{-4}	220	395	8.1	454	1538
5	1	.6	3×10^{-4}	350	330	8.1	529	1652
12	1	.6	3×10^{-4}	220	512	3.4	602	1920

*nominal case

The results presented in Table 14 show that the thermal hazards of 37.5 kW/m^2 are expected to occur within approximately 500 m of the spill for most of the scenarios evaluated. For the 2 m^2 three-hole breach, it was assumed that individual pools would form; whereas, for the 5 m^2 three-hole breach, a single pool was assumed to form. The release from the three holes was considered to happen simultaneously. It should be noted that these conditions consider cascading damage resulting from fire or cryogenic-induced failure.

Most of the studies reviewed assume that a single, coherent pool fire can be maintained for very large pool diameters. This would be unlikely due to the inability of air to reach the interior of a fire and maintain combustion on an LNG pool that size. Instead, the flame pool envelope would break up into multiple pool fires (herein: 'flamelets'), the heights of which are much less than the fuel bed diameter used in the calculations by the four previously discussed studies. This breakup into flamelets results in a much shorter flame height than that assumed for a large pool diameter. In reality, L/D (height/pool diameter) would probably be much smaller than that assumed by the correlations in many studies, which predict an L/D ratio between 1.0 and 2.0. A more realistic ratio could be less than 1.0 [Zukoski 1986] [Corlett 1974] [Cox 1985].

Because the heat radiated by the flamelets would be far less than the heat radiation calculated in the many studies (based on a large pool fire), the amount of radiative heat flux that an adjacent object receives would be less, thereby decreasing the size of the thermal hazard zone. As discussed in Appendix D, the use of a mass fire assumption could reduce hazard distances for large spills. The development of fire whirls might increase the hazard zone. Therefore, this type of pool fire model should be carefully considered to improve thermal hazards analysis from potential large spills.

The results presented suggest that the potential thermal hazards for large spills can vary significantly, based on the uncertainty associated with potential spill sizes, dispersion variations, and threats. Based on the estimated pool size for large spills, even with the possibility of reduction in effects for mass fires as opposed to single pool fires, high thermal hazards approaching 37.5 kW/m^2 could probably extend to approximately 500 meters. The thermal hazards between 500 meters and 1600 meters decrease significantly. The hazards would be low, approximately 5 kW/m^2 beyond 1600 m from even a large spill. Based on these observations, approximate hazard zones seem to exist between 0 – 500 m, 500 – 1600 m, and over 1600 m, and were used to develop guidance on managing risks for LNG spills.

5.1.2 Evaluation of Vapor Dispersion Hazard of Intentional LNG Spills

In most of the scenarios identified, the thermal hazards from a 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, such as an intentional spill without a tank breach, an immediate ignition source might not be available and the spilled LNG could, therefore, disperse as a vapor cloud. For large spills, the vapor cloud could extend to more than 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.

As mentioned in Section 4, the impact from a vapor cloud dispersion and ignition from a large spill can extend beyond 1600 meters, based on our review of external data discussed in Appendix C. 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. Consideration of risk mitigation measures, such as development of procedures to quickly ignite a dispersion cloud and stem the leak, 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 LFL for intentional events, calculations were performed using VULCAN, as discussed in Section 4. A low wind speed and highly stable

atmospheric condition were chosen because this state has shown to result in the greatest distances to LFL from experiment, and thus should be the 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. For intentional events, two cases were run, one for the nominal case of a 5-m^2 hole and one tank breach, and the other for a 5-m^2 hole and three tanks breached. This case is the largest spill; hence, it should give the greatest LFL for intentional events. As indicated in Table 15, the dispersion distance to LFL for intentional events might extend from nominally 2500 m to a conservative maximum distance of 3500 m for this unlikely event.

While previous studies have addressed the vapor dispersion issue from a consequence standpoint only, the risk analysis performed as part of this study indicates that the potential for a large vapor dispersion from an intentional breach is highly unlikely. This is due to the high probability that an ignition source will be available for many of the initiating events identified, and because certain risk reduction techniques can be applied to prevent or mitigate the initiating events identified. The significant distances, though, of a potential vapor dispersion suggest that LNG vapor dispersion analysis and risk mitigation measures should be carefully considered to protect adequately both the public and property.

Table 15: Dispersion Distances to LFL for Intentional Spills

HOLE SIZE (m^2)	TANKS BREACHED	POOL DIAMETER (m)	SPILL DURATION (min)	DISTANCE TO LFL (m)
5	1	330	8.1	2450
5	3	572	8.1	3614

The analyses from the fire and vapor dispersion calculations suggest that high thermal hazards from intentional events extend significantly from the spill location. Table 16 summarizes the general impacts on both public safety and property for intentional breaches and spills. In this table, high impact would include a thermal intensity in the range of 37.5 kW/m^2 and low values would correspond to thermal intensities in the range of 5 kW/m^2 .

These results should be used as guidance, bearing in mind that these distances will vary, based on site-specific factors and environmental conditions.

Table 16: Estimated Impact of Intentional LNG Breaches & Spills on Public Safety & Property

EVENT	POTENTIAL SHIP DAMAGE AND SPILL	POTENTIAL HAZARD	POTENTIAL IMPACT ON PUBLIC SAFETY[a]		
			~500 m	~500 – 1600 m	>1600 m
Insider Threat or Hijacking	Intentional, 2-7 m^2 breach and medium to large spill	▪ Large fire	High	Medium	Low
		▪ Damage to ship	High	Medium	Low
		▪ Fireball	Medium	Low	Very Low
	Intentional, large release of LNG	▪ Large fire	High	Medium	Low
		▪ Damage to ship	High	Medium	Low
		▪ Vapor cloud fire	High	High - Med	Medium
Attack on Ship	Intentional, 2-12m^2 breach and medium to large spill	▪ Large fire	High	Medium	Low
		▪ Damage to ship	High	Medium	Low
		▪ Fireball	Medium	Low	Very Low

[a] 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

6 RISK REDUCTION STRATEGIES

A customized, risk management approach is necessary because every LNG site has unique features. Performance-based safety requirements are often used in instances where there is a lack of good information on operational consequences or hazards. In many cases, safety information does exist and, based on available data, prescriptive safety requirements described by codes, standards, or other regulations are often developed and recommended. For combined safety and security applications, where threats can change or grow rapidly, performance-based regulations and strategies can often provide the flexibility needed to respond to the evolving security and safety needs.

To obtain the most complete picture of the potential consequences in a given breach scenario, a target-mechanism-consequence model is suggested. The target is the vulnerable element on which some mechanism acts to produce an undesired consequence. For example, a private residence (target) on a nearby shore can be ignited by radiant energy from a burning LNG spill (mechanism) that might lead to loss of property (consequence). Following the example, an LNG spill might trace to a number of causes, such as structural insult or premature off-loading of LNG. This section identifies some targets, mechanisms, and consequences that might be useful in developing approaches to manage risks at existing or future LNG terminal sites.

6.1 Target – Mechanism – Consequence Model

Target

Targets are usually identified as physical objects or subsystems, but people (operators, residents, etc.) are targets as well.

Table 17: Targets Table

TARGETS AFLOAT	FIXED TARGETS IN WATER	TARGETS ASHORE
LNG tanker	Bridge	LNG storage terminal
Other tanker (e.g., gasoline)	Tunnel	Adjacent industry
Security escort	LNG terminal or other pier	Residential & business districts
Rescue vessel	Ship channel	Roadways
Pleasure boat	Oil rig	Airport

Mechanism

Failure mechanisms can be either accidental or intentional; and they can be categorized under physical, cyber and communications, and interpersonal.

Table 18: Mechanisms Table

PHYSICAL	CYBER AND COMMUNICATIONS	INTERPERSONAL
Collisions & other impacts	On-ship communications	Sabotage
Brittle fracture (cryogenic)	On-ship control	Espionage
Bulk explosions	Harbor master communications	Infiltration
Directed explosions (shaped charge)	Process control and data acquisition systems	Subversion
Fire dynamics	Ship to ship and ship to shore communications	Diversion
Cryogenic liquid dynamics	Tactical and emergency communication systems	Hiding

Consequence

Intentional mechanisms (deliberate acts) can often produce greater consequences than accidental mechanisms because the perpetrator can maximize the effects of an attack by choosing the time and place. In fact, the perpetrator might coordinate several, simultaneous attacks, thus compounding the consequences. Consequences can include local, cascading, and delayed effects. All these effects must be considered in developing an overall risk reduction and risk management approach.

Table 19: Consequences Table

LOCAL	CASCADING	DELAYED
Death or injury to tanker crew	Death or injury to escort vessel crews	Death or injury to rescue vessel crews
Damage or loss of LNG vessel	Damage or loss of escort vessels	Disruption of future LNG deliveries
Blockage of waterway	Hold on operations at other waterways	Denial of future operations at other waterways
Fire damage to nearby structures or infrastructures	Loss of use of other infra-structures	Denial of future operations at receiving terminal
Public deaths and/or injuries	Public deaths and/or injuries	Loss of use of infrastructures or properties
	Economic losses	Economic losses and loss of energy supplies

6.2 Risk Management Strategies: Prevention and Mitigation

Many factors can impact risks to public safety and property from an LNG spill: design, materials selection, manufacturing methods, inspection and testing, assembly techniques, worker training, and safety operations, among others. For example, two ship design features that can impact risk are hull type (single vs. double) and hull material (steel vs. a more exotic material). Other significant factors include terminal location and design, port handling elements (e.g., tugboats and firefighting equipment), communications systems, and emergency response capabilities.

It is important to realize that a decision involving large capital expense can have long-lasting effects (e.g., LNG terminal site selection). For this reason, it is imperative to consider carefully all risk management decisions in order that residual or future risks can be managed to an acceptable level.

In general, risk can be managed by prevention or mitigation. Prevention seeks to avoid an accident or attack; mitigation reduces the effects of an accident or attack. Table 20 provides some general strategies for prevention and mitigation. Combinations of these types of strategies can improve both safety and security involving either accidental or intentional incidents.

While the prevention and mitigation strategies identified in the table are possible, many might not be cost-effective or even practical in certain locations or applications. Risk management should be based on developing or combining approaches that can be effectively and efficiently implemented to reduce hazards to acceptable levels in a cost-effective manner.

This type of approach has been in use and is in use by the LNG industry, the Coast Guard, and public safety organizations to ensure the safety of the transportation of LNG. These efforts include a number of design, construction, safety equipment, and operational efforts to reduce the potential for an LNG spill. Existing safety and security efforts for LNG vessels are noted following Table 20 [Scott 2004].

Regardless, all LNG vessels that enter the U.S. must meet both domestic regulations and international requirements. Domestic regulations for LNG vessels were developed in the 1970's under the authority of the various vessel inspection statutes now codified under Title 46 of the United States Code, which specifies requirements for a vessel's design, construction, equipment, and operation. These regulations closely parallel international LNG requirements; but are more stringent in the following areas: the requirements for enhanced grades of steel for crack-arresting purposes in certain areas of the hull, specification of higher allowable stress factors for certain independent type tanks, and prohibition of cargo venting as a means of regulating cargo temperature or pressure.

Table 20: Prevention and Mitigation Strategies

PREVENTION	MITIGATION
ISOLATION ▪ physical separation (distance) ▪ physical barriers ▪ keep-out or exclusion zones (buffers) ▪ interrupted operations (aircraft, bridge traffic)	RECOVERY OPERATIONS ▪ plans in place & current ▪ equipment & people in place & ready ▪ drills ▪ evacuation plans
VOID SPACES WITH INERT GAS	MAINTAIN MOBILITY (tanker + towing)
INERTING OF VOID SPACES	LIMIT SPILL AMOUNTS & RATES
VARIED TIMES OF OPERATIONS	SECURITY EMERGENCY RESPONSE FORCES
INTELLIGENCE ▪ communication links in place & ready ▪ timely updates ▪ interagency communication links	FIRE-FIGHTING CAPABILITIES ▪ leak detectors ▪ deluge systems ▪ radiant barriers (high-pressure high-density foam systems) ▪ backup fire fighting capabilities
INCREASED MOBILITY (tugs)	REDUNDANT MOORING & OFFLOADING CAPABILITIES
ARMED SECURITY ESCORT (boat, aircraft or on-board)	OFFSHORE MOORING & OFFLOADING CAPABILITIES
SWEEPS (divers, sonar, U.S.CG boarding)	SPEED LIMITS
SURVEILLANCE (on-ship, on-land, underwater & aerial)	CRYOGENICALLY-HARDENED VESSEL
EMPLOYEE BACKGROUND CHECKS	SHIP ARMOR, ENERGY-ABSORBING BLANKETS
TANKER ACCESS CONTROL PROGRAM	MISSILE DEFENSE SYSTEM
STORM PREDICTION & AVOIDANCE PLANS	REDUNDANT CONTROL SYSTEMS
SAFETY INTERLOCKS	BACKUP FUEL SOURCE (oil)

All LNG vessels in international service must comply with the major maritime treaties agreed to by the International Maritime Organization (IMO), such as the International Convention for the Safety of Life at Sea, popularly known as the "SOLAS Convention," and the International Convention for the Prevention of Pollution from Ships, known as the "MARPOL Convention." In addition, LNG vessels must comply with the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, known as the "IGC Code."

Before being allowed to trade in the United States, operators of LNG carriers must submit detailed vessel plans and other information to the Coast Guard's Marine Safety Center (MSC) to establish that the vessel has been constructed to the higher standards required by U.S. regulations. Upon satisfactory plan review and on-site verification by Coast Guard marine inspectors, the vessel is issued a Certificate of Compliance. The Certificate of Compliance is valid for a two-year period, subject to an annual examination by Coast Guard marine inspectors, who verify that the vessel remains in compliance with all applicable requirements.

Because of the safety and security challenges posed by transporting millions of gallons of LNG, vessels typically undergo a more frequent and rigorous examination process than conventional crude oil or product tankers. LNG vessels are boarded by marine safety personnel prior to U.S. port entry to verify the proper operation of key navigation, safety, fire fighting, and cargo control systems.

LNG vessels are subject to additional security measures. Many of the security precautions for LNG vessels are derived from analysis of "conventional" navigation safety risks, such as groundings, collisions, propulsion, and steering system failures. These precautions pre-date the events of September 11, 2001, and include such items as traffic control measures for special vessels that are implemented when an LNG vessel is transiting or approaching a port and security zones around the vessel to prevent other vessels from approaching it. Also included are escorts by Coast Guard patrol craft and, as local conditions warrant, coordination with other Federal, State and local transportation, law enforcement and/or emergency management agencies to reduce the risks to, or reduce the interference from, other port area infrastructures or activities. All such measures are conducted under the authority of existing port safety and security statutes, such as the Magnuson Act (50 U.S.C. 191 et. seq.) and the Ports and Waterways Safety Act.

Since September 11, 2001, additional security measures have been implemented, including the requirement that all vessels calling in the U.S. must provide the Coast Guard with a 96-hour advance notice of arrival (increased from 24 hours advance notice, pre-9/11). This notice includes information on the vessel's last ports of call, crew identities, and cargo information. Based on vessel-specific information, the Coast Guard conducts at-sea boardings, in which Coast Guard personnel conduct special "security sweeps" of the vessel and ensure that "positive control" of the vessel is maintained throughout its port transit. This is in addition to the safety-oriented boardings previously described.

One of the most important post-9/11 maritime security developments has been the passage of the Maritime Transportation Security Act of 2002 (MTSA). Under the authority of MTSA, the Coast Guard has developed new security measures applicable to vessels, marine facilities, and maritime personnel. The domestic maritime security regime is closely aligned with the International Ship and Port Facility Security (ISPS) Code. Under the ISPS Code, vessels in international service, including LNG vessels, must have an International Ship Security Certificate (ISSC). To be issued an ISSC, the vessel must develop and implement a threat-scalable security plan that establishes access control measures, security measures for cargo handling and delivery of ships stores, surveillance and monitoring, security communications, security incident procedures, and training and drill requirements. The plan must also identify a Ship Security Officer who is responsible for ensuring compliance with the ship's security plan.

For an LNG terminal, regulations developed under the authority of the Ports and Waterways Safety Act assign to the Coast Guard the responsibility for safety issues within the "marine transfer area" of LNG terminals. The "marine transfer area" is defined as that part of a waterfront facility between the vessel, or where the vessel moors, and the first shutoff valve on the pipeline immediately before the receiving tanks. Safety issues within the marine transfer area include electrical power systems, lighting, communications, transfer hoses and piping systems, gas detection systems and alarms, firefighting equipment, and operations such as approval of the terminal's Operations and Emergency Manuals and personnel training.

New maritime security regulations have been recently developed for terminal facilities. These regulations require the LNG terminal operator to conduct a facility security assessment and develop a threat-scalable security plan that addresses the risks identified in the

assessment. Much like the requirements prescribed for vessels, the facility security plan establishes access control measures, security measures for cargo handling and delivery of supplies, surveillance and monitoring, security communications, security incident procedures, and training and drill requirements.

6.3 Risk Reduction Examples

Table 21 below presents selected scenarios that provide examples of potential events and several prevention and mitigation approaches that could be used to reduce risks to public safety and property. Following the table, examples are given for each category of how these prevention and mitigation strategies can be implemented individually or in combination to reduce risks and consequences for a given location.

Many of the strategies identified are already under consideration or being implemented by the Coast Guard. Other strategies identified might be considered in conjunction with existing strategies at many sites. While risks can seldom be reduced to zero, prevention of the higher consequence events can significantly reduce hazards to public safety and property and facilitate mitigation of the remaining lower consequence and lower risk events.

As discussed in Section 3, prevention and mitigation strategy implementation should key on effectiveness, costs, and operational impacts. The level of risk reduction required should be determined in conjunction with local public officials and public safety organizations such as police and fire departments, emergency response services, port authorities, the Coast Guard, and other appropriate stakeholders.

Risk reduction strategies that are effective at one site might not be effective at another site. Therefore, the examples provided in Table 21 below should be considered in the context of how a risk management approach might be customized to yield benefits to public safety and property while having limited operational impacts.

Table 21: Examples of Risk Prevention and Mitigation Strategies for Potential Threats

SCENARIO	TARGETS	MECHANISM	POTENTIAL CONSEQUENCES		RISK REDUCTION MEASURES	
			LOCAL	CASCADING	PREVENTION	MITIGATION
Ramming	Fixed targets afloat or ashore	Mechanical distortion	Fire & ship damage	Large-scale fire	▪ Control of ship ▪ Increased mobility ▪ Tug escort	▪ Absorbing barriers on fixed targets ▪ Fire-fighting capability
Triggered Explosion	Fixed targets afloat	Pre-placed, coordinated explosion	Ship damage	Large-scale fire, blockage of waterway	▪ Early interdiction and surveillance ▪ Sweeping ▪ Intelligence ▪ Control of ship	▪ Emergency response force ▪ Evacuation plans ▪ Towing option
Insider Takeover or Hijacking	Fixed targets afloat or ashore	Standoff & negotiation, or explosion	Elevated public concern or fire & ship damage	Public demands to cease operations or large-scale fire	▪ Early interdiction & searches ▪ Control of ship ▪ Employee background checks	▪ Emergency response force ▪ Evacuation plans
Terrorist	Target afloat	Vessel carrying explosives	Fire & ship damage	Large-scale fire and blockage of waterway	▪ Security zones ▪ Safety halo around ship ▪ Intelligence	▪ Emergency response force ▪ Evacuation plans ▪ Towing option

Ramming

Ramming could occur between an LNG tanker and a fixed object or between a boat and an LNG tanker. As noted in Appendix B, unless the LNG tanker speed is above 5 – 7 knots or the object is very sharp, ramming of the LNG tanker into an object will not likely penetrate both hulls and the LNG cargo tank. Likewise, if the LNG tanker is rammed by a small boat, such as a pleasure craft, the kinetic energy is insufficient to penetrate the inner hull of a double-hulled LNG ship.

Therefore, while ramming does not appear to be a major concern or present significant hazards, changes in some safety and security operations could reduce the chances of a ramming event. For example, requiring tug escorts for LNG ships in high consequence areas would reduce the potential for an insider to ram intentionally an LNG vessel into a critical infrastructure element. Another option would be to ensure that crewmembers have been properly evaluated and the ship interdicted and searched sufficiently in advance of entry into the U.S. to thwart a hijacking attempt or insider sabotage. These efforts reduce the ability of an adversary to pick the time, place, and target for a ramming event and reduce the risk from a potential ramming scenario.

Triggered Explosion

Triggered explosion events assume pre-placed explosives, either on the ship or in a fixed location. At some sites, sweeping of the waterway, harbor bottom, and terminal areas for explosives or mines might be required. This is especially true for high hazard areas, shallow waterways, or terminals where explosives might be hidden. To prevent sabotage of an LNG cargo tank through a triggered explosive on board a ship, the same type of early interdiction, searches, and control of the ship discussed in the ramming prevention scenario could be applicable.

Insider Takeover or Hijacking

A number of security measures, including armed security control aboard the ship and early interdiction and inspection of the ship prior to its entry into the U.S., could prevent many of the large breaching scenarios identified in Sections 4 and 5. This could significantly reduce hazards levels and enable spill mitigation measures available to emergency response organizations to be used effectively.

A ship hijacking should be considered credible through coordinated efforts by insiders or others. The threat could proceed with the breach and spill of an LNG cargo tank through use of planted or smuggled explosives or by overriding offloading system safety interlocks to discharge LNG intentionally onto the ship, onto unloading terminal equipment, or onto the water. While a number of operational procedures have been implemented to help prevent this type of potential scenario, control and surveillance of an LNG ship must be appropriately maintained to ensure adequate time to respond to a potential hijacking event.

External Terrorist Actions

External terrorist attacks could come from a number of avenues, including attack of the LNG ship with a wide range of munitions or bulk explosives. A U.S.S Cole-type attack is often suggested as a potential attack scenario, as well as attacks with munitions such as rocket-propelled grenades, or missiles or attacks by planes. Depending on the size of the weapon or explosive charge and the location of the attack, the potential breach and LNG spill will vary.

Common approaches to prevent or mitigate these events are to make structures more resistant to attacks or to increase the standoff distance between the initiation of explosives and the ship. While security zones are presently used effectively for safety considerations at most of the LNG import locations in the U.S., a security halo for an LNG ship would have to be much smaller and effectively maintained to develop the security zones needed to prevent some of these events. Such measures could prevent a potential attacker from approaching close enough to cause severe damage to an LNG vessel. This security zone might require different escort ships and escort procedures, improved overhead and subsurface surveillance, enhanced training, or enhanced security response procedures.

6.4 Recommended Focus for Risk Prevention

The threats considered and the safety and security measures employed to address them must be based on site-specific and location-specific conditions. The level of risk prevention or mitigation required will depend on the site and its location relative to major population areas and critical infrastructures. In all cases, the risk reduction strategies identified should be

considered from a cost-effectiveness viewpoint; i.e. reducing risks to acceptable levels in the most cost-effective manner possible for a given site and location.

To guide risk management efforts and reduce impact on operations, Sandia recommends defining threat-scalable safety and security measures, and then tying safety and security related operations to these levels, which is the approach taken by the Department of Homeland Security for its threat advisory system. In this way, for each threat condition, protection and operations changes can be implemented in order to maintain the level of risk to public health and safety at acceptable levels.

Although the Department of Homeland Security defines threat levels, this might or might not be appropriate for an LNG transport system. As a minimum, Sandia suggests three levels — normal, off normal, and emergency. Unlike Homeland, whose sole focus is security, LNG would extend this formalism both to security and to safety.

Generally, the safety efforts currently in place for LNG transportation over water have been very effective in preventing accidents and appear to be adequate. At some locations, however, security efforts required to prevent intentional breaching events might have to be increased in order to reduce the risks to public health and safety. Since 9/11, current safety and security efforts have been increased and are continuing to evolve to meet the challenges of ever changing security threats.

As shown in Tables 20 and 21, multiple security strategies are available to help prevent or mitigate these events and often are complementary with existing LNG safety strategies already in practice. Suggested general security improvements to address the three major intentional breach scenarios should account for site-specific conditions and hazards and include (as required):

- Appropriate off-shore LNG ship interdiction and inspections for explosives, hazardous materials, and proper operation of safety systems;
- Appropriate monitoring and control of LNG ships when entering U.S. waters and protection of harbor pilots and crews;
- Enhanced safety zones around LNG vessels (safety halo) that can be enforced;
- Appropriate control of airspace over LNG ships; and
- Appropriate inspection and protection of terminal areas, tug operations prior to delivery and unloading operations.

Effective implementation of these types of security measures, along with complementary measures such as improved intelligence and cooperation, could reduce the potential for several types of intentional events. (The types of measures needed to reduce specific threats are discussed in more detail in an associated classified report [Hightower 2004].
A reduction in threats would reduce the potential sizes of breaches, and associated spills and hazards. This could significantly reduce the risks to people and property from an LNG spill over water.

Before implementation of specific safety or security measures is contemplated at a site, a baseline risk analysis should be conducted, a minimum acceptable risk estimated, and

vulnerabilities and hazards evaluated. After the initial risk analysis has been completed, prevention and mitigation measures or strategies can then be considered and evaluated. These can then be compared to assess if they provide the enhancements required to reduce the risks of an LNG spill to acceptable levels for a site.

6.5 Application of the Risk Management Process

So far, in this section we have discussed risk reduction for areas or activities within the larger system that includes the LNG tanker, the waterways it travels, and neighboring infrastructures. We used the risk management guidance and safety information developed in this report to assess ways to enhance operations and reduce the potential risks to the public. Hopefully, this will provide the reader with suggestions on how to consider various issues, including terminal location and site conditions, operational conditions, environmental effects, and safety and security concerns and measures. To be feasible, such a process must be effective from a surety standpoint, affordable, possible to implement in a timely fashion, minimize environmental impact, and be otherwise amenable to regulators and stakeholders.

We are not intending to suggest a "cookbook" methodology for selecting new sites; however, we want the reader to understand what type of issues should be considered and what various measures should be applied to try to achieve appropriate levels of protection of public safety and property for LNG imports.

Applying the Risk Management Process to LNG Imports

Risk management of an LNG import facility should be viewed as a system that includes the LNG tanker, the import terminal facilities and location, the navigational path, and the nearest neighbors along the navigational path and at the import terminal. Four classes of attributes affect the overall risks. These include:

- The context of the import facility – location, site specific conditions, LNG import, importance to the region;
- Potential targets and threats – potential accidental events, credible intentional events, and ship or infrastructure targets;
- Risk management goals– identification of levels of consequences to be avoided, such as injuries and property damage, LNG supply reliability required; and
- Protection system capabilities – LNG tanker safety and security measures, LNG import operations safety and security measures, and early warning and emergency response/recovery measures.

In the risk management process shown in Figure 3, the four attributes discussed are then evaluated to determine if the protection system in place can effectively meet the risk management goals identified for a specific import terminal site and operations. If so, then the safety and security measures and operations developed for the LNG import operations are adequate. Import operations should be reviewed on a regular basis to assess whether changes in context, targets or threats, risk management goals or risk management systems have changed such that a reassessment of risks is needed.

If the initial risk assessment determines that the identified risk management goals are not being met, then potential modifications in location and site conditions, import operations, safety and security measures, emergency response and early warning measures should be assessed to determine effective improvements in the overall risk management system Below,

we provide a summary of the elements that should be considered for LNG import facility applications for each step of the risk management process identified in Figure 3 of this report. These steps provide a context of how the safety analysis and risk guidance provided in this report can be used to evaluate options to protect property and public health and safety associated with LNG import terminals and operations.

Step One - Characterize Assets

In this step, the context of the LNG facility such as location, site-specific conditions, and nominal operations should be identified and developed. Information that should be collected and considered includes:

- **Type and Proximity of Neighbors (Sections 3.3, 4.2, and 5.1)**
  - Distance to residential, commercial, and industrial facilities or other critical infrastructures such as bridges or tunnels, and
  - Transit – Near or in major ship channel or remote from channel
- **Environmental Conditions (Sections 3.2 and 3.3)**
  - Wind-driven Spill Movement & Dispersion – prevailing wind direction, speed, and variability,
  - Severe Weather Considerations – hurricanes, storm surges,
  - Tidal-driven Spill Movement & Dispersion – height, current, and influence on spill movement and dispersion,
  - Seismic issues - ground displacement, soil liquefaction, and
  - Temperature issues – ice, thermal impediment to operations
- **Nominal Operational Conditions (Sections 2.1, 2.2, and 3.3)**
  - LNG tanker size and design,
  - Expected frequency of shipments,
  - Importance of LNG Shipments – Available storage, seasonal demands, percentage of regional or local supply, and
  - Transit – additional traffic (near other large ships, pleasure boats) and distance to it; transit near critical infrastructures, such as other terminals, commercial areas, or residential areas; number of critical facilities along transit; distance to critical facilities along transit.

Step Two – Identify Potential Threats (Sections 4.1 and 5.1)

In this step, the potential or likely threats expected for the facility, based on site location and relative attractiveness of either an LNG tanker or other nearby targets, should be identified.

- **Accidental Event Considerations –** shipping patterns, frequency of other large ships, major objects or abutments to be avoided, warning systems, weather impacts on waterways or operations,
- **Intentional Event Considerations –** threat levels identified by Homeland Security, identified threats, past threats and shipping attacks, difficulty of attack scenarios for a given site, and

- **Attractiveness of Targets –** impact of LNG tanker attack, impact on facilities near navigational route, impact on other facilities near site not associated with LNG operations.

Step Three - Determine Risk Management Goals and Consequence Levels (Section 6.1)

Identify risk management goals or consequence levels for LNG operations, including potential property damage and public safety (including injury limits). Setting of the goals and levels would be conducted in cooperation with stakeholders, public officials, and public safety officials. Consideration should be given to evaluating a range of potential risk management goals and consequence levels. In this way, an assessment of the range of potential costs, complexity, and needs for different risk management options can be compared and contrasted. Common risk management goals and consequence level considerations should include:

- Allowable duration of a loss of service, ease of recovery,
- Economic impact of a loss of service,
- Damage to property and capital losses from a spill and loss of service, and
- Impact on public safety from a spill – potential injuries, deaths.

Step Four - Define Safeguards and Risk Management System Elements (Section 6.2)

This step includes identifying all of the potential safety and security elements and operations available on the LNG tanker, at the terminal, or in transit. They include not only safety features but also safety and security-related operations and emergency response and recovery capabilities. These include:

- **Operational Prevention and Mitigation Considerations**
  - LNG tanker safety/security features,
  - Proximity and availability of emergency support – escorts, emergency response, fire, medical and law enforcement capabilities,
  - Early warning systems,
  - Ship interdiction and inspection operations and security forces, and
  - Ability to interrupt operations in adverse conditions – weather, wind, waves.
- **Protective Design**
  - Design for storm surges, blasts, thermal loading,
  - Security measures – fences, surveillance, exclusion areas,
  - Effective standoff from residential, commercial, or other critical infrastructures based on recommended hazard distances from an LNG spill over water, and
  - Redundant offloading capabilities.

Step Five - Analyze System and Assess Risks (Sections 3.3, 4.2, and 5.1)

In this step, the defined risk management goals and consequence levels should be compared to the existing system safeguards and protective measures. This effort would include evaluation of each element of the event tree identified in Figure 4 for a potential spill that might occur for the site-specific conditions, threats, and calculated hazard distances and hazard levels.

If the system safeguards in place provide protection of public safety and property that meet risk management goals, then the overall risks of an LNG spill would be considered compatible with public safety and property goals. The risk management process should be updated regularly to assess whether changes in threats or threat levels, operations, LNG tanker design, or protective measures have occurred that would impact the ability of the system safeguards to meet identified or improved public health and safety goals.

Step Six – Assess Risk Prevention and Mitigation Techniques (Sections 6.2 and 6.3)

If the potential hazard distances and hazard levels calculated exceed the consequence levels and risk management goals for the LNG terminal and import operations, then the enhanced risk mitigation and prevention strategies identified in Table 20 should be considered. While many of the options listed would be possible for a given site, developing approaches or combinations of approaches should be considered that can be effectively and efficiently implemented and that provide the level of protection, safety, and security identified for the LNG operations at each site.

7 GUIDANCE: SAFETY AND RISK ANALYSIS AND RECOMMENDATIONS

As discussed throughout this report, several major issues are associated with the potential for a large LNG spill over water. They include the potential for an accidental or intentional act that could cause an LNG spill, evaluation of the dynamics of the potential spill and LNG dispersion, the potential consequences that might occur from the range of spills, and strategies or efforts that might be employed to either prevent or mitigate the risks of a spill. Because costs to prevent and mitigate the potential consequences of an extreme event such as an LNG spill can be extensive, performance-based risk management approaches can be used to ensure that public safety and property are effectively protected.

In this study, a risk management approach is suggested for reducing the risks of LNG spills over water. Such an approach provides a systematic method for considering the potential of a breach event, assessing the expected LNG dispersion and potential consequences, and identifying prevention and mitigation strategies to reduce risks for site-specific conditions. Using available ship and experimental data, Sandia was able to evaluate both accidental and intentional breach scenarios of an LNG cargo tank. These efforts included assessments of past LNG spill and dispersion testing and modeling, estimates of hazards from an LNG spill, and identification of approaches to prevent or mitigate large LNG spills over water.

Modeling and assessing the impacts of potentially large LNG spills over water is a challenge that would benefit from additional, large-scale experiments to validate analysis techniques and approaches. These efforts would help reduce the uncertainty and improve the accuracy in assessing the impact and associated consequences of large LNG spills over water. Additional testing might best be conducted as part of a joint public/private effort with industry and government agencies to ensure widespread acceptance and support.

7.1 Guidance: Using Models for Spill and Hazard Evaluations

A detailed review of LNG dispersion and fire modeling methods and approaches suggests that current computational models require many assumptions. Table 22 shows the impact different parameters have on a consequences or hazards analysis. The table should be used as guidance on the level of detail needed in evaluating hazards from an LNG spill. Major categories that need to be included are:

- Identification of hole size, location, and ignition conditions,
- Inclusion of site specific conditions - wind, topography, waves, currents, structural interactions,
- Fuel spill and spread assumptions, and
- Gas dispersion assumptions with wind conditions, terrain, and obstacle considerations

Analyses that do not include these categories will not be able to identify accurately the risks and hazards to public safety and property.

A wide range of simplified models and approaches exists, and the applicability to LNG spills and comparisons with LNG spill data has been previously conducted, as discussed in

Appendix C. While these studies provide insight into the appropriate models to use, several additional factors should be considered in applying these models to a specific problem. These include:

- Model documentation and support – assumptions and limitations, comparison with data, model change control and upgrade information, and user support;
- Appropriate modeling of the physics of a spill – time-varying spill and dispersion analysis, vapor and pool ignition and burning, and water and fire impact on LNG spill spread and vaporization;
- Modeling of the influence of environmental conditions (wind, waves, water current, air, and water temperature, and humidity) on liquid and vapor dispersion, flame tilt, and spill and fire dynamics; and
- Peer review of applications of models, and peer review of the applications of the models.

By considering these factors, many existing models and tools can be used in many cases to provide adequate, general guidance on potential hazards associated with an LNG spill over water.

The fire hazards addressed in this study have been evaluated using integral or similarity models that can be readily applied in practice. Simplified models with the appropriate input parameters can be used with reasonable confidence for calculating the heat flux to objects at a long distance (more than the LNG pool diameter) from a fire that is not heavily influenced by nearby structures [Gritzo and Nicolette, 1997]. Under such conditions, the main uncertainties in the simplified models are due to 1) the inability of these models to represent fires at very large (50 m or more in diameter) scales, and 2) uncertainty in the input parameters required by these models.

Where an analysis reveals that potential impacts on public safety and property could be high and where interactions with terrain, buildings, or structures can occur, modern, validated, CFD models can be applied to assess spill, dispersion, vaporization, and fire hazards to improve analysis of site-specific conditions. CFD models solve the fluid dynamics equations, coupled with the reacting flow properties that result in the thermal hazard posed by fires. Rather than treating the shape of the flames as cylindrical (as assumed by simple or integral models), validated CFD-based techniques predict the flame shape as influenced by adjacent objects and structures. Comparison with experimental data indicates that the point source model and the solid flame model do not accurately predict heat flux levels when the pool is non-uniform, such as would occur when there is object interaction. As such, CFDs are better able to provide predictions of the heat flux to engulfed structures and, therefore, can be used to analyze cascading effects where hazards might induce additional failures and subsequent fire hazards. Because they include additional physics, fewer input parameters are required and, once validated, they can better represent fires at very large scales.

Table 22: Importance of Parameters/Assumptions for Assessing LNG Spills/Fires/Explosions

ASSESSMENT OF SCENARIO	ESTIMATED IMPACT ON HAZARDS
Specification Of Initial Conditions	
Hole size and location	High
Ignition potential	High
Specification Of Boundary Conditions	
Wind/atmospheric conditions	High
Topography of site	High
Pool surface and properties (waves, thermodynamic properties, etc.)	High
Nearby structures	Med
Modeling Assumptions And Features	
Fuel spill	Med
Simple hole	Med
Vaporization enhanced by turbulence mixing	Med-High
Spread Model: smooth surface	High
Spread Model: fuel composition	Med-Low
Spread Model: atmospheric conditions	High
Spread Model: RPT	Med
Dispersion	
Dense gas	High
Under vs. above water release	High
Atmospheric conditions	High
Terrain/obstacles	High
Ignition	
Fuel composition	High
Ignition time of event (from puncture or impact)	High
Fire	
Burning rate	Med-High
Surface emissive power	High
Flame shape at large scale	High
Obstacles	High
Atmospheric conditions	High
Fuel composition	High

Detailed models require more computational capability and user expertise; therefore, they are less desirable for widespread application. However, validated, detailed models can be used to develop correction factors for simplified models that can, in turn, be widely employed with confidence to assess hazards. These tools can also be used to explore the potential passive (such as vapor barriers or firebreaks) or active (such as water spray) mitigation techniques.

Development of validated CFD models will require implementation of equations to represent phenomena, including: 1) the dynamics of cryogenic liquids, including evaporation and spread on water, and 2) the mixing and burning of low temperature natural gas vapor in very large plumes. These models must be verified (i.e. ensure that the equations are being solved

correctly) and validated (i.e. ensure that the right equations are being solved for the application of interest) through analysis efforts and comparisons with high quality data.

Validation of detailed models for LNG applications is beyond the scope of this study; but such models have been applied in numerous other cases to evaluate large fire hazards from liquid hydrocarbons such as jet fuel [Gritzo and Nicolette 1997] [Suo-Antilla and Gritzo 2001] [Gritzo and Nicolette 1998]. The essential features of the validation process have been documented in the literature [Gritzo et al., 2004].

Our evaluation suggests that modern, validated CFD models should be further refined and used as appropriate to improve site-specific thermal hazard and consequence analyses where interaction with terrain, buildings, or other structures might occur. Table 23 presents various, CFD models that could be used for the listed applications. These types of models can address complex geometries, and include additional physical modeling capabilities that allows them to be more easily extrapolated to larger spills.

Table 23: Suggested Models for Enhanced Spill, Dispersion, and Fire Dynamics Analyses

APPLICATION	SUGGESTED MODELS & APPLICATIONS
Tank Emptying	Modified orifice model that includes the potential for LNG leakage between hulls
Spreading	Free-surface CFD code (e.g. application extension of FLOW-3D, STORM/CFD2000)
Dispersion	CFD code (e.g. FEM3C, FLUENT, CFX, Fuego)
Fire	CFD code (e.g. FLACS, CFX, FDS, Phoenics, Kameleon, Vulcan, and Fuego)

7.2 Safety Analysis Guidance and Recommendations

The positive safety record of LNG vessels and the LNG transportation industry over the past 30 years is indicative of the extensive attention to safety being conducted through the cooperation of LNG importers, LNG transporters, the U.S. Coast Guard, emergency management and response teams, and by the risk and safety management considerations employed to improve LNG shipping and handling operations. Such considerations include:

- Double-hulled ship designs,
- Appropriate safety systems to reduce the potential for damage,
- Security management and escort of LNG ships operating in harbors and waterways, and
- Vessel movement and control zones (e.g., safety and security zones) to reduce the potential for impacts with other ships or structures.

These efforts have all significantly prevented or mitigated the potential for an accidental LNG cargo tank breach. While existing safety measures have been very effective, intentional attempts to breach an LNG cargo tank are now being considered as potential spill scenarios. Many recent studies have begun to consider both types of events and assess the safety and hazard issues of a subsequent fire or explosion of the spilled LNG. To date, most of these studies usually concentrate on postulating a spill scenario and calculating potential hazards and consequences without considering the likelihood of such an event. In addition, they often do not include experimental validation of the assumptions or analyses for the conditions

postulated, nor do they consider prevention or mitigation strategies that could reduce the impact or hazards of the postulated events.

The following three conclusions provide a summary of the major results of an LNG cargo tank breach, spill, and dispersion, and the results of a hazard evaluation analysis developed from what we think are credible accidental and intentional spill scenarios.

1. The most significant impacts to public safety and property exist within approximately 500 m of a spill, with lower impacts at distances beyond 1600 m, even for very large spills.
2. Under certain conditions, it is possible that multiple LNG cargo tanks could be breached, either as a result of an initial event, or as a consequence of cryogenic or fire-induced structural damage.
3. Based on this possibility, multiple breach and cascading LNG cargo tank damage scenarios were analyzed. While possible under certain conditions, they are likely to involve no more than two to three cargo tanks at any one time. These conditions will not greatly change the hazard ranges noted in General Conclusion Number 1 above, but will increase expected fire duration.

7.2.1 Accidental Breach Scenario Conclusions

1. Accidental LNG cargo tank damage scenarios exist that could potentially cause an effective breach area of 0.5 to 1.5 m^2.
2. Due to existing design and equipment requirements for LNG carriers, and the implementation of navigational safety measures such as traffic management schemes and safety zones, the risk from accidents is generally low.
3. The most significant impacts to public safety and property from an accidental spill exist within approximately 250 m of a spill, with lower impacts at distances beyond approximately 750 m from a spill.

7.2.2 Intentional Breach Scenario Conclusions

1. Several credible, intentional LNG cargo tank damage scenarios were identified that could initiate a breach of 2 m^2 –12 m^2 with a probable nominal size of 5 – 7 m^2.
2. Most of the intentional damage scenarios identified produce an ignition source such that an LNG fire is likely to occur immediately.
3. Some intentional damage scenarios could result in vapor cloud dispersion, with delayed ignition and a fire.
4. Several intentional damage scenarios could affect the structural integrity of the vessel or other LNG cargo tanks due to ignition of LNG vapor trapped within the vessel. While possible under certain conditions, these scenarios are likely to involve no more than two to three cargo tanks at any one time, as discussed in Sections 4 and 5.
5. Rapid phase transitions are possible for large spills. Effects will be localized near the spill source and are not expected to cause extensive structural damage.

6. The potential damage from spills to critical infrastructure elements such as bridges, tunnels, industrial/commercial centers, LNG unloading terminals and platforms, harbors, or populated areas, can be significant in high hazard zones.
7. In general, the most significant impacts from an intentional spill on public safety and property exist within approximately 500 m of a spill, with lower impacts at distances beyond approximately 1600 m from a spill, even for very large spills.

7.3 Risk Management Guidance for LNG Spills over Water

Based on this study, guidance is provided to support performance-based LNG spill prevention, spill management, and hazard evaluations for marine LNG import facilities. The consideration of operations, safety precautions, prevention strategies, and consequence modeling and evaluation approaches should be focused on reducing the risks of a potential LNG spill as identified and developed with public safety organizations, public officials, and appropriate stakeholders for a specific site and conditions..

The following guidance is provided to assist risk management professionals, emergency management and public safety officials, and other port security stakeholders in developing and implementing appropriate risk management strategies and processes.

7.3.1 General Risk Management Guidance

For both accidental and intentional spills, we recommend the following:

- The use of effective security and risk management operations that include enhanced interdiction, detection, delay procedures, risk management procedures, and coordinated emergency response measures, can reduce the risks from an accidental or intentional breaching event;
- Implemented risk management strategies should be based on site-specific conditions and the expected impact of a spill on public safety and property. Less intensive strategies would often be sufficient in areas where the impacts of a spill could be low.
- Where analysis reveals that potential impacts on public safety and property could be high and where interactions with terrain or structures can occur, modern, validated computational fluid dynamics models can be used to improve analysis of site-specific hazards.

7.3.2 Guidance on Risk Management for Accidental Spills

Zone 1

These are areas in which LNG shipments transit narrow harbors or channels, pass under major bridges or over major tunnels, or come within approximately 250 meters of people and major infrastructure elements, such as military facilities, population and commercial centers, or national icons. Within this zone, the risk and consequences of an accidental LNG spill could be significant and have severe negative impacts. Thermal radiation could pose a severe public safety and property hazard and can damage or significantly disrupt critical infrastructure located in this area.

Risk management strategies for LNG operations should address both vapor dispersion and fire hazards. Therefore, the most rigorous deterrent measures, such as vessel safety or

security zones, waterway traffic management schemes, and establishing positive control over the vessel are options to be considered as elements of the risk management process. Coordination among all port security stakeholders is essential. Incident management and emergency response measures should be carefully evaluated to ensure adequate resources (i.e., firefighting, salvage, etc.) are available for consequence and risk mitigation.

Zone 2

These are areas in which LNG shipments and deliveries occur in broader channels or large outer harbors, or within approximately 250 m – 750 m of major critical infrastructure elements like population or commercial centers. Thermal radiation transitions to less severe hazard levels to public safety and property.

Within Zone 2, the consequences of an accidental LNG spill are reduced and risk reduction and mitigation approaches and strategies can be less extensive. In this zone, risk management strategies for LNG operations should focus on approaches dealing with both vapor dispersion and fire hazards. The strategies should include incident management and emergency response measures such as ensuring areas of refuge (enclosed areas, buildings) are available, development of community warning signals, and community education programs to ensure persons know what precautions to take.

Zone 3

This zone covers LNG shipments and deliveries that occur greater than approximately 750 m from major infrastructures, population/commercial centers, or in large bays or open water, where the risks and consequences to people and property of an accidental LNG spill over water are minimal. Thermal radiation poses lesser risks to public safety and property.

Within Zone 3, risk reduction and mitigation strategies can be significantly less complicated or extensive. Risk management strategies should concentrate on incident management and emergency response measures that are focused on dealing with vapor cloud dispersion. Measures should ensure areas of refuge are available, and community education programs should be implemented to ensure that persons know what to do in the unlikely event of a vapor cloud.

7.3.3 Guidance on Risk Management for Intentional LNG Spills

Zone 1

These are areas where LNG shipments occur in either narrow harbors or channels, pass under major bridges or over tunnels, or come within approximately 500 meters of major infrastructure elements, such as military facilities, population and commercial centers, or national icons. In these areas, the risk and consequences of a large LNG spill could be significant and have severe negative impacts. Thermal radiation can pose a severe public safety and property hazard and can damage or significantly disrupt critical infrastructure located in this area.

Risk management strategies for LNG operations should address vapor dispersion and fire hazards. The most rigorous deterrent measures, such as vessel safety or security zones, waterway traffic management schemes, and establishing positive control over the vessel are elements of the risk management process. Coordination among all port security stakeholders

is essential. Incident management and emergency response measures should be carefully evaluated to ensure adequate resources (i.e., firefighting, salvage, etc.) are available for consequence and risk mitigation.

Zone 2

These are areas in which LNG shipments and deliveries occur in broader channels or large outer harbors, within approximately 500 m – 1.6 km of major critical infrastructure elements, such as population or commercial centers. Within Zone 2, the consequences of even a large LNG spill are reduced. Thermal radiation transitions to less severe hazard levels to public safety and property.

Risk management strategies for LNG operations that occur in this zone should focus on fire and vapor dispersion hazards. The strategies should include incident management and emergency response measures such as ensuring areas of refuge (enclosed areas, buildings) are available, development of community warning signals, and community education programs to ensure persons know what precautions to take.

Zone 3

This zone covers LNG shipments and deliveries that occur greater than approximately 1.6 km from major infrastructures, population/commercial centers, or in large bays or open water, where the risks and consequences to people and property of a large LNG spill over water are minimal. Thermal radiation poses lesser risks to public safety and property. Within Zone 3, risk reduction and mitigation strategies can be less complicated or extensive than Zones 1 and 2. Risk management strategies should focus on incident management and emergency response measures for dealing with vapor cloud dispersion. Measures should ensure that areas of refuge are available, and community education programs should be implemented to ensure that persons know what to do in the unlikely event of a vapor cloud.

7.4 Key Conclusions: Safety Analysis and Risk Management

This study provides guidance on performance-based risk management approaches for analyzing and managing the threats, hazards, consequences, and risks to public safety and property due to an LNG spill over water. Based on the results of this study, we provide the following key conclusions:

1. The system-level, risk-based guidance developed in this report, though general in nature (non site-specific), can be applied as a baseline process for evaluating LNG operations where there is the potential for LNG spills over water.
2. A review of four recent LNG studies showed a broad range of results, due to variations in models, approaches, and assumptions. The four studies are not consistent and focus only on consequences rather than both risks and consequences. While consequence studies are important, they should be used to support comprehensive, risk-based management and planning approaches for identifying, preventing, and mitigating hazards to public safety and property from potential LNG spills.
3. Risks from accidental LNG spills, such as from collisions and groundings, are small and manageable with current safety policies and practices.

4. Risks from intentional events, such as terrorist acts, can be significantly reduced with appropriate security, planning, prevention, and mitigation.
5. This report includes a general analysis for a range of intentional attacks. The consequences from an intentional breach can be more severe than those from accidental breaches. Multiple techniques exist to enhance LNG spill safety and security management and to reduce the potential of a large LNG spill due to intentional threats. If effectively implemented, these techniques could significantly reduce the potential for an intentional LNG spill.
6. Management approaches to reduce risks to public safety and property from LNG spills include operation and safety management, improved modeling and analysis, improvements in ship and security system inspections, establishment and maintenance of safety zones , and advances in future LNG off-loading technologies. If effectively implemented, these elements could reduce significantly the potential risks from an LNG spill.
7. 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, available intelligence, threat assessments, safety and security operations, and available resources.
8. While there are limitations in existing data and current modeling capabilities for analyzing LNG spills over water, existing tools, if applied as identified in the guidance sections of this report, can be used to identify and mitigate hazards to protect both public safety and property. Factors that should be considered in applying appropriate models to a specific problem include: model documentation and support, assumptions and limitations, comparison with data, change control and upgrade information, user support, appropriate modeling of the physics of a spill, modeling of the influence of environmental conditions, spill and fire dynamics, and peer review of models used for various applications. As more LNG spill testing data are obtained and modeling capabilities are improved, those advancements can be incorporated into future risk analyses.
9. Where analysis reveals that potential impacts on public safety and property could be high and where interactions with terrain or structures can occur, modern, validated computational fluid dynamics (CFD) models can be used to improve analysis of site-specific hazards, consequences, and risks.
10. LNG cargo tank hole sizes for most credible threats range from two to twelve square meters; expected sizes for intentional threats are nominally five square meters.
11. The most significant impacts to public safety and property exist within approximately 500 m of a spill, due to thermal hazards from fires, with lower public health and safety impacts at distances beyond approximately 1600 m.
12. Large, unignited LNG vapor releases are unlikely. If they do not ignite, vapor clouds could spread over distances greater than 1600 m from a spill. For nominal accidental spills, the resulting hazard ranges could extend up to 1700 m. For a nominal intentional spill, the hazard range could extend to 2500 m. The actual hazard distances will depend on breach and spill size, site-specific conditions, and environmental conditions.

13. Cascading damage (multiple cargo tank failures) due to brittle fracture from exposure to cryogenic liquid or fire-induced damage to foam insulation was considered. Such releases were evaluated and, while possible under certain conditions, are not likely to involve more than two or three cargo tanks for any single incident. Cascading events were analyzed and are not expected to greatly increase (not more than 20%-30%) the overall fire size or hazard ranges noted in Conclusion 11 above, but will increase the expected fire duration.

APPENDIX A
RECENT LNG SPILL MODELING REVIEW

1 INTRODUCTION

This appendix reviews four recent reports developed over the past two years that assess the impacts of large LNG spills over water. A summary of the assumptions, models, and results of the analyses in each of the studies is presented first. Next, the differences in the studies are highlighted relative to the influence and impact the various assumptions and models have on the outcome and results. The review identifies potential concerns and uncertainties with each study and provides recommendations for the development of interim analysis techniques and processes to better and more consistently assess the consequences and hazards of LNG spills.

Four studies were evaluated to assess whether they provided a definitive determination of the lateral extent and thermal hazards of a large-scale release of LNG from a tanker over water. The studies evaluated were:

- Lehr, W. and Simecek-Beatty, D. "Comparison of Hypothetical LNG and Fuel Oil Fires on Water." Report by the National Oceanic and Atmospheric Administration (NOAA), Office of Response and Restoration, Seattle, WA, 2003, DRAFT [Lehr and Simicek-Beatty 2003].
- Fay, J.A. "Model of spills and fires from LNG and oil tankers." Journal of Hazardous Materials, B96-2003, 171-188, 2003 [Fay 2003].
- "Modeling LNG Spills in Boston Harbor." Copyright© 2003 Quest Consultants, Inc., 908 26th Ave N.W., Norman, OK 73609; Letter from Quest Consultants to DOE (October 2, 2001); Letter from Quest Consultants to DOE (October 3, 2001); and Letter from Quest Consultants to DOE (November 17, 2003) [Quest 2003].
- "Liquefied Natural Gas in Vallejo: Health and Safety Issues." LNG Health and Safety Committee of the Disaster Council of the City of Vallejo, CA, January 2003 [Vallejo 2003] [Koopman 2004].

Following is a summary of the major assumptions, models, and results concerning the potential hazards from an LNG spill from each of the four reports reviewed.

2 ASSUMPTIONS, MODELS, AND RESULTS FOR EACH STUDY

2.1 Lehr Study

The report provided by *Lehr* contrasts accidental spills from ships carrying refined petroleum products versus LNG [Lehr and Simicek-Beatty 2003]. Quantitative estimates are made of spread rate, maximum pool area, burn rate, burn duration, and effective thermal radiation. The following provides a summary of the assumptions, models, and results from this report, for LNG spills only.

2.1.1 Breach Scenario Assumptions

No assumptions were made regarding how a spill might occur.

2.1.2 Spreading Model

The spread rate model does not take into account the mass loss due to evaporation while the pool is spreading if ignition does not occur immediately. The pool radius is a function of spill rate for continuous spills or volume spilled for an instantaneous spill.

If ignition occurs immediately and the spill is instantaneous, an approximate relation is used, which is a function of minimum pool thickness, burn regression rate, and source leak rate.

The pool is spreading on a quiescent surface. Waves are not considered.

Viscosity and surface tension of the LNG are neglected.

The model assumes that the LNG will spread in a uniform circle.

2.1.3 Dispersion Model

Dispersion is not considered.

2.1.4 Flame model

The flame is modeled as a circular cylinder that radiates upward and uniformly over the cylinder's surface. Flame tilt due to wind is not considered. Flame height is approximate according to the empirical correlation by Thomas [Thomas 1965].

Incident thermal radiation to an object is determined by calculating the product of the average emissive power at the flame surface, an atmospheric transmission factor, and a geometric view factor. An average emissive power is calculated by an empirical correlation taken from the Society of Fire Protection Engineers Handbook.

The transmission factor is calculated by a relation from Glasstone and Dolan, who base their work on thermal radiation from a nuclear bomb explosion [Glastone and Dolan 1977].

Burn regression rate is according to values give from experiments performed by Raj [Raj et al. 1979]. The rates were found to vary from 0.4 to 1 mm/s.

2.1.5 Results

The results are given for one example, an instantaneous LNG spill of 500 m^3. The pool is burning while it is spreading.

A maximum spread velocity of 1 m/s results after a few seconds.

The maximum burn time is approximately two – three minutes.

At maximum radius and flame height, the radiation fraction of the heat of combustion is 0.21.

At a distance of 500 m from the pool's edge, a maximum average radiant heat flux of 7 kW/m^2 is obtained.

The pool radius calculated was not stated.

2.2 Fay Study

Fay provided an analysis of the spreading of LNG, duration of a pool fire burn, and heat release. These quantities are expressed in terms of the cargo tank geometric properties [Fay 2003]. The following provides a summary of the assumptions, models, and results from this analysis.

2.2.1 Breach Scenario Assumptions

No assumptions were made regarding how a spill might occur.

2.2.2 Spreading Model

The spreading model includes the vaporization of the pool as the pool spreads.

The pool is assumed to spread in the shape of a uniform semi-circle.

The pool is spreading on a quiescent surface. Waves are not considered.

Viscosity and surface tension of the LNG are neglected.

Breaches above and below the water's surface are considered.

A value of $(5 – 7) \times 10^{-4}$ m/s is used for the vaporization rate of LNG on water.

2.2.3 Dispersion Model

Dispersion is not considered.

2.2.4 Flame model

The flame is not modeled.

Radiant flux to an object is approximated by taking a fraction of the heat release rate, averaged over the fire's duration, and dividing by the square of the distance to an object. The radiation flux heat release rate fraction is assumed as 0.15.

2.2.5 Results

The example given assumes 14,300 m^3 of LNG from a single tank spills onto the water. The values for maximum pool area are given as a function of puncture area. A total vaporization rate of 8 x 10^{-4} m/s is used to account for heating from the water below and fire above the LNG.

For the equivalent puncture area given in the *Quest* report of 19.63 m^2 (5 m dia. hole), the maximum pool radius calculated by *Fay* is 252 m, assuming the shape is a circle. For a semicircle, the radius is 357 m.

The burn duration for this rupture area and pool area is reported as 3.3 minutes.

The distance from the fire to an object at which the radiant flux is 5 kW/m^2 is 1.9 km.

2.3 Quest Study

Quest conducted an analysis of the consequence of a potential release of LNG from an LNG tanker at Boston Harbor [Quest 2003]. They considered how a potential release could occur and provided an analysis of the spreading of LNG, as well as the flammable hazards after the release. The following provides a summary of the major assumptions and models that *Quest* used, and its analytical conclusions.

2.3.1 Breach Scenario Assumptions

The scenario considered is a ship-to-ship collision in the outer harbor of Boston. It is assumed that the tanker has five LNG membrane tanks holding 25,000 m^3 each, to allow for a total holding capacity of 125,000 m^3. The ships separate after the collision.

A hole results from the collision just above the waterline in one of the five tanks only. The largest hole size that results is five meters.

LNG at a pressure of 1.45 psig and temperature of –160.5 C leaks from the hole. The LNG is composed of 96.97% methane, 2.62% ethane, 0.316% propane, and trace amounts of other compounds.

No explosions occur.

2.3.2 Spreading Model

The LNG will spill onto the water and spread. A simple orifice model is used to determine that it will take two minutes for the ruptured tank to empty to the waterline, spilling 12,500 m^3 of LNG.

The model assumes that the LNG will spread in a uniform circle.

The spread rate is a function of spill rate, vaporization rate, and pool radius.

A value of 0.18 kg/m^2 is used for the vaporization flux of LNG on water.

Viscosity and surface tension of the LNG are neglected.

Waves will affect the spreading. This feature is accounted for by assuming that the waves are a simple cycloid shape. The wave effect on spreading is incorporated through a conditional statement at the boundary of the pool; namely, the pool will stop spreading once the LNG drops below 60% of the wave height. The effect of waves also increases the vaporization flux by 27% due to the increase in surface area.

Three averaged wave heights, taken from NOAA Boston Harbor buoy data, are considered: 0.575 m, 0.682 m, and 1.24 m.

2.3.3 Dispersion Model

A vapor cloud will form and disperse. This was modeled by using Quest's software dispersion code 'CANARY,' which accounts for transient release rates, initial velocity of the released gas, initial dilution of the vapor, thermodynamics, gas cloud density relative to air, and mixture behavior. Another code, DEGADIS, was also used for comparison.

Three different wind speeds were considered: 1.5 m/s (F stability class), 5.0 m/s (D stability class), and 9.0 m/s (D stability class). Stability class refers to atmospheric stability. F class is extremely stable and results in the greatest amount of time for the released gases to mix with the atmosphere. D class is neutrally stable; thus mixing will occur faster in class D than in F class.

2.3.4 Flame model

The fuel is assumed to ignite because of the collision.

The flame is modeled as an elliptical cylinder; thus, a tilted flame. The base of the flame is assumed to increase due to flame drag and is approximated by an empirical correlation [Moorehouse 1982]. Flame angle is calculated by using an empirical formula by Welker and Sliepcevich [Welker and Sliepcevich 1970]. Flame length is approximated by an empirical correlation [Dorofeev et al. 1991]. The flame is divided into two zones: a clear zone with no smoke, and a zone in which a fraction of the flame is obscured by smoke. The length of the clear zone is determined by an empirical correlation [Pritchard and Binding 1992].

2.3.5 Results

Quest concluded the following values from its analyses:

Table 24: Model Results (Quest Study)

WIND SPEED (m/s)	WAVE HEIGHT (m)	MAXIMUM LNG RADIUS	TOTAL TIME TO BURN SPILL (min)	DISTANCE TO:		
				22.1 kW/m^2	12.6 kW/m^2	4.73 kW/m^2
1.5	0.575	78 m (257 ft)	14.3	226 m (740 ft)	309 m (1,015 ft)	497 m (1,630 ft)
5.0	0.672	73 m (239 ft)	16.6	270 m (885 ft)	351 m (1,150 ft)	531 m (1,740 ft)
9.0	1.24	55 m (180 ft)	28.6	281 m (920 ft)	349 m (1,145 ft)	493 m (1,615 ft)

At these radiant flux levels, the following occur:

Table 25: Impact of Radiation (Quest Study)

22.1 kW/M^2	Structural steel weakens after prolonged exposure to this flux level.
12.6 kW/M^2	Vapors evolving off of a wooden structure might ignite after several minutes of exposure to this flux level if ignition source is present
4.73 kW/m^2	Second-degree skin burns are possible after 30-seconds exposure to this flux level.

For the dispersion calculations of the vapor cloud:

Table 26: Dispersion Calculations (Quest Study)

WIND SPEED (m/s)	STABILITY CLASS	MAXIMUM LNG RADIUS	DISTANCE TO LOWER FLAMMABILITY LIMIT	
			Canary	Degadis
1.5	F	80 m (261 ft)	4,030 m (13,220 ft)	3,400 m (11,155 ft)
5.0	D	73 m (239 ft)	1,050 m (3,445 ft)	1,900 m (6,230 ft)
9.0	D	55 m (180 ft)	340 m (1,115 ft)	1,100 m (3,610 ft)

2.4 Vallejo Study

This study is specific to a particular locale, which includes land and marine facilities for a potential LNG import facility [Vallejo 2003]. The *Vallejo* authors discuss a wide range of initiating events, from accidents to natural events to malevolent acts, and assess the qualitative likelihood of each; but no spill analysis is tailored to different initiating events. The report also includes ideas for mitigation options to enhance safety. Ronald P. Koopman retired from Lawrence Livermore National Laboratory provided the dispersion and thermal hazard results. The report also provides the analysis and results performed by *Quest*. The following pertains only to the work performed by R. P. Koopman. [Koopman 2004]

2.4.1 Breach Scenario Assumptions

The report discusses a variety of ways that a breach to an LNG cargo tank can occur, such as terrorism, operational errors, and maritime accidents. It was not stated how a rupture occurs for the example calculations given.

2.4.2 Spreading Model

Both one-meter and five-meter diameter holes in one 25,000 m^3 LNG ship tank were analyzed. The National Ocean Atmospheric Administration's code, ALOHA (Aerial Locations of Hazardous Atmospheres), was used to calculate the spill from the ship tank. In 6 min., 14,300 m^3 were spilled from the five-meter diameter hole and in 35 min from the one-meter diameter hole. The five-meter diameter hole resulted in a pool with a maximum area of 110,000-130,000 m^2. Vaporization rates of $5x10^{-4}$ m/s were used for evaporation from the water alone, and $8x10^{-4}$ m/s when fire was present.

2.4.3 Dispersion Model

The Lawrence Livermore National Laboratory's SLAB atmospheric dispersion model for denser than air releases were used for the dispersion calculations. Dispersion calculations were performed for two different wind speeds and stability class conditions: 2 m/s (F stability class) and 5 m/s (D stability class). Calculations were performed for two different hole sizes, 1 and 5 meters in diameter.

2.4.4 Flame Model

A pool fire was considered the result due to ignition of 14,300 m^3 of LNG from a tanker. Distances cited were based on a point source model. Attenuation due to atmospheric water vapor was not included. A fireball calculation was also performed, but for a land-based storage tank. Vapor cloud fires were also discussed; but no calculations were performed.

2.4.5 Results:

Pool fire heat radiation results:

Table 27: Fire Heat Radiation Results (Vallejo Study)

HOLE SIZE (m)	DISTANCE TO RADIANCE FLUX LEVEL OF:		
	30 kW/m^2	17 kW/m^2	5 kW/m^2
5 (16.4 ft)	0.35 miles (563 m)	.5 miles (804 m)	0.8 miles (1287 m)

Dispersion calculations of the vapor cloud results:

Table 28: Vapor Cloud Dispersion Calculations (Vallejo Study)

HOLE SIZE DIAMETER (m)	WIND SPEED (M/S)	PASQUILL-GIFFORD ATMOSPHERIC STABILITY	DISTANCE TO LOWER FLAMMABILITY LIMIT miles (meters)*
5	2	F	2.8 miles (4506 m)
5	5	D	1.5 miles (2414 m)
1	5	D	0.7 miles (1126 m)

*Does not consider the limiting effect of topography

3 SUMMARY OF LNG SPILL ASSUMPTIONS AND RESULTS FROM EACH STUDY

Tables 29 and 30 and Figure 6 summarize both the assumptions and the results of each of the reports reviewed.

Table 29: Summary of Study Assumptions

STUDY	TIME TO EMPTY (min)	VAPORIZES DURING SPREAD	WAVE EFFECTS INCLUDED	SHAPE OF POOL	IGNITION TIME	FLAME MODEL	COMBUSTION MODE	IGNITION OCCURS AT POOL, NOT IN VAPOR CLOUD
Lehr	Instantly	Yes	No	Circle	Instantly upon release	Solid cylinder	Diffusion flame; No explosion	Yes
Fay	Varies with hole size	Yes	No	Semi-circle	Instantly upon release	Point source	Diffusion flame; No explosion	Yes
Quest	2	Yes	Yes	Circle	Instantly after spread	Solid cylinder; including tilt for wind effects	Diffusion flame; No explosion	Yes
Vallejo	Varies with hole size	Yes	No	Circle	Instantly upon release	Point Source	Diffusion flame; No explosion	Yes

Table 30: Summary of Study Results

STUDY	FUEL SPILL VOLUME (m^3)	AREA OF FUEL SPILL (m^2)	"SKIN BURN" DISTANCE[a] (m)	"PAPER IGNITION" DISTANCE[b] (m)	FIRE DURATION (min)
Lehr	500 (hole area not specified)	Not reported	500[c]	Not reported	2-3
Fay[e]	14,300 ($20m^2$ hole area)	200,000	1900	930	3.3
Quest	12,500 ($20m^2$ hole area)	9503	490 [d]	281[d]	28.6
Vallejo	14,300 ($20m^2$ hole area)	120,000	1290	660	9.0

[a] A thirty-second exposure to heat levels of 5 kW/m^2 causes second-degree skin burns(blisters) at this distance.
[b] A seventeen-second exposure to heat levels of 22 kW/m^2 causes newspaper to ignite at this distance. (Ref.: SFPE Handbook of Fire Protection Engineering, 2nd ed., National Fire Protection Association, (1995).
[c] Distance from edge of spill
[d] Assuming a wind speed of 9 m/s (20 mph).
[e] Considers a range of hole sizes. This size chosen for comparison.

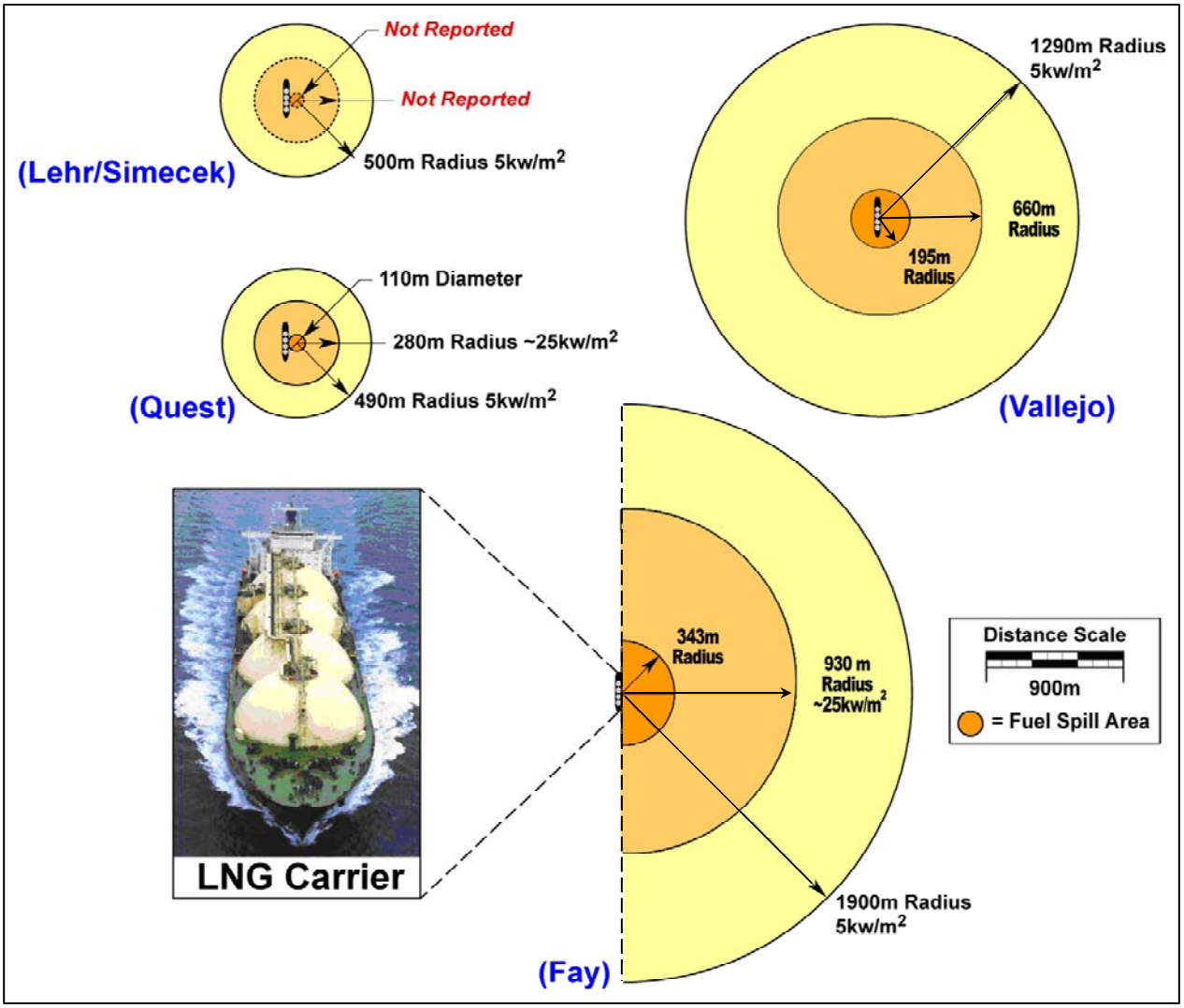


Figure 6. Graphical Summary of the Results of the *Lehr, Fay, Quest & Vallejo* Studies

(Yellow = 5kW/m^2; lt. Orange = 25 kW/m^2; dk. Orange = fuel spill radius)

4 WHY THE STUDIES DIFFER

The following discussion provides comparisons among the different reports and explains why different results are obtained. It is not intended to be an assessment of the merit or validity of the reports.

It is difficult to provide a direct comparison of the results among the reports because each provides a different scenario and/or example assumptions. The example case given by *Lehr* is especially difficult to compare to the other three reports because of the much lower amount of LNG spilled. Pool diameter, radiant flux, and burn duration will depend upon the scenario or example assumptions used, as evident from the reports. Obviously, a larger pool fire would result if all of the five cargo tanks were ruptured due to a larger amount of fuel spilled.

Direct comparison is also difficult due to the lack of information in these reports. The *Lehr* and *Vallejo* reports do not state the pool area values they calculated. *Quest* does not provide surface emission powers used in their heat transfer calculations. The *Vallejo* report does not provide information on the flame model that was used.

In *Quest*, the time of ignition of the pool is unclear in the analysis. *Quest* states that a higher effective vaporization rate results due to back-radiation from the pool flame. When this is included in their model, it reduces the time to vaporize the pool, but not the pool radius. Apparently, the pool is allowed to fully spread with the effect of waves included before ignition results. This contradicts the statement made that ignition occurs because of the collision, which would indicate immediate ignition.

In order to obtain some idea of the effect of including vaporization from back-radiation on pool radius, consider a steady-state situation in which the flow rate into the pool is balanced by both the flow rate provided through vaporization from heating from below by the water and by heating from above by the flame. If an average flow rate of 40,056 kg/s (obtained from *Quest*) and a vaporization rate of 8×10^{-4} m/s (.346 kg/m^2 s) are used, a pool radius of 192 m results. Thus, reducing the radius below that of *Quest*'s value of 253 m before the effect of waves is included. This is an approximation because, in reality, the flow rate decreases with time; whereas this example assumes an infinite source to provide a steady flow rate.

Of the reports, it is possible to somewhat compare the results given for pool area by *Quest* and *Fay*, because the amount spilled is similar; 12,500 versus 14,300 m^3 of LNG, and both can be compared for equivalent hole sizes. The value given for pool radius by *Quest*, before including the effect of waves, is 253 meters. *Fay* reports a value of 252 m, if the radius is calculated based upon the shape of a circle. Thus, the two reports compare favorably for pool area when waves are not considered. *Quest* found that, by including the effect of waves, the pool radius decreased to 55 m for the high wind case. This is why *Quest* reports a significantly different value for pool radius. *Fay* considered a perfectly smooth surface upon which the fuel spreads, while *Quest* considered the impeding action of waves.

The value reported by *Quest* and *Fay* for the distance required for an object to receive a radiant flux of approximately 5 kW/m^2 is significantly different: 493 m versus 1900 m,

respectively. One obvious reason for this difference is that *Fay's* analysis predicts a much larger pool fire. For instance, by using the relation that *Fay* used to determine the radiant flux at the distance and pool area given by *Quest*, the distance is 353 m at which the radiant flux is 5 kW/m^2. Thus, pool area will make a significant difference.

Fay also did not model the flame in his analysis. The relation he used provides a crude approximation to the thermal radiation emitted by a pool fire. The radiant flux emitted by a pool fire to an object is dependent upon many factors, such as pool size, fuel type, flame shape, and view factors.

The reports by *Lehr* and *Fay* use reasonable values for the burn rate of LNG. *Quest* does not explicitly provide the value that they used, though it can be inferred that they used a value of approximately 2.1×10^{-4} m/s (.09 kg/m^2 s). The range of burning rate values, determined experimentally by other researchers, has been found to be: 3.2×10^{-4} m/s (35 m dia.) [Johnson 1992], 2.5×10^{-4} m/s (18 m dia.) [Drake and Wesson 1976] and $2.1 - 4.2 \times 0^{-4}$ m/s (30 m dia.) [Mizner and Eyre 1983].

The burn duration of 28.6 minutes given by *Quest* is reasonable, given the pool radius and the amount spilled. It is difficult to check this accurately, because the amount of fuel left after vaporization during spreading is unknown. A burn time of 31.6 minutes results, assuming a mass flux value of 0.3 kg/m^2 s (from heating from water below and heating above), pool radius of 55 m, and 12,500 m^3 of LNG. A longer burn time for this example occurs because it is assumed that all of the LNG spilled is available for burning. For a pool radius of 252 m, a burn time of 1.7 minutes results if 14,300 m^3 is assumed available, and a mass flux of 0.3 kg/m^2 s is assumed. This assumes a pool that is ignited after it spreads to 252 m. *Fay* reports a burn time of 3.3 minutes using a spill volume of 14,300 m^3, 252 m pool radius, and mass flux of 0.345 kg/m^2 s. His burn time differs because it pertains to a pool that is burning while it is spreading.

Thus, there is a trade-off between the size of the fire and burn duration. For fires of increasing size, the burn duration decreases. It is interesting to note that *Quest* reported it took two minutes for 12,500 m^3 of LNG to spill from a five meter diameter hole, and that *Fay*'s result for pool diameter for the same hole size results in a burn time of 3.3 minutes. *Fay*'s spill time would have been longer, because he was considering 14,300 m^3. Thus, the time taken to spill would have been approximately equivalent to the time taken to burn in *Fay*'s example.

Following is a table summary comparing the results of *Quest* and *Fay*:

Table 31: Summary of Results [Quest vs. Fay]

STUDY	HOLE SIZE (m)	VOLUME SPILLED (m^3)	POOL RADIUS; NO WAVES (m)	POOL RADIUS; WAVES (m)	DISTANCE TO 5 kW/m^2	BURN DURATION (min)
Quest	5	12,500	253	55	493 m**	28.6
Fay	5	14,300	252	Not considered	1900 m*	3.3

*Using *Fay*'s combustion model, this value would be 353 m, if the pool had a 55 m radius.
**Based upon 55 m radius pool

5 IDENTIFICATION OF GAPS AND LIMITATIONS IN THE STUDIES

In the context of a comprehensive risk analysis, one needs to overlay onto the event tree in Figure 4 the body of knowledge provided by the four studies. The missing pieces are the gaps identified. It is evident at the highest level that the four reports omit consideration of many aspects within the context of the event tree.

Additionally, the reports do not cover several potential types of consequences not involving LNG ignition (e.g., asphyxiation, cryogenic burns to humans, cryogenic damage to the ship's structure). Thus, several potential consequences of an LNG spill are not considered.

In addition, risk assessment modeling of mitigation of potential harm to people, facilities, or the LNG ships was not provided. Although the scope of this evaluation did not include remediation of the shortcomings within the four studies, it does pose those missing issues and subsequent analysis techniques that should be considered on a site-specific basis.

5.1 LNG Cargo Tank Breach Modeling

All of the studies assumed breach scenarios. Better definition of realistic breach scenarios and LNG tanker breach and spill calculations should be investigated for site-specific conditions evaluated. Specific intentional breach scenarios are not well known; but general scenarios such as hijackings, terrorist attacks, and insider-supported actions are events that have occurred in the past and should be commonly considered. Prevention and mitigation concepts should be considered to address these impacts, especially in high consequence, highly industrialized or highly populated areas.

5.2 LNG Liquid Transport Modeling

Quest's analysis indicates that the effect of waves is significant. Their model, however, is a very simplistic representation of a standing wave. The boundary condition they invoked to account for waves is one-dimensional and has only a bounding effect, rather than an effect that aids in spreading. Models that are more sophisticated should be considered, such that the physics of traveling waves are included. From the experiments by Mizner and Eyre, the pool formed was far from circular, and was more of a 'boom-a-rang' shape. This indicates that the dynamics of waves can indeed have a significant effect on pool spreading.

5.3 LNG Combustion Modeling

All of the reports use very simplified models, solid flame or point source, to determine the radiant heat flux from the flame. Far more sophisticated methods to model the flame are currently available. Due to increased computer capabilities, validated CFD codes exist for chemically reacting flows that have radiation and soot models. These codes also have the capability to model the effect of wind on the flame by invoking a wind boundary condition. Thus, flame tilt due to wind effects can be captured. It is recommended that these codes be used to model the flame, rather than the solid flame or point source models used in these studies.

All the reports assume that the fuel ignites immediately and that only a pool fire results.

As an example of a different combustion scenario, the experiments performed by Mizner and Eyre involved an ignition source 130 meters away from the spill source. A vapor cloud developed above the spill, propagated towards the ignition source and ignited. They observed that the flame propagated in two modes in the vapor cloud, as a pre-mixed flame in regions where air and fuel were mixed within the flammability limits, and as a diffusion flame in fuel-rich regions. The diffusion flame propagated back to the spill point, whereupon a pool fire resulted. Thus, pre-mixed and diffusion modes of burning can occur. The implication of this deals with the potential occurrence of explosion in pre-mixed regions, given potential breach conditions and ignition sources.

5.4 LNG Plume Modeling

The LNG plume (vapor cloud) calculations contained in the *Quest* and *Vallejo* studies are performed with standard, simplified plume models (SLAB, which is employed in CANARY and DEGADIS). These models are appropriate for dense gas dispersion such as would occur initially after an LNG spill, as discussed in the report and as supported by Lazaro et al [Lazaro et al. 1997]. The parameters used in the calculations (wind speed and stability class) are consistent with the weather data obtained. Note that these simplified plume models neglect important phenomena that might be significant.

The first phenomenon of concern is the plume itself. The plume changes characteristics during its evolution, so designation as a dense gas plume or a Gaussian plume (non-dense gas) changes with time. The initial release of the cold vapor qualifies the plume as a dense gas, because the density is significantly greater than the ambient air.

Second, the topography of the area is not considered. Due to the surrounding topography, the initially heavy gas plume will tend to be channeled along surrounding low areas, potentially decreasing the spread of the plume and increasing the plume concentration. Dependent upon the wind direction, the plume could either be directed towards populated regions or out over the water. If the predominant wind direction at a site is toward more populated regions and will initially be confined by surrounding terrain, more severe conditions might exist.

The third point is the influence of the ship and the surrounding structures on the plume behavior. Depending upon the wind direction and the location of the breach, the effect of the ship might significantly decrease the plume concentrations near the ship, due to increased mixing from turbulent eddies.

All of the phenomena of concern (topography, plume characteristics, influence of ship) can be addressed through the use of validated CFD codes such as FEM3A. FEM3A has been specifically developed to deal with LNG releases by the Gas Technology Institute and is specified in 49 CFR 193 as a model to include topographical or obstacle (ship) effects [Havens and Spicer 2002]. The use of FEM3A in predicting LNG vapor dispersion is illustrated by Chan [Chan 1992].

To assess LNG plume behavior at different times of the year for different wind conditions, it is recommended that CFD calculations using FEM3A (or its more recent version, FEM3C) or an equivalent be performed in the future using appropriate topography and hypothetical ship location scenarios. These simulations will allow for a much more mechanistic determination of the plume characteristics and the influence of the various phenomena discussed above.

5.5 LNG Spill Overpressure Considerations

The *Lehr, Fay, Quest, and Vallejo* studies did not address the possibility of overpressure and resultant damage, either from ignition on the ship or over open water. The LNG-Air explosion information discussed in Section 3 addresses these issues and concerns. Evaluation of the possibilities of events that could lead to this type of impact is discussed in Appendix D and should be considered on a site-specific basis.

6 RECOMMENDATIONS BASED ON REVIEW OF THE FOUR STUDIES

Each of the studies reviewed contains gaps and limitations in analyzing the risks and consequences of a major LNG spill over water. Several potential actions should be considered:

- Risks of potential large-scale, open-water LNG spills should be studied using modern risk analysis and risk assessment methods and techniques.
- More detailed and sophisticated LNG tanker modeling coupled with experimental validation should be undertaken, especially with respect to breach/ship interactions, ignition of escaping natural gas, LNG dispersion, and potential human and structural impacts and damage.
- These analyses should be supported by validation at the appropriate scale with the latest experimental data.
- Improvements in risk management and prevention and mitigation strategies and technologies should be evaluated to help identify the most cost effective approaches for reducing the probability, consequences, and risks to public safety and property of a large-scale LNG spill over water.

Following these efforts, guidelines for defining improved assumptions and improved approaches for simplified risk and consequence analyses could be developed, in collaboration with national and international experts, for adoption nationwide, similar to approaches already developed for locating land-based LNG storage facilities. This would help ensure that accurate and consistent approaches are used to calculate the site-specific hazards and reduce the risks of a potential large LNG spill over water.

APPENDIX B
THREAT ANALYSIS AND SPILL PROBABILITY

1 INTRODUCTION

High consequence operations such as the transportation of LNG imply potential risks to people, facilities, and equipment. Effectively evaluating the risks of a large LNG spill over water requires that the potential consequences be considered in conjunction with the probability of an LNG cargo tank breach and spill, along with the range of physical or operational measures that can be employed to prevent or reduce the hazards and risks of a potential spill. Appendix B discusses the modeling and analysis conducted of the probability and likelihood of an LNG cargo tank breach from a range of threats and the associated size of the breach.

2 ASSUMPTIONS, MODELS, AND THREAT ANALYSIS

The breach of an LNG carrier can include both accidental and intentional scenarios. While potential accidents are commonly considered in the development of safety equipment and systems, operational directives, and risk management and emergency response plans, intentional acts such as sabotage, intentional grounding, or even physical attacks in the past have often not been considered. However, under existing international situations, intentional attacks and the security and protection of critical infrastructures and systems must be considered.

For this study, a wide range of potential accidental and intentional breachings of LNG cargo tank scenarios were evaluated. Scenarios considered were based on discussions with intelligence agencies and a review of emerging hostile activities around the world [Krane 2000]. This historical information was used to develop credible threat scenarios. For these scenarios, modeling and analysis tools were used to establish a range of expected or likely breaches of an LNG cargo tank and the results presented in Table 36 below.

2.1 Accidental Breaching Evaluations

As noted in Section 2 of this report, the LNG industry has an exemplary safety record with only eight marine accidents over the past 40 years in which LNG was spilled, but without resultant fires. 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.

Sandia had previously conducted sophisticated 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. A summary of the analysis of a 90-degree collision of a large container ship (50,000 metric ton class ship) and a double-hull tanker (80,000 metric ton class) is shown in Figure 7 and collisions with smaller ships are shown in Figure 8 [Ammerman 2002]. The

analysis tool included an approximately 250,000 finite element model of both the impacting vessel and the double-hulled tanker using PRONTO-3D run on a massively parallel computer with 256 processors. This is a transient dynamic, explicitly integrated, Lagrangian solver of the equations of motion. The analysis tracked the progressive failure of the struck ship as the striking ship penetrated. As noted in these figures, 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, kinetic energy is approximately one to two million N·m. Figure 8 shows that this level of 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. This, therefore, can be used to estimate the minimum size of a penetration to cause a penetration and spill in a grounding event. Because of the design of LNG ships, the penetration could be even greater in many cases. The results for this analysis were compared with initial collision information from the recent Baltic Carrier collision at approximately 12 knots. The results of these analyses over-predict, by about 15%, the external hole size measured for that collision

Based on these analyses, several observations can be made. First, LNG vessels, because of their additional insulation and third level of containment, would require deeper penetrations 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 1-2 knots higher for an LNG vessel. This would suggest the required velocity to cause a breach of an LNG cargo tank during a 90 deg collision with a large vessel to be 6-7 knots. Collisions at shallower angles would need to be several knots higher in order to penetrate an LNG cargo tank. Referring to Figure 7, collisions with larger vessels than those considered in the analysis could cause slightly larger holes, which should be considered in developing accident prevention strategies

An additional element to consider in the accident scenario is that the hole size developed probably is not the size of the spill orifice. 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 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 12knots is expected to produce an effective hole area of no more than approximately one square meter for an LNG spill. If larger spills do occur, hole sizes could approach those calculated for intentional breaches.

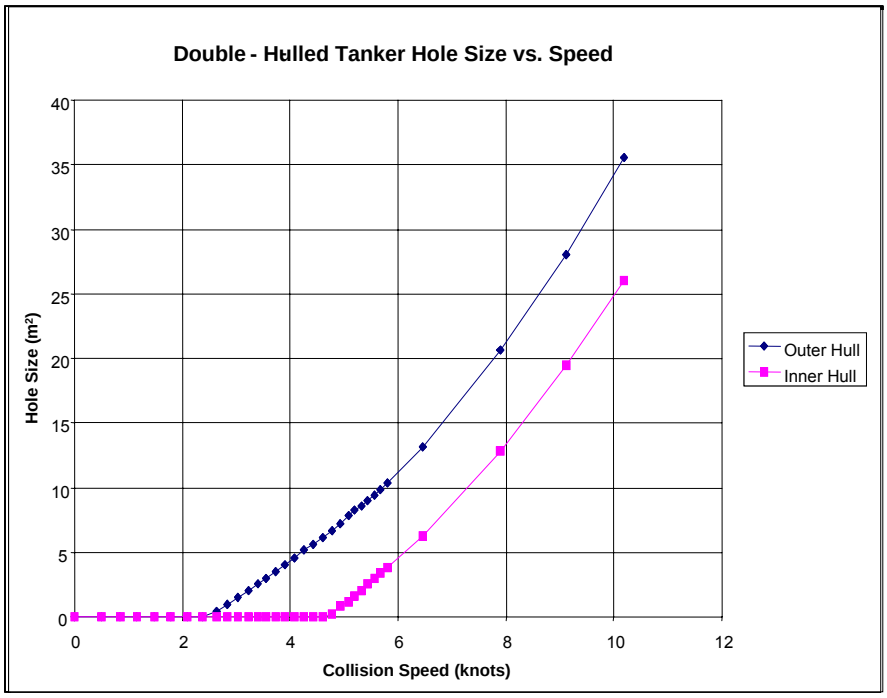


Figure 7. Study Estimate of Speed Required to Create a Given Hole Size

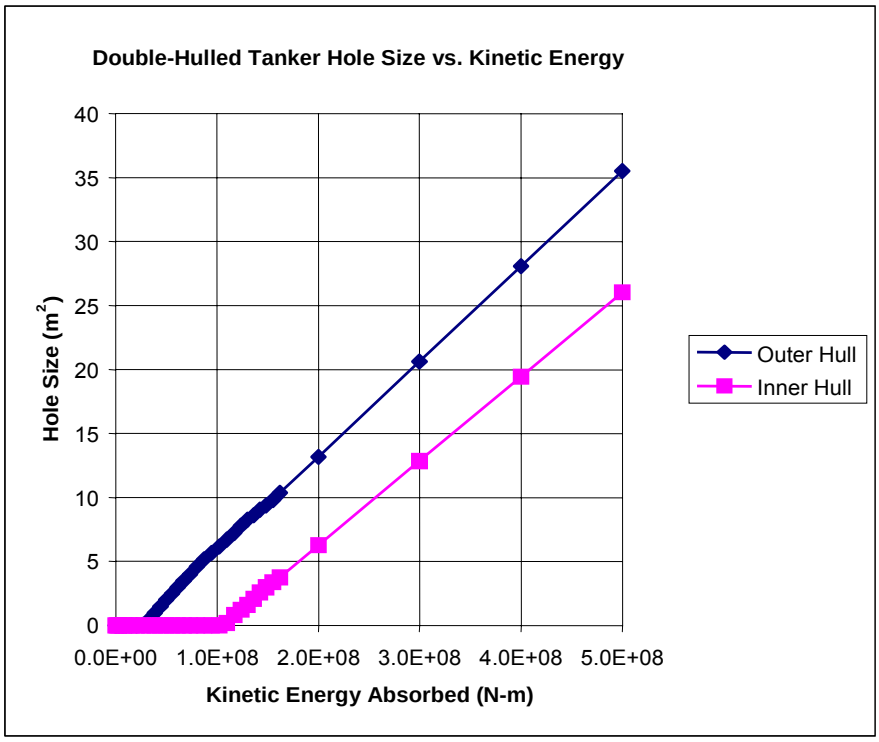


Figure 8. Double-Hull Tanker Study of Energy Required to Create a Given Hole Size

2.2 Intentional Breaching Evaluations

The breach of an LNG cargo tank from an intentional act should include evaluation of a range of threats, including sabotage, insider threats, and external attacks. A wide range of attacks against ships has been documented, including hijackings, attacks with small missiles and rockets, and attacks with bulk explosives [Krane 2000]. While this range of threats must be considered when assessing the vulnerability and consequences of an intentional attempt to breach an LNG vessel, the actual threats and consequences are sensitive.

While a discussion of the specific threats and expected consequences is inappropriate for this report, it is appropriate to discuss the range of breaches that were calculated for a wide range of intentional events. A summary of the modeling and analysis efforts developed and conducted to calculate the potential breaches from various intentional scenarios is presented in an associated classified report [Hightower 2004].

Many reports currently published postulate a potential hole size of as much as 20 – 25m^2 from a major accident or intentional breach. A computational shock physics code, CTH, and material data were used to calculate expected breach sizes for several different intentional scenarios. CTH is Eulerian finite volume code and is required to estimate and analyze the large-scale deformations and material responses under very high strain rates that a developed due to high velocity penetration or explosion scenarios.

Several different intentional breaching scenarios were evaluated. They ranged from sabotage and hijacking to other types of physical attacks. The intentional scenarios evaluated included those events deemed credible from intelligence and historical data. A credible event means that a group (or groups) could have the general means and technical skill to accomplish successfully an intentional breach.

Based on the analyses for both LNG tanker designs, the range of hole sizes calculated from an intentional breach of an LNG cargo tank is between 2 – 12 m^2. Our analysis suggests that, in most cases, an intentional breaching scenario would not cause a tank breach of more than 5 – 7 m^2. This is a more appropriate value to use in calculating potential hazards from spills. As shown in Table 36, it is possible to create a breach in more than one LNG cargo tank under certain intentional scenarios. In addition, in some intentional scenarios, a breach might be such that spilled LNG could stay substantially if not totally within the ship ballast and double hull spaces.

3 LNG BREACH SUMMARY

Based on the breach scenarios identified and evaluated, realistic hole sizes of between 2 – 12 m^2 appear possible. The general sizes are shown in Table 32 for both accidental and intentional breaches. For both LNG tanker designs, a breach could occur in the LNG cargo tanks either above or below the water line. This will impact the amount of LNG spilled onto the water surface and the amount of LNG that might be spilled into the internal ballast areas between the hulls, vacant hold areas, etc.

As shown conceptually in Figure 5, based on the evaluation of the available void space between the hulls, in some cases almost all of the LNG spilled in a breach might be captured

within the LNG vessel. While this will reduce the volume of LNG spilled onto the water and the potential spill surface size, it could negatively impact the structural integrity of the LNG vessel. This has been evaluated and is discussed in Appendix D.

Table 32: Estimated LNG Cargo Tank Breach Sizes for Various Scenarios

BREACH EVENT	BREACH SIZE	CARGO TANKS BREACHED
Accidental Collision with Small Vessel	none	none
Accidental Collision with Large Vessel, (90° @ 7 knots)	none	none
Accidental Collision with Large Vessel, (90° @ 12knots)	5-12m^2 (effective breach: 0.5 – 1m^2)	1
Accidental Grounding	none	none
Intentional Breach	0.5 m^2	1
Intentional Breach	2 m^2	3
Intentional Breach	2-12m^2	1
Intentional Breach	5 m^2	2
Intentional Spill	Premature offloading of LNG	none

The risk of a breach of an LNG cargo tank due to an accident, such as a collision or grounding, appears to be minimal. The risk of such a breach can be easily reduced through a number of operational mechanisms that includes 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. The Coast Guard currently uses all these methods. The safety and hazard issues from an accidental breach appear manageable and adequate with current safety policies and practices based on the safety records of LNG vessels in port.

The intentional breaches shown above in Table 32 cover several events, including a range of possible attacks and insider threats. The large hole sizes calculated, while smaller than commonly assumed in many studies, still provide the potential for large LNG spills and need to be looked at closely. A wide range of operational strategies, though, might be available to prevent or mitigate many of the identified intentional breach scenarios.

APPENDIX C
LNG SPILL AND DISPERSION ANALYSIS

1 INTRODUCTION

This appendix provides an in-depth literature review of experimental and technical studies associated with the dispersion and potential thermal hazards of an LNG spill from either an accidental or intentional event. A broad range of potential modeling and analysis issues associated with spills and potential thermal hazards is identified and discussed.

Table 33 provides an overview of existing LNG spill testing data.

Table 33: Largest Spill Volumes Tested to Date Giving Pool Radius and/or Distance to LFL

EXPERIMENT	SPILL SIZE (m^3)	SPILL RATE (m^3/min)	POOL RADIUS (m)	DOWNWIND DISTANCE TO LFL (m) (Max)
ESSO	0.8 – 10.8	9 – 17.5	7 – 14	400
U.S.CC	3 – 5.5	1.2 – 6.6	~ 7.5	Not measured
Maplin Sands (dispersion tests)	5 – 20	1.5 – 4	~ 10	190 ± 20 m
Maplin Sands (combustion tests)	10.35	4.7	~15	Not measured
Avocet (LLNL)	4.2 – 4.52	4	6.82 – 7.22	220
Burro (LLNL)	24 – 39	11.3 – 18.4	~5	420
Coyote (LLNL)	8 – 2 8	14 – 19	Not reported	310
Falcon (LLNL)	20.6 – 66.4	8.7 – 30.3	Not reported	380

2 LIQUID POOL

2.1 Spreading

2.1.1 Experiments

The experiments summarized in the table below, measuring dispersion only, provide information on pool radius. Thus, mass fluxes are due to the heat transfer from water contact and not from fire.

Table 34: Largest Spill Volumes Tested to Date Giving Pool Radius and Max. Flux Rate

EXPERIMENT	VOLUME SPILLED (m^3)	POOL RADIUS (m)	MASS FLUX (kg/m^2 s)
Boyle and Kneebone (Shell)	0.02 – .085 Quiescent water surface (laboratory)	1.97 – 3.63	0.024 – 0.195 Increased with amount spilled & amount of heavy hydrocarbons.
Burgess et al.	0.0055 – 0.36 (pond)	0.75 – 6.06	0.181
Feldbauer et al. (ESSO)	.8 – 10.8 (Matagorda Bay)	7 – 14	0.195
Maplin Sands	5 – 20 (300 m dyke around inlet)	~10	0.085
Koopman et al. (Avocet LLNL)	4.2 – 4.52 (pond)	6.82 – 7.22	Not reported

2.1.2 Models

Several models have been developed for the spread of LNG on water [Otterman 1975] [Georgakis et al. 1979] [Briscoe and Shaw 1980] [Raj and Kalelkar 1974] [Fay 1973] [Hoult 1972] [Might and Perumal 1974]. Otterman and Briscoe provide model-to-model comparisons for spills on the order of 103 – 104 m^3. The majority of models assume that spreading is driven only by gravity, and ignore the action of waves and currents, preferential boiling, and pool break-up.

The following models are typical approaches used to model the spread of LNG on water. These models are being described because they have been compared to experiments and they account for the heat flux to the LNG from water.

Opschoor developed a model for the spread and evaporation of LNG on open and confined quiescent water surfaces [Opschoor 1980]. For unconfined water surfaces, the model assumes that boiling occurs in the film-boiling mode and that no ice formation occurs. For confined water surfaces, the model assumes that, during the spreading phase, no ice formation occurs due to film boiling and that, after spreading, an ice layer forms due to a decrease in the temperature difference between LNG and water such that film boiling cannot be maintained, resulting in contact between the LNG and water. The results were compared with experiments by Shell for spills of 38kg (.09 m3) [Boyler and Kneebone 1973]. There was agreement with evaporation rate for confined water surfaces for the ice formation period, and fair agreement for confined water surfaces for pool

radius. When compared to experiments by the U.S. Bureau of Mines (163 kg), the model under-predicts the pool radius over time [Burgess et al. 1970].

Waite incorporates heat transfer, preferential boil-off of methane (90%) and ethane (10%), and gravity spreading of the pool [Waite et al. 1983]. The model was compared to experiments conducted by U.S. Bureau of Mines [Burgess et al. 1970] and Shell [Fay 1973], which had spills of 163 kg (0.36 m^3) and 38 kg (.09 m^3), respectively. Assuming a heat flux typical for film boiling (~25 kW/m^2), the model had fair agreement, within 20%, on the pool radius found in these experiments. This heat flux value gave better agreement than the heat flux typically assumed of 100 kW/m^2. No ice formation occurred for unconfined spills.

Brandeis and Ermak developed a numerical model based on the depth-averaged, shallow water equations [Brandeis and Ermak 1983]. Instantaneous and continuous spills that included the effect of mass and heat transfer, shear forces, and surface tension were modeled. Pool break-up was accounted for by including the effect of shear forces and surface tension. It was found that the time necessary to reach a steady-state radius for continuous spills increased as surface shear stress increased. The steady-state pool radius was not affected. The results were compared to experiments performed by Boyle and Kneebone on a 0.0817 m^3 spill, and indicated good agreement.

Cavanaugh developed a code (LSM90) that simulates multi-component spills on land or water that accounts for flashing liquid, entrainment as aerosol, liquid pool evaporation, and heat and mass transfer effects [Cavanaugh et al. 1994]. Spreading is driven by gravity and the actions of waves are not modeled. Results were compared to the Esso [Feldbaur et al. 1972] and Burro [Koopman 1982] series of experiments. The difference between experimental and computed results for evaporation rate varied from 1 – 48%, with eight out of ten cases within 14%. The average difference for pool size comparison was 12%. The spill size for which the comparison was made was not stated.

2.2 Pool Boiling

2.2.1 Experiments

Boe performed laboratory scale experiments with liquefied methane-ethane and methane-propane mixtures boiling on water [Boe 1998]. The results indicated that addition of ethane or propane affects the boil-off rate. High initial boil-off rates were observed for methane rich mixtures similar to that of typical LNG compositions. The boil-off rates increased by a factor of 1.5 – 2 from that of pure methane, when either ethane or propane was added to methane to obtain a 97% methane mixture. It was concluded that there is a breakdown of film boiling due to closer contact between the mixture and water, causing a higher heat flux and lower surface temperature below that to maintain a continuous vapor film.

Results by Drake on laboratory scale experiments showed that LNG had a higher boiling rate than pure methane on a bound-free surface [Drake et al. 1975]. The rate of boiling increased with time and foaming of the LNG occurred on the water surface. These

results agree with Valencia-Chavez and Reid on laboratory scale confined spills [Valencia-Chavez and Reid 1979].

2.2.2 Models

Conrado and Vesovic developed a model to investigate the influence of chemical composition on the spill behavior of LNG and LPG for unconfined water surfaces [Conrado and Vesovic 2000]. Spreading based upon a gravitational-inertia balance, heat transfer, and vaporization was included in the model. They point out that preferential evaporation occurs and that boiling does not take place at a constant temperature. They found that a decrease in the rate of vaporization, due to the change in composition of the pool, occurs in the later stages of the pool. The vaporization rate for LNG versus methane was found to be different. By not considering preferential boil-off, this would result in underestimating the evaporation time by about 20%. For instantaneous spills, results indicate that neglecting evaporation while spreading is a reasonable assumption. They conclude that models should use the properties of LNG as opposed to those of pure methane.

2.3 Rapid Phase Transition (RPT) Explosions

2.3.1 Experiments

Coyote Tests - 1981 [Goldwire et al. 1983] [McRae et al. 1984] [Morgan et al. 1984] [Rodean et al. 1984] [Ermak et al. 1983] [Ermak et al. 1982]

The Coyote series is a continuation of the Burro test series to further study combustion hazards and rapid phase transition (RPT) explosions. They were performed by Lawrence Livermore National Laboratory (LLNL) and the Naval Weapons Center at China Lake, California, and sponsored by the U.S. DOE and the Gas Research Institute. To study RPTs, 13 spills of 3 – 14 m^3 with flow rates of 6 – 19 m^3/min were performed with fuel of varying ratios of methane, propane, and ethane. Five spills of 8 – 28 m^3 with flow rates of 14 – 17 m^3/min were also performed, obtaining dispersion and combustion data under a variety of meteorological conditions.

Six of the 18 Coyote spills produced RPT explosions. Most were early RPTs that occurred immediately with the spill, and in some cases continued for the duration (over a minute) of the spill. They were generally located near the spill point and appeared to be primarily underwater. Delayed RPTs, occurring at the end of the spill and located away from the spill point out on the LNG pool surface, were also observed. Delayed RPTs occurred on three tests.

The results indicate that, for the spill sizes tested, the pre-spill composition is not a good indication of the likelihood of an RPT. Enger and Hartman from Shell performed a series of small-scale experiments (~0.1 m^3) and found that there is a composition envelope within which RPTs can occur [Enger and Hartman 1972]. The Coyote tests found RPTs occurring outside this envelope, indicating that other mechanisms become dominant for larger spills.

Water temperature appeared be correlated with the occurrence of RPTs. RPTs occurred with the water temperature above 17°C, except for one test in which the water was 11.6°C and the adjustable spill plate was removed, indicating that the depth of penetration might affect the occurrence of RPTs as well. The strength of RPTs was found not to correlate with impact pressure. This is in contrast to what was found for laboratory-scale spills by Jazayeri, in which cryogens were impacted with water and a correlation was found between RPT strength and impact pressure [Jazayeri 1975].

Spill rate was found to correlate with maximum RPT yield. An abrupt increase in the RPT explosive yield was found at around 15 m^3/min, from which the strength increased by five orders of magnitude, to 18 m^3/min. The maximum equivalent free-air, point source TNT explosion that occurred was 6.3 kg for about an 18 m^3/min spill rate.

2.3.2 Models

Vapor explosions have been extensively studied in the nuclear power industry and in the industrial process industry, such as foundries. Research on LNG/water explosions has been principally at laboratory scale [Khalil et al. 1988] [Anderson and Armstrong 1972] [Katz and Sliepcevich 1973]. Several theoretical models have been proposed to explain the formation of RPTs, though none has addressed the large-scale behavior observed in the Coyote experiments. There are several recent reviews of the various theories proposed to explain steam explosions [Berthoud 2000] [Schubach 1996] [Fletcher and Theofanous 1994].

The prevalent theory is the superheat theory, which proposes that film boiling occurs immediately after LNG is spilled on water. Then, due to possible instabilities and a decrease in the temperature difference, the film boiling vapor layer collapses in localized areas, resulting in liquid/liquid contact. This direct contact results in rapid vaporization from the increased heat transfer so that a pressure wave is produced to achieve an explosion. For an explosion to occur, the water must be equal to, or slightly greater than, the superheat temperature of LNG ($\mathbf{T}_{superheat} < \mathbf{T}_{water} < \mathbf{1.1}\ T_{superheat}$). Superheat temperature for methane, ethane, propane, and butane are 168, 269, 326, and 376°K, respectively [Khalil et al. 1988]. The superheat temperature of hydrocarbon mixtures is approximately the mole fraction average of the superheat temperatures of the components [Porteous and Blander 1975].

It has been shown that much different behavior occurs at larger scales, which is not predicted from smaller scale studies. For instance, Enger et al. concluded from laboratory scale experiments that the methane content of LNG must be less than the 40 mole % for RPT explosions to occur; but this was found not to be the case for the much larger spills in the Coyote tests, as previously discussed. It has been shown for both laboratory scale and larger field tests that composition, as well as water temperature, is a factor in the occurrence of rapid phase transitions.

Napier and Roochland raise the issue of rapid phase transitions causing ignition by either electrostatic discharge or frictional sparks created near the explosion, or by shock heating of the methane-air mixture [Napier and Roochland 1984]. Based on using shock tube analysis, they concluded that shock heating of unconfined flammable mixtures of methane to the

auto ignition temperature (813°K) is not possible. The experimentally determined temperature available is 450°K; the theoretical is 500°K. They state that ignition is possible via an electrostatic discharge or frictional sparks; but that these ignition modes are difficult to quantify. The ignition source would have to be located on the boundary of the RPT, where the fuel concentration is between the flammability limits.

3 DISPERSION

3.1 Experiments

The following describes experiments on the dispersion characteristics of vapor clouds formed from LNG spills onto water. Only the largest spill volume tests have been reviewed and discussed. Smaller spill volume tests have been performed and are listed in the recent review on cryogenic spills by Thyer [Thyer 2003].

Shell Jettison Tests – 1973 [Kneebone and Prew 1974]

Shell performed a series of six tests in which LNG was jettisoned from the 'Gadila,' a 75,000 m^3 capacity ship. The primary objectives of the tests were to determine the feasibility of emergency jettison of fuel with high discharge rates while the ship is stationary, as well as low discharge rates while the ship is moving. The flow rates tested ranged from 2.7 to 19.3 m^3/min, lasting a total of ten minutes, and producing total volumes spilled that ranged from 27 to 193 m^3. Four tests were performed while the ship was moving from 3 to 10.5 knots, and two stationary tests were performed, one of which was with the highest volume spilled. The methane, ethane, and propane content by mole percent were 87.11%, 9.05%, and 2.75%, respectively. Two different jet nozzle sizes were used (51 and 102 mm) located 18 m above the water. The relative humidity was between 80 and 85%, and wind speed ranged from 1.9 to 5.1 m/s.

Measurements were taken of the following: ship speed, wind speed and direction, air and seawater temperature, distance of liquid and vapor cloud from the ship, and electrostatic field strength in the jet exiting the nozzle. Concentration measurements were not taken. Infrared camera results indicated that, with the 51 mm nozzle, LNG pools on the sea surface did not form and only isolated patches formed for the 102 mm nozzle. This could be due to the LNG evaporating before it reached the sea surface, because it was released from an elevated horizontal jet. Thus, ice formation or RPT explosions were not observed. It was visually observed that the clouds completely dispersed within 15 – 20 minutes after the discharge was completed for the 102 mm nozzle at a discharge rate of 19.3 m^3/min.

For the highest volume spilled, 193 m^3 (3.9 m/s wind), the visible plume appeared to be uniform over its entire length and had a height of 10 – 12 m, maximum continuous width of 550 m, and length of 2250 m. The length was observed continuing to increase after the test.

Maplin Sands Tests – 1980 [Puttock and Blackmore 1982] [Blackmore and Summers 1982] [Blackmore et al. 1982] [Colenbrander and Puttock 1983]

Tests were conducted at Maplin Sands, England by the National Maritime Institute and were sponsored by Shell. These tests were performed to obtain dispersion and thermal radiation data on 20 spills of LNG and 14 spills of propane onto water. The spill point was surrounded by a 300 m diameter dyke to retain the tide. For instantaneous spills, the spill volumes tested were 5-20 m^3, and for continuous spills, the spill rates tested were 1.5-4 m^3/min. Tests were performed for average wind speeds of 3.8-8.1 m/s.

Results indicate that the LFL is reached within the visible boundary of the vapor cloud for the humidity range of 50-100%. A rapid phase transition (RPT) was observed in one of the instantaneous LNG spills. The maximum overpressure was 18 mbar and damage to the barge used to carry out the instantaneous spill occurred.

The dispersion behavior of the cloud was affected by the method of LNG release. For an underwater release, a more buoyant cloud resulted, whereas with an above water release, a lower and longer downwind cloud resulted. A typical pool radius was roughly 10 m, and the evaporation rate was calculated to be approximately 2 x 10^{-4} m/s (0.085 kg/m^2s). Using a 3-second average measurement, the maximum dispersion distance to LFL for a spill rate of 3.2 m^3/min and wind speed of 5.5 m/s was 190±20m downwind of the spill.

Burro Tests – 1980 [Koopman et al. 1982, a&b] [Koopman et al. 1978]

The Burro tests were performed by LLNL and the Naval Weapons Center at China Lake, California, and sponsored by the U.S. DOE and the Gas Research Institute. A total of eight LNG releases onto water were performed, with spill volumes ranging from 24 to 39 m^3, spill rates of 11.3 – 18.4 m^3/min, wind speeds from 1.8 to 9.1 m/s, and atmospheric stability conditions from unstable to slightly stable. Dispersion occurred over water for 29 m from the spill source on a pond, then over land for 80 m, where the terrain was irregular with a rise of 7 m. Beyond this point, the land was relatively level.

These tests were preceded by the Avocet series of discovery experiments for 5 m^3 spills [Koopman et al. 1978]. The Avocet tests were performed in order to gain insight into the measurements necessary for the larger spills to be tested in the Burro series of experiments. It was concluded that a large array of instruments would be necessary for larger tests and that wind speed variations have a significant effect on liquid spread and the boil-off rate of the pool.

Measurements of wind speed and direction, gas concentration, temperature, humidity, and heat flux from the ground were made at various distances from the spill and at various elevations. Gas measurements were averaged over a 10-second duration. High-frequency data indicated that significant fluctuations about the 10-second-average occurred such that the flammable extent of the gas cloud will be larger than is indicated by the mean LFL contour.

In one of the tests, the cloud caused displacement of the atmospheric flow and resulted in the wind speed decreasing to almost zero within the cloud. The dense cloud was able to dampen turbulent mixing by stable stratification and, thus, the wind was able to flow over the cloud as if it were a solid object. This test was performed under a low wind speed of 1.8 m/s, slightly stable atmosphere, and spill rate of 16 m^3/min (28.4 m^3). For the other tests with higher wind speeds, this effect was not observed. The cloud was wider and lower in height than that of any other test. The maximum radial distance to LFL at 1 m elevation was approximately 420 m. The cloud also remained over the spill region after the spill ended, in contrast to the other tests, in which the cloud propagated downwind within 10 – 20 seconds after spill termination.

Differential boil-off was observed in the tests where ethane and propane enrichment up to 40% in the cloud occurred late in the spills and propagated downwind up to 140 m. It was also found that a relative increase in absolute humidity is correlated to an increase in gas concentration.

RPT explosions with a maximum overpressure (static) of .72 psi were measured 30 m from the RPT itself. The explosions were strong enough to cause damage to the facility.

Falcon Tests – 1987 [Wiersma and Williams 1989]

The Falcon tests were conducted at Frenchman Flat in Nevada by LLNL and sponsored by the Gas Research Institute and the U.S. DOT. The objectives of the tests were to provide a database on LNG vapor dispersion from spills involving obstacles and to assess the effectiveness of vapor fences for mitigating dispersion hazards. The testing was performed on a 40 x 60 m pond, enclosed by an 88 m long by 44 m wide by 9.1 m high vapor fence. A 22 m wide by 13.7 m high barrier was erected upwind of the pond, in order to simulate the obstruction of a storage tank.

Five tests were performed with spill rates of 8.7 – 30.3 m^3/min (20.6 – 66.4 m^3), wind speeds of 1.7 – 5.3 m/s, and methane concentrations of 88 – 94.7%. Gas concentration and temperature measurements were taken at towers both upwind and downwind of the spill

The test with the highest volume, 66.4 m^3 (spill rate 28.7 m^3/min), and most stable atmospheric conditions (Falcon 1) resulted in the vapor cloud overfilling the vapor fence on all four sides. Pre-spill wind tunnel simulations predicted that the cloud would stay within the fence. It was speculated that this was due to enhanced, turbulent mixing from the high spill rate and partly due to superheating of the LNG from the water beneath. This could not be substantiated, due to insufficient measurements of concentration and temperature in the source area. A maximum downwind distance to LFL of 330 m was measured for this case.

Tests were performed with and without the vapor fence. With the fence in place, the downwind distance to the 2.5% concentration on the ground was reduced from approximately 380 m to 235 m and a substantial reduction in the hazardous areas was achieved. The persistence of the cloud at a 2.5% concentration near the center of the spill

was 530 s with the fence versus 330 s without the fence. Although the fence reduced the downwind distance of the hazardous area and delayed cloud arrival time, it prolonged the cloud persistence time within the fence, thereby prolonging the potential for ignition.

Large RPT explosions occurred approximately 60 sec. after the spill; and a fireball started inside the vapor fence at 81 sec. for Falcon 5, which had a spill rate of 30.3 m^3/min, total volume of 43.9 m^3, and methane content of 88%. Only limited data outside the fence was obtained up to about 100 sec. Rapid phase transitions also occurred with Falcon 3, with a spill rate of 18.9 m^3/min, total volume of 50.7 m^3, and methane content of 91%.

3.1.1 Models

Dense gas dispersion models generally fall into the following categories: Navier-Stokes based, Lagrangian nonlinear puff, shallow layer or two-dimensional integral, one-dimensional integral, and simplified empirical. The following will describe these models and discuss various codes representative of these model types.

Navier-Stokes Based Models

The most complex models are those based on Navier-Stokes. These models computationally solve time-averaged, three-dimensional, turbulent transport equations that come from conservation of mass, species, momentum, and energy balances. Usually, turbulent transport is modeled using a first order, eddy diffusivity approximation, in which eddy diffusion tensors are specified by ad-hoc equations. The most well known code of this is FEM3 [Chan 1992] [Chan et al. 1984] [Chan et al. 1987] [Leone et al. 1985] [Ermak 1982] and its subsequent upgraded versions, up to FEM3C [Chan 1994] [Chan 1997].

Developed by Lawrence Livermore National Laboratory, FEM3 uses a Galerkin finite element scheme in space and a finite difference scheme in time. The latest version (FEM3C) flows over variable terrain and objects, as well as complex cloud structures, such as vortices and bifurcation. Both isothermal and non-isothermal dense gas releases, as well as neutrally buoyant vapor emissions, can be modeled. FEM3C can model multiple simultaneous sources of instantaneous, continuous, and finite-duration releases. FEM3C also incorporates a phase change model that accounts for water vapor interaction in the cloud; and it has the option to use the k-epsilon turbulent transport equations, which is a second order turbulence model.

Limitations of these codes are in the approximations and assumptions that are used to model turbulence and buoyancy effects. They are the most computationally expensive among the model types, but with increasing computing power, this is not as problematic as it was ten years ago or more.

Lagrangian Nonlinear Puff Models

Gaussian puff models are typically for buoyant or neutrally buoyant releases, such as from an elevated stack source. Recently, the code called SCIPUFF (Second-order Closure Integrated Puff), developed by Titan Research and Technology, includes a dense gas release model [Sykes et al. 1999]. SCIPUFF uses a Lagrangian puff dispersion model that captures nonlinear interaction among a collection of Gaussian puffs to represent a

three-dimensional, time-dependent concentration field. Dense gas effects are captured by using the conservation of vorticity moment equation. Turbulent diffusion is based on a second-order closure model. Finite duration, unsteady, and multiple sources can be modeled, as well as flow over flat or complex terrain. Comparisons to dense gas field data on maximum concentration over all sampling locations at a given distance and over the sampling period from Maplin, Burro, and Coyote tests show the model predicting concentration values within a factor of two.

Shallow-Layer Models

Shallow-layer models use equations that assume the lateral dimensions are much greater than the vertical dimension, which is representative of dense gas releases where low wide clouds result. One such model, TWODEE, has been developed for dense gas releases by Hankin and Britter [Hankin 2003] [Hankin and Britter 1999]. Depth-averaged variables are solved in two dimensions (lateral) using the conservation equations. Empirical correlations are used to determine the entrainment rate. The ability to model the effects of complex terrain and phase changes can be incorporated into this model. It is a compromise between Navier-Stokes based models and one-dimensional integral models, though it still requires an order of magnitude greater computational time than one-dimensional integral models.

One-Dimensional Integral Models

One-dimensional integral models such as SLAB [Ermak 1980], HEGADAS [Colenbrander and Puttock 1983] and DEGADIS [Spicer and Havens 1989] use similarity profiles that assume a specific shape for the crosswind profile of concentration and other properties. The downwind variation of spatially averaged crosswind values is determined by using the conservation equations in the downwind direction only. These models include eddy diffusivity models for turbulent transport. The weakness of these models is that they cannot capture flow around obstacles or over complex terrain. The DEGADIS and SLAB models are used widely in the both public and private sectors. In addition to jet releases, both can model buoyancy-dominated, stably stratified, or neutral releases. There are some models of this type, such as GASTAR, developed by Cambridge Environmental Research Consultants (CERC), that incorporate the effect of terrain, such as variable slopes and ground roughness and obstacles, including porous, into the integral formulation.

Empirical Models

The simplest models are modified Gaussian puff/plume models that are principally based upon the conservation of species equation. The downwind concentration profiles are represented by ad hoc equations. The cloud is assumed to have a specific shape with air entrainment occurring at the cloud edges and the interior of the cloud is assumed to have a uniform composition. Empirical models by Germeles and Drake, Fay and Lewis, Burgess et al. Feldbauer et al., SAI, U.S. Federal Power Commission, and U.S. Coast Guard are compared by Havens [Havens 1981].

3.1.2 Model Evaluation Studies

Fifteen integral models, including publicly available and proprietary, were evaluated in a validation exercise by Hanna, et al., in which calculations were compared to data from eight field experiments that included the Maplin Sands, Burro, and Coyote test series [Hanna et al. 1993]. SLAB, HEGADAS, DEGADIS, and GASTAR were able to predict maximum plume centerline concentrations and plume width for these field tests to within a factor of two. It was noted that all of the models were unable to reproduce the variation of concentration with averaging time from field data because they assume that the cloud has a dense gas 'core' that is unaffected by averaging time.

Mercer compared several integral models against one another (and not to experimental data) by considering twenty-five cases that varied in wind speed, atmospheric stability, roughness length, spill volume, and pool radius [Mercer et al. 1994]. For each case, the density of the release was twice that of air and only instantaneous releases were considered. The models varied within a factor of three to five, and the greatest differences among them arose out of the case with low wind speed, F-stability class, and large roughness length.

An evaluation protocol of dense gas dispersion models has been developed through a program called SMEDIS, a European Union research project funded by the Environment and Climate Research Program [Daish 2000] [Carissimo et al. 2001]. Several dense gas dispersion models were assessed from their publication and are listed in Figure 9.

Table 35 shows the data sets to which the models were compared. The evaluation procedure incorporates validation, verification, and scientific assessment for simple, as well as complex, situations that include aerosols, topography, and obstacles. Screening tools, integral models, shallow-layer models and validated CFD models were compared among a dataset of field and wind tunnel data. It was found that all models were globally better at predicting arc-wise measurement, such as centerline maximum concentration, than point-wise statistical measures, suggesting that is more difficult to predict the general cloud shape.

For a particular model type, Tables 36 and 37 show the percentage of model results that were within a factor of two in the experimental results. Table 36 shows results for arc-wise comparison and Table 37 for point-wise comparison. The validated CFD models performed better overall on statistical measures of geometric variance, mean relative square error, and fraction within a factor of two. It was also noted that more information is necessary from field experiments on sensor accuracy and data uncertainty in order to define acceptable agreement with model predictions.

Table 1 The models participating in SMEDIS (HSE = Health and Safety Executiv Health and Safety Laboratory; CUED = Cambridge University Engineering Departmer model uses a worst-case approach and has not been included in the statistical analysis

Model	Developer
Screening tools	
Britter-McQuaid Workbook	HSE and CUED (UK)
VDI Guideline 3783 Part 2	Meteorologisches Institute (Germany)
Integral models	
AERCLOUD	Finnish Meteorological Institute (Finland)
DEGADIS	US Coastguard, US-EPA and Gaz Research Institute (USA)
DRIFT	AEA Technology (UK)
EOLE	Gaz de France (France)
ESCAPE	Finnish Meteorological Institute (Finland)
GASTAR	CERC Ltd. (UK)
GReAT	Risø National Laboratory (Denmark)
HAGAR	BG Technology (UK)
HGSystem	Shell Research (UK)
OHRAT/Multi-stage	Det Norske Veritas (UK/Norway)
PHAST/UDM	Det Norske Veritas (UK/USA)
SLUMP	W.S. Atkins Safety and Reliability (UK)
WHAZAN/HVYCLD	Det Norske Veritas (UK/USA)
Shallow-layer models	
DISPLAY-1	EC Joint Research Centre (Italy)
DISPLAY-2	EC Joint Research Centre, Ispra (Italy)
SLAB	Lawrence Livermore National Laboratory (USA)
SLAM	Risø National Laboratory (Denmark)
TWODEE	HSE/HSL (UK)
CFD Models	
ADREA–HF	NCSR 'Demokritos' (Greece)
CFX	AEA Technology (UK)
COBRA	Mantis Numerics Ltd. (UK)
FLACS	Christian Michelsen Research (Norway)
FLUENT	FLUENT (UK)
KAMELEON FireEx 98	SINTEF (Norway)
MERCURE	Electricité de France (France)
STAR-CD	Computational Dynamics Ltd. (UK)

Figure 9. The Models Participating in the SMEDIS Database and Validation Exercise

[Carissimo, et al. 2001]

Table 35: Dataset Groups Selected Based on Questionnaires Returned by All Participants.

[Carissimo, et al. 2001]

IDENTIFIER	SCALE	MATERIAL	SOURCE TYPE	NUMBER OF TESTS	COMPLEX EFFECTS
Burro	Field	LNG	Pool	8	fast aerosol evaporation
Desert Tortoise	Field	Ammonia	Jet	4	Aerosol
FLADIS-Riso	Field	Ammonia	Jet	16	Aerosol
BA-Hamburg	Wind tunnel	Sulphur hexafluoride	Continuous instantaneous	146	Obstacles, slopes
BA-propane	Field	Propane	Jet-cyclone	51	Aerosol, fences
BA-TNO	Wind tunnel	Sulphur hexafluoride	Continuous instantaneous	13	Fence
Thorney Island	Field	Freon	Instantaneous	30	Fence, building
EMU-Enflo	Wind	Krypton	Continuous	2	Building, real site

Table 36: Arcwise Comp: Fractional Results w/in a Factor of Two of Experimental Results

[Carissimo, et al. (2001)]

MODEL TYPE				
Case with:	Workbook	Integral	Shallow-layer	CFD
No effect	0.40	0.74	0.65	
Obstacle	0.42	0.79	0.53	0.89
Aerosols	0.43	0.69	0.32	0.75
Terrain		0.33	0.67	0.71

Table 37: Pointwise Comp: Fractional Results w/in a Factor of Two of Experimental Results

[Carissimo, et al. 2001]

MODEL TYPE				
Case with:	Workbook	Integral	Shallow-layer	CFD
No effect	0.40	0.42	0.47	
Obstacle	0.30	0.34	0.34	0.54
Aerosols	0.31	0.39	0.36	0.55
Terrain		0.43	0.53	0.77

3.1.3 Model Directory

The Office of the Federal Coordinator for Meteorology (OFCM) has published a directory of a number of transport and dispersion models for the release of hazardous materials into the atmosphere [http://www.ofcm.noaa.gov/atd_dir/pdf/frontpage.htm]. An in-depth compilation and description of the models are provided, as well as model validation and

verification information. No assessment or comparison of model performance is provided.

4 POOL FIRE AND VAPOR CLOUD STUDIES

LNG pool and vapor cloud fire experiments and their results are summarized in Table 38. A detailed description of these experiments is provided in the following sections.

Table 38: Large Scale LNG Fire Studies

STUDY	SPILL TERRAIN	SPILL VOL. (m^3)	SPILL RATE (m^3/min)	POOL DIA. (m)	SURFACE EMISSIVE POWER (kW/m^2)		BURN RATE (10^{-4} m/s) OR kg/m^2 s	FLAME SPEED FOR VAPOR CLOUD FIRES (m/s)
					Pool fire	Vapor cloud fire		
U.S.CG China Lake Tests	Water	3 – 5.5	1.2 – 6.6	15 (max)	220 ± 50	220 ± 30	4 – 11 (measured) (.18 – .495)	8 –17 (relative to cloud)
Maplin Sands	Water	5 – 20	3.2 – 5.8	30 (effective)	203 (avg) (178–248 range)	174 (avg) (137–225 range)	2.1 (calculated) (.0945)	5.2 – 6.0
Coyote	Water	14.6 - 28	13.5 – 7.1	Not measured	Not measured	150 - 340	Not measured	30 – 50 (near ignition sources – decayed rapidly with distance)
Maplin Sands	Land	No report	NA	20	153 (avg) 219 (max)	NA	2.37 (measured) (0.106)	NA
Montoir	Land	238	NA	35	290 – 320 (avg narrow angle) 257-273 (avg wide angle) 350 (max)	NA	3.1 (measured) (0.14)	NA

4.1 LNG Fire Experiments over Water

U.S. Coastguard China Lake Tests – 1978 [Schneider 1979] [Raj et al. 1979] [Schneider 1980]

A series of 16 tests were performed spilling 3-5.5 m^3 of LNG onto water with spill rates of 0.02-0.11 m^3/s at the Naval Weapons Center. The objective of the tests was to measure the thermal radiation output of two types of LNG fires over water, pool fires and vapor cloud fires. Three type of experiments were performed: immediate ignition of the LNG pool, delayed ignition in which ignition occurred after the spill started but before the evaporation was complete, and downwind ignition of the vapor cloud. Of the 16 tests, 7 were pool fire tests, 3 were delayed ignition tests, and 6 were vapor cloud fire tests.

For pool fires, spot surface emissive powers were obtained near the base of the flame indicating a value of 210 ± 20 kW/m^2 using narrow angle radiometers, and average emissive power for the entire surface of the flame was 220 ± 50 kW/m^2 using wide angle radiometers. These values represent averages over all tests. The percentage of methane in the LNG used for each test varied from 75 to 95 %. The highest spot emissive power of 250 kW/m^2 occurred with the highest concentration of methane. Average flame heights varied from 25 to 55 meters and fluctuated ±10 m for individual tests. The average flame length to diameter ratios varied from approximately 3 to 4, with a peak value of 6. A maximum pool fire diameter of 15 meters was observed.

For the delayed ignition tests, the fire failed to spread rapidly through the fuel, even when multiple flares were used as ignition sources, so that an optically thick flame was not established.

For the vapor fires, surface emissive powers were obtained indicating a value of 220 ± 30 kW/m^2, using narrow-angle radiometers, and 200 ± 90 kW/m^2, using wide-angle radiometers. Vapor fires were observed to propagate along the ground back towards the pool. The flame height to width ratio averaged about 0.5. Flame speed relative to the gas cloud varied from 8 to 17 m/s. Fireballs were not observed for these spill sizes.

The measured regression rates varied from $4x10^{-4}$ to $11x10^{-4}$ m/s. For higher spill rates, it was observed that the regression rates were higher, speculated as possibly due to the interaction between the jet and water effectively increasing the heat transfer area.

Maplin Sands Tests – 1980 [Mizner and Eyre 1983] [Hirst and Eyre 1983]

Tests were conducted on extensive tidal mudflats at Maplin Sands, England by the National Maritime Institute and sponsored by Shell. These tests were performed to obtain dispersion and thermal radiation data on 20 spills of 5 – 20 m^3 of LNG and 14 spill of 13-31 m^3 of propane onto water. The spill point was surrounded by a 300 m diameter dyke to retain the tide. Twenty-four continuous and ten instantaneous spills were performed. Wind speed and direction, relative humidity, and radiation measurements taken with 26 wide-angled radiometers were recorded. Tests were performed in wind speeds from 4 to 8 m/s.

In only 11 tests ignition was possible, 7 LNG and 4 LPG, due to various difficulties. This could be due to the ignition points placed at cloud peripheries where inhomogeneous and lean burn regions exist. Thus, some ignitions did not result in sustained burns. Ignition points were placed 90 to 180 m downwind of the spill point. Radiation and diffusion flame analysis results were reported for 4 LNG tests. Of the four tests reported, 3 were continuous spills with a spill rate range of 3.2-5.8 m^3/min with a spill duration up to 1 minute, and one instantaneous with a spill volume of 12 m^3.

In all of these tests a vapor cloud fire developed, and for one test the vapor cloud fire propagated back to the spill point for a pool fire to form. This pool fire lasted only for a few seconds before the fuel ran out and did not have time to develop completely. As noted by the authors incomplete photographic records also made the analysis of this test

difficult. In order to determine surface emissive power the pool fire was modeled as a tilted cylinder. An effective pool diameter was calculated by approximating the actual flame base area as an ellipse. An effective pool diameter of 30m (crosswind) was calculated for the LNG pool fire. From this test, an approximate fuel regression rate of 2.1×10^{-4} m/s was calculated. For the LNG pool fire, an average surface emissive power of 203 kW/m^2 with a range of 178-248 kW/m^2 was measured.

The flame propagated in the vapor cloud in two modes: as a pre-mixed weakly luminous flame that moved downwind from the ignition point, and as a luminous diffusion flame that moved upwind and propagated through the fuel-rich portions of the cloud and burned back gradually to the spill point. Video recordings indicated that pre-mixed burning took place in gaps in the vapor cloud and that the fuel/air concentration was not homogenous. Expansion of the combustion products principally took place vertically.

Diffusion flame propagation speeds of 5.2-6.0 m/s, and average pre-mixed flame propagation speeds of 5 m/s moving with the wind, were measured. The wind speed range was too narrow to determine possible flame propagation dependency on wind speed. Flame generated overpressures were under 0.4 mbar.

In one continuous spill test the pre-mixed flame propagated through the vapor cloud up to 130 m from the spill point. The flame height-to-width ratios of the vapor cloud fires were in the range of 0.2 to 0.4. For vapor cloud fires, an average surface emissive power of 174 kW/m^2 with a range of 137-225 kW/m^2 was measured.

Coyote Tests – 1981 [Rodean et al. 1984]

The Coyote tests were performed by LLNL and Naval Weapons Center at China Lake, California and sponsored by the U.S. DOE and the Gas Research Institute. The burning of vapor clouds from LNG spills on water were studied in order to determine fire spread, flame propagation, and heat flux. Data on 4 spills of 14.6-28 m^3 with flow rates of 13.5-17.1 m^3/min were performed with fuel of varying ratios of methane, propane, and ethane. Tests were performed in wind speeds from 4.6 to 9.7 m/s and atmospheric stability conditions from unstable to neutral. Gas concentration measurements were averaged over a 2 s period.

The ignition point was located near the cloud centerline about 60 to 90 m downwind of the spill source, and ignition was performed using either a flare or a jet. The flames were observed to begin near the center of the cloud and propagate radially outward, downwind and upwind toward the spill source. Both visible yellow luminous and transparent flames were observed. Pool fires occurred but measurements were not taken.

It as found that the pre-ignition 5%-gas-concentration contours are not indicative of the potential burn area and its location. The actual burn area was observed to propagate further downwind and to the sides than indicated by the pre-ignition contours. The instantaneous 5% gas concentration contours closely coincided with the burn region when 2-s-averaging of concentration measurements were used.

In the test with the highest flow rate or total volume spilled (17.1 m^3/min or 28 m^3), rapid phase transition (RPT) explosion increased the distance to the downwind LFL by about 65% and the total burn area by about 200%. The flame extended up to 280 m downwind and had a maximum width of 60 m. The authors note that the increase was caused by an increased source rate and by enrichment in higher hydrocarbons. The puffs of vapor from the RPT explosions cause momentary increases in concentration as they propagate downwind.

The test conducted in the lowest wind speed and most stable atmospheric conditions had the broadest vapor fire cloud with a maximum width of 130 m and downwind distance of 210 m, and it displayed a bifurcated structure.

Flame heights appeared to vary directly with the pre-ignition height of the combustible mixture near the ignition source. The ratio of flame height to cloud height varied from 5 to 10. The clouds were 3-8 m in height. Flame speeds with peak values of 30 m/s were observed near weak ignition sources and 40-50 m/s for strong ignition sources. Speed decreased as a function of distance from the source and no flame acceleration was observed. Overpressures of only a few millibars were measured, not enough to cause damage.

Heat flux (radiative and convective) measurements inside the vapor cloud fires were found to be in the range of 150-340 kW/m^2. External radiative flux values for the bright yellow portion of the flames were in the range of 220-280 kW/m^2 using wide and narrow-angle radiometers. These measurements were noted as being suspect because the sensors were not protected by a heat sink or water-cooling. This resulted in the sensors heating up and the signal becoming distorted as the heat load increased. This was true for all but one test that did not have the sensor engulfed by the flame.

4.2 LNG Fire Experiments Over Land

Maplin Sands Tests – 1982 [Mizner and Eyre 1982]

Tests sponsored by Shell were performed to measure the thermal radiation from 20m diameter land-based pool fires of LNG, LPG and kerosene using both wide and narrow-angle radiometers. The following were also measured: mass burning rate, fuel composition, wind speed and direction, relative humidity, and metal surface temperatures close to the fire. Video and still photographs were taken upwind and crosswind of the fires. The average surface emissive power was determined by measurements made using wide-angle radiometers and the use of a solid flame model representing the flame as a tilted cylinder. One test was performed for each fuel.

The flame appeared roughly cylindrical in shape and tilted due to a 6.15 m/s wind. For the LNG fire the production of black soot appeared much higher in the flame and was significantly less than that produced by LPG or kerosene. The measured mean flame length using video recordings for the LNG fire was 43 m with a flame length-to-diameter ratio of 2.15. The Thomas correlation for flame length-to-diameter ratio predicts a value of 1.88, if the measured burning rate is used, underestimating the observed mean flame

length by 12.6%. The measured burning rate was 0.106 kg/m^{2}s (2.37 x10^{-4} m/s) for LNG, versus 0.13 kg/m^{2}s (2.17 x10^{-4} m/s) for LPG.

The average surface emissive power for the LNG pool fire was 153 kW/m^2, while LPG had a much lower value of 48 kW/m^2, due to the greater smoke shielding. The maximum measured value using narrow-angles radiometers for the LNG fire gave values up to 219 kW/m^2.

Montoir Tests – 1989 [Nedelka et al. 1989]

These tests were collaboration among many sponsoring companies: British Gas, British Petroleum, Shell, Elf Aquitaine, Total CFP, and Gaz de France with tests performed by British Gas, Midlands Research Station, Shell, and Thornton Research Center. Tests on 35m diameter LNG pool fires on land were performed at a facility near the Montoir de Bretagne methane terminal.

Three LNG pool fire experiments over a wind speed range of 2.7 to 10.1 m/s were performed. The maximum volume of LNG poured into the 35 m diameter bund was 238m^3. The following were measured: flame geometry, incident thermal radiation at various ground level positions, spot and average flame surface emission, gas composition in pool, fuel mass burning rate, and flame emission spectra in both the visible and infrared regions.

Small regions of the flame were examined using a narrow angle radiometer. These measurements correspond to 'spot surface emissive power' values, whereas average surface emissive power measurements use wide angle radiometers and refer to an average over the flame surface and are interpreted based upon the flame shape. Two types of average surface emissive powers were employed: one based upon an idealized cylindrical flame shape that includes the smoky part of the flame, and the other based from cine photographs that represent the actual areas of clear flame.

A mass burn rate for a methane fire was obtained as long as the methane concentration in the pool was above 40%, or when vapors above the pool were measured to have at least 99-mole percentage methane content. During the methane pool fire burn time, the ethane content in the vapors above the pool was less 0.2-mole %. Keeping the methane content in the pool above 40% avoided the high smoke shielding that can occur from the ethane or propane in the fuel and the decrease in the mass burn rate from the increased conduction into the fuel due to higher boiling points of ethane or propane.

It was observed that the fires had an intensely bright region extending from the base to at least half of the total flame height, and the rest was obscured intermittently by smoke, which was much more than that produced in a 20m diameter LNG fire. The shape of the fire was observed to be complex and was noted as difficult to represent using simple geometries.

The average mass burning rate among the 3 fires was 0.14 kg/m^{2}s.

Flame drag ratios up to 1.29 for high wind speeds, and 1.05 for low wind speeds were measured. Flame drag ratio is defined as the flame base length in the direction of the wind divided by the pool diameter

At 140 m from the burn center, the incident thermal flux was measured as approximately 15 kW/m^2 downwind, 5 kW/m^2 crosswind, and 3 kW/m^2 upwind during a wind speed range of 7.0 – 10.1 m/s.

In the lower 10 m of the flame, typical time averaged spot surface emissive powers of 290 – 320 kW/m^2 were measured in the crosswind direction. Values up to 350 kW/m^2 averaged over 5 – 10 s periods were measured. These values are much greater than that of smaller pool fires where at comparable positions, values of 140 – 180 kW/m^2 for a 6.1m diameter fire and 170 – 260 kW/m^2 for a 10.6m diameter fire has been observed.

Average surface emissive power values in the range of 230 – 305 kW/m^2 from individual instruments were measured. Average values for each experiment were in the range of 257 – 273 kW/m^2. These were based upon a flame shape using cine photographs. Values were also obtained by utilizing a flame shape based upon a tilted cylinder with length calculated from the Thomas equation and tilt angle from the Welker and Sleipcevich equation. The values obtained were much lower with a range of 130 – 180 kW/m^2. With both methods, the average surface emissive power was plotted for pool diameters of 6.1, 10.6, 20, and 35. The graph indicated that the rate of increase of the average surface emissive power for increasing pool diameter is decreasing. The authors note that it is not expected that a much greater value would be obtained for larger pool fires.

4.2.1 Models

Generally, three approaches can be identified to model thermal radiation from pool fires. These models are classified as point source, solid flame, and field. Schneider provides a review of the first two models and various vapor cloud and fireball models pertaining to LNG [Schneider 1980].

The simplest model is the point source model, in which the emission of thermal radiation is treated in a global manner by assuming the radiation source is a point and that the radiation decays as the inverse square of the distance from the source. An assumed fraction of the heat of combustion is used to approximate the thermal radiation emitted, the uncertainty of which increases with large pool fires due to the lack of data. It is also assumed that the receiving surfaces are oriented to receive the maximum thermal radiation. The near field, approximately 3 – 5 diameters, cannot be captured with this model because the geometric considerations between the emitting flame and receiving surfaces become important. Radiation attenuation in the atmosphere is also not accounted for with this model. The effects of wind tilting the flame and the presence of objects interacting with the flame cannot be captured. This model is not a typical approach used today, but was a first attempt to capture the thermal radiation from pool fires.

The next level of complexity is the solid flame model, which configures the surface of the flame with a simple geometry, usually cylindrical [Brown et al. 1974] [Raj and Atallah 1975] [Lautaski 1992] [Johnson 1992]. The thermal radiation is emitted uniformly from this surface and the total radiant power is based upon empirical correlations with pool diameter. Modeled is the geometric view factor, which is the fraction of radiant energy that is received by an object's field of view. Also accounted for is the attenuation of the thermal radiation in the atmosphere. In order to capture the tilting of the flame due to wind, a tilted cylindrical flame shape is typically used. Flame length, tilt and drag necessary to determine flame shape and view factors, are based upon empirical correlations. For pool fires with simple pool geometries, these models provide good agreement with experiment. Johnson found agreement within one standard deviation from the average measured heat flux for a range of pool sizes, 1.8 – 35 m in diameter. The disadvantage of these models is the inability to model more complex flame shapes such as those arising from complex pool shapes or object interaction with the flame.

The most sophisticated models are the validated field models (CFDs) that incorporate the equations that govern fluid flow; that is, Navier-Stokes. Because pool fires are turbulent for the scale of interest, turbulence models are used, typically the k-epsilon model. Combustion models typically assume that combustion is mixing-controlled, rather than controlled by the chemical reaction time. The radiant transport equation along with simplifying assumptions is used to model thermal radiation. Soot models are also incorporated, which invoke empirical models.

Simplified models, such as the solid flame model, have been typically used for thermal hazard zones that assume a circular pool. The point source model has also been used, which assumes that the fire originates from a point, implying that the pool is uniform from the point. For a spill scenario with no object interaction, this is a logical geometrical shape to assume for the pool. If there is object interaction, an oval or rectangular configuration could occur; for example, a trench fire, which is a pool fire with a rectangular configuration. It is of interest to compare the performance of the point source model and solid flame model to such a configuration. Thus, both models were compared to a trench fire [Croce et al 1984].

Comparison was made with a trench dimension of 23.5 x 1.83 meters. The measured wind speed was 1.83 m, average flame length 3.4 m, flame tilt 56.8 degrees, flame drag ratio 2.96, burning rate .054 kg/m^2 s, and average surface emissivity of 135 kW/m^2. The radiative fraction used for the point source calculation was .348, based upon a relation by Moorhouse and Pritchard for radiative fraction as a function of surface emissive power and flame height to diameter ratio. The effective pool diameter is 7.4 m for the given trench dimensions. Thus, the surface emissive power and flame height to diameter ratio was taken into account through the radiative fraction value. The flame height to diameter ratio of 1.49 was calculated using a Moorhouse correlation that includes the effect of wind. The measured burn rate value from experiment was also used for the point source calculation. The view factor for a tilted cylinder to an object was calculated by formula derived by Sparrow [Sparrow 1963].

Figure 10 indicates that both models over predict the measured heat flux at most crosswind, upwind, and downwind locations. The point source model slightly under predicts the heat flux at intermediate distances. The comparison to downwind provides the best agreement to experiment, about five pool diameters from the pool center for the point source model. The percent difference between the experimental data and the point source model results for heat flux measurements downwind range from 4 to 30%, crosswind from 33 to 228%, and upwind from 218 to 293%. The solid flame model predicts a much higher heat flux value, because the predicted flame height for the assumed circular pool is much higher than the experimental value, 11 m vs. 3.4 m. Thus, the discrepancy can principally be attributable to flame break up.

The experiments showed the flame breaking up into flamelets, or individual fire plumes. Thus, the flame height is shorter than that of a circular pool fire with equivalent area. This comparison indicates that the point source model and the solid flame model do not accurately predict heat flux levels when the pool is non-uniform, such as would occur when there is object interaction.

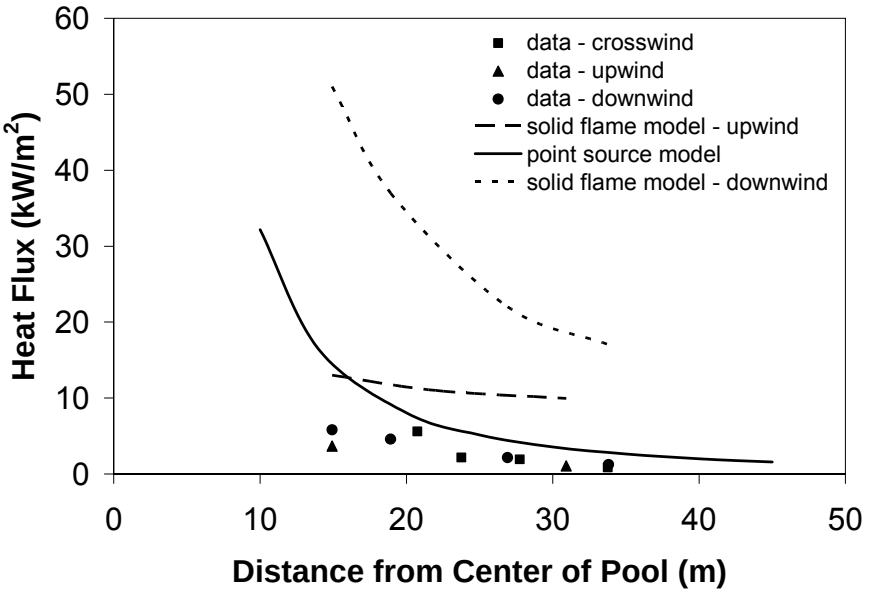


Figure 10. Flame Model Comparison with Trench Fire Data

The disadvantage of field models is the computational running time compared to integral models that represent the fire as cylindrical flame. Although, with the emergence of more powerful computers, this is less problematic. These codes can now be run on personal computers and workstations, instead of super computers. The advantage of field models is that complex flame shapes can be captured, such as that arising from object/flame interaction as from an LNG ship and a pool fire, for example. Vapor cloud fires and fireballs can also be modeled with these codes.

Various field models are available, such as FLACS, CFX, Phoenics, Kameleon, and Vulcan. These codes vary in their capability to model explosion, fireballs, flash fires, and/or pool fires.

4.3 Detonation Studies

U.S. Coastguard China Lake Tests – 1978 [Parnarouskis et al. 1980] [Lind and Witson 1977]

Tests were performed in a detonation tube and 5m and 10m radius hemispheres. Both explosive-initiated and spark-ignited tests were performed on methane-air and methane-propane mixtures. For the detonation tube experiments, the methane-air mixture did not detonate using a 5 g or 90 g booster, nor did it detonate with spark ignition. Methane-air mixtures did not detonate with explosive charges up to 37 kg for the 10m diameter hemisphere tests. Methane-propane mixtures of 60-40, 70-30, and 85-15 did detonate using a 1 kg high explosive booster for the 5m hemisphere tests

Experiments were also performed to test a postulated accident scenario in which the vapor formed during an LNG spill mixes with air to form a flammable mixture and then diffuses into a culvert system. The mixture in the culvert ignites and the combustion wave accelerates then transitions to a detonation that exits the culvert and detonates the remaining unconfined vapor cloud. The detonation charge used in the culvert was a 13 kg explosive. Detonations in the vapor mixture occurred when propane concentrations were 6% or greater and the culvert measured 2.4 meters in diameter. From these detonations, the shock wave was felt at a town 22 km from the test site.

Vander Molen and Nicholls – 1979 [Vander Molen and Nicholls 1979]

Experiments were performed to measure the effect of ethane addition to methane air clouds on detonation. A stoichiometric mixture with air was maintained for every mixture of methane and ethane tested. The ethane concentration ranged between 0 and 5.66% by volume of the total methane-ethane-air mixture or, equivalently, 10% to 50% by volume of the fuel mixture. The experiments were performed using a sectored shock tube of 147.6 cm radius and 5 cm width to model a 20-degree pie shaped sector of a cylinder cloud. A stable detonation was characterized as a wave propagating with a non-decaying constant velocity. For an ethane content of 1% by volume in the methane-ethane-air mixture or a 10% ethane by volume content in the fuel, 5.5 grams of condensed explosive or critical initiating blast energy of 25,000 J/cm was needed to result in a detonation.

4.3.1 Reviews

There have been several reviews on detonations of hydrocarbon/air mixtures [Lee and Moen 1980] [Moen 1993] [Nettleton 2002]. It was pointed out by Moen that weak ignition of vapor clouds in an unconfined and unobstructed environment is unlikely to result in a deflagration to detonation (DDT), even for more sensitive fuel/air mixtures; but it is likely with confinement and the presence of obstacles [Moen et al. 1980]. The occurrence of DDT depends upon the degree of confinement, obstacles configuration, ignition source, initial turbulence, and the fuel-air mixture. Nettleton indicates that the understanding of how confinement, temperature, pressure, and mixture composition influence the initiation

source and distance to DDT is not complete. Further work must be done before prediction can be made whether DDT will occur for any given spill scenario.

4.3.2 Flame Acceleration Studies

Moen et al. – 1980 [Moen et al. 1980]

This is a series of works performed at McGill University in Montreal, Canada, on flame acceleration and deflagration to detonation transitions [Chan et al. 1983]. The influence of obstacles on flame acceleration of methane/air mixtures was investigated in a cylindrical vessel 30.5 cm in radius. The effect of obstacles was to increase flame speed of up to 130 m/s, 24 times the velocity without obstacles. The high flame speeds could only be maintained with repeated obstacles, which provide large-scale flow field distortions associated with flame acceleration.

Urtiew – 1982 [Urtiew 1982]

The work was motivated by the possibility that terrain or obstacles might create semi-confined flame paths that could lead to flame acceleration. Flame acceleration of propane-air mixtures in semi-confined geometries with obstacles was investigated. Propane-air mixtures were spark-ignited in an open top and end test chamber, 90 cm long, 30 cm high, and 15 cm wide. It was found that obstacles caused the flame to accelerate from 2 – 3 m/s up to 4 – 6 m/s. Further flame acceleration up to 20 m/s occurred when the obstacles were raised slightly above the chamber floor and by varying the location of the ignition source. It was concluded that further work is needed to determine the mechanisms leading to continuous acceleration in semi-confined geometries.

Harrison and Eyre – 1987 [Harrison and Eyre 1987]

A series of tests was performed to investigate the effect of obstacle arrays on flame acceleration of pre-mixed natural gas/air and propane/air mixtures. A wedge-shaped enclosure was used which had an open top and bounding sidewalls forming a 30 degree wedge of 30 meters long and 10 meters high. This aspect ratio was used so that a shape representative of a dense cloud would be modeled.

A series of horizontal pipes were placed in the wedge to provide optimal flame acceleration. Blockage ratios of 20 and 40 percent based upon the percentage of the obstacle grid were used. Unobstructed and obstructed tests were performed using a low energy fuse head igniter. The effect of grid height, blockage ratio, grid spacing, and the total number of grids was investigated. Unobstructed LNG/air mixtures produced low flame speeds of 8 – 9 m/s in the first few meters and overpressures of 4 – 5 mbars, which decayed with a 1/r relationship in the far field.

Grids with low blockage ratios or low height produced overpressures of 29 – 63 mbars decaying as 1/r and flames speeds of 37 – 51 m/s, not sufficient to cause severe structural damage. The test with the great congestion obtained a maximum flame speed of 119 m/s and overpressure of 208 mbars decaying as 1/r, which can be sufficient to cause structural damage to buildings in the immediate vicinity of the cloud. In all tests, flame speed and overpressures decayed rapidly after the flame emerged from the grid of obstacles,

typically within 5m of the last grid. Thus, the size of the obstacle array, not the size of the gas cloud, defined the size of the pressure source.

Shell – 2001 [Bradley et al. 2001]

Flame acceleration was investigated in a vented box structure, 10 m long, 8.75 m wide, and 6.25 m high using methane/air and propane/air mixtures ignited using a conventional spark plug. Results indicate that an initial stable and subsequent unstable flame propagation regime occurs. In the unstable regime, instabilities grow to wrinkle the flame and increase the flame speed. Flame speed measurements up to a radius of approximately 3 m indicate that flame speed increases with radial distance and varies as the square root of time. Past this distance, the walls of the test structure interfered with flame propagation.

5 DISCUSSION

There are many theoretical and experimental gaps related to understanding the dynamics and subsequent hazards of an LNG spill on water. Filling some of the gaps is currently impossible due to experimental and computational limitations. The following discussion addresses gaps that can be filled with current capabilities, and is indicative of first priorities to improve abilities to address hazards associated with an LNG spill.

There is a large disparity between the available experimental data and the scales of interest. Figure 11 shows a comparison of the spills sizes tested to date and that are possible from a single LNG cargo tank for a large hole. Table 38 specifies spill volumes tested, spill rate, pool radius, and distance to LFL for these various tests. The available experimental results are two to three orders of magnitude less than the scales of interest. It is evident that there is a lack of large-scale spill data for model comparison.

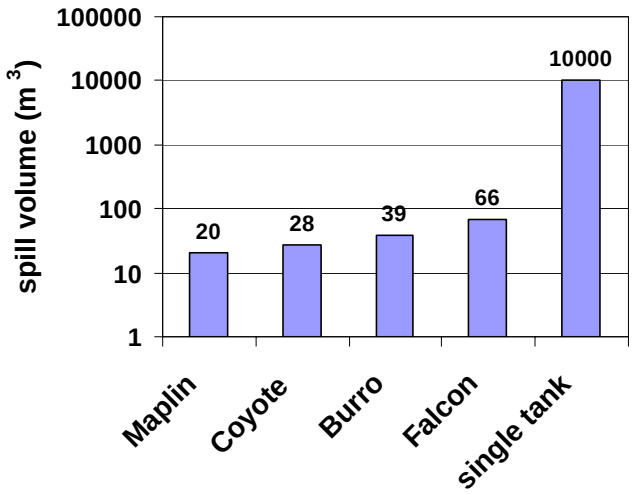


Figure 11. Log Scale Comparison of Experimental Spills vs. Possible Cargo Tank Spills

- Of the larger spill tests performed, there have been only a few LNG pool fires on water tests where measurements were taken. This was for a spill size of 10.35 m^3, which is far below the spill volume that could occur for a 2 or 12m^2 hole in one tank of a vessel. This pool fire lasted only for a few seconds before the fuel ran out and did not have time to fully develop. It was also noted that photographic records necessary for analysis were incomplete. In order to determine the thermal radiation hazard from a pool fire, the surface emissive power needs to be determined. The pool fire tests on land indicate that the surface emissive power increases for pool diameters up to 35 m. Whether the maximum surface emissive power was obtained is uncertain, though most likely it isn't much higher than that measured for 35 m. It is difficult to determine whether the surface emissive power and the pool mass flux has leveled off for pool fires on water since only one test of

a larger scale has been performed. Thus, more data on large-scale LNG pool fires on water is needed. More tests on the order of spill volumes of 10 m^3 should be performed, and ideally on the order of 100 m^3, so that maximum surface emissive powers and pool mass fluxes are reached. Also, at these larger scales, a regime may be revealed at which a single coherent pool fire cannot be maintained, but rather a break up into multiple pool fires occurs.

- LNG pool fire simulations on water using a field or validated CFD dynamics code have only recently begun to be used. These codes can capture object interaction with the flame as well as vapor cloud fires. A simulation of a pool fire and its impact on the LNG ship will provide improved estimates of cascading damage.
- Probability of ignition of the LNG from initial damage is uncertain for some initiating events and should be experimentally investigated.
- It is questionable whether the spill sizes investigated to date give an indication of the atmospheric dispersion that would occur for very large spills. The significance of the Burro tests results for the dense cloud displacement effect is that the cloud does not dissipate as quickly due to the lack of turbulent mixing and thus will persist for a longer time. This result has hazard implications that might be more profound for very large spills in which the mass of the dense cloud will be greater.
- The achievable overpressures of RPT explosions for very large spills (~ 100 m^3/min) and the possible upper bounds of damage to structures have not been evaluated.
- Determining the spreading and vaporization of the LNG pool is instrumental in determining the evolution of the vapor cloud and subsequent related hazards. If this part is performed incorrectly, the rest of the analysis is severely affected. This feature was evident from the recent four studies that were compared. The prominent issue raised from the comparison is the effect of waves on spreading and vaporization. Wave action would increase the evaporation rate due to the increased surface area and increased heat transfer rate from the lower levels of the water due to the mixing action of the waves. Traveling waves would irregularly spread the LNG pool. The effect of waves on spreading and vaporization should be investigated experimentally, and a free-surface code such as FLOW-3D should be used to simulate spills at the larger scales.

APPENDIX D
SPILL CONSEQUENCE ANALYSIS

1 INTRODUCTION

]A wide range of experimental information on LNG spills and associated analyses must be considered and evaluated in an effort to assess the potential consequences of the breach and associated spill of an LNG cargo tank. The consequences or potential hazards to the public of a large LNG spill over water will depend on:

- Potential damage to an LNG cargo tank from either an accidental or intentional breach and the size, location, release rate and volume of LNG spilled;
- Environmental conditions such as wind, tides and currents, and waves that could influence the spread or orientation of a potential LNG spill over water;
- Potential hazards resulting from an LNG spill over water, such as cryogenic damage or thermal damage to the vessel or other LNG cargo tanks, which might lead to cascading failures of additional LNG cargo tanks or several damage to the LNG vessel;
- The location and magnitude of a potential LNG spill where the hazards from a spill, such as fire and thermal radiation, might impact or damage other critical infrastructures or facilities such as bridges, tunnels, petrochemical or power plants, government buildings or military facilities, national icons, or population or business centers; and
- Potential impact on the regional natural gas supplies from the damage of an LNG vessel, unloading terminal, or loss of use of a waterway or harbor due to the immediate or latent affects of a spill.

The risk-based assessment approach discussed in Section 3 of the main body of this report and the event tree in Figure 4 was developed for potential LNG breaches and associated consequences, and provides the basis for evaluating the potential events that might ensue from either an accidental or intentional breach of an LNG cargo tank and are discussed in this Appendix.

2 ASPHYXIATION POTENTIAL AND IMPACTS

Methane, an ingredient of LNG, is considered a simple asphyxiant; but it has low toxicity to humans. In a large-scale LNG release, the cryogenically cooled liquid LNG would begin to vaporize upon its release due to the breach of an LNG cargo tank. If the vaporizing LNG does not ignite, the potential exists that the LNG vapor concentrations in the air might be high enough to present an asphyxiation hazard to the ship's crew, pilot boat crews, emergency response personnel, or others that might encounter an expanding LNG vaporization plume.

To date, experimental data show that vaporization from an LNG spill tends to spread essentially in a cigar-shaped, disk pattern due to the high-density characteristics of LNG. The vapor cloud spreads out in a mostly broad, flat configuration, generally with a plume of

10 – 30 feet in height. This is much different from the traditional Gaussian-type distributions, most often assumed for atmospheric dispersion of many common pollutants.

Beard described a study of the effects of hypoxia on the cognitive abilities of 100 test subjects in a low-pressure chamber. The threshold for reduced mental performance occurred at an oxygen partial pressure of 85 torr for three of the test subjects. This is equivalent to an oxygen concentration of 11.1 % at sea level. Approximately 75% of the test subjects showed reduced mental performance at 65 torr oxygen pressure, which is equivalent to 8.5 % oxygen at sea level. These data were most likely obtained on a cohort of physically fit, medically qualified individuals.

ANSI Z88.2-1992 provides the data in Table 39 for inhalation of air that is deficient in oxygen [ANSI 1992].

Table 39: Response of a Person to Inhalation of Atmosphere Deficient in Oxygen

% O_2 AT SEA LEVEL	OXYGEN PARTIAL PRESSURE (mmHg)	PHYSIOLOGICAL EFFECTS
20.9	159	Normal
19	144	Some adverse physiological effects, but they are unnoticeable.
16	121	Impaired thinking and attention. Reduced coordination.
14	106	Abnormal fatigue upon exertion. Emotionally upset. Faulty coordination. Poor judgment.
12.5	95	Very poor judgment and coordination. Impaired respiration that might cause permanent heart damage. Nausea and vomiting.
<10	<76	Inability to perform vigorous movement. Loss of consciousness. Convulsions. Death.

ANSI Z88.2-1992 requires air-supplying respirators for workers who enter an atmosphere having less than 16% oxygen at sea level. The ANSI standard assumes that nearly all workers will be able to escape from an atmosphere having 16% oxygen, even if it requires a moderate amount of exercise, such as climbing a ladder. When oxygen concentrations are less than 19.5% oxygen at sea level, ANSI Z88.2-1992 requires workers to use air-supplying respirators that have an emergency air supply for escape purposes. It assumes that some workers will be injured or debilitated by a 12.5% oxygen atmosphere, to the point at which they could not escape. ANSI's recommendations are intended to protect nearly all workers; and it assumes that workers are medically qualified and fit for duty. Workers are, on average, more fit than the general population.

To summarize, any reduction in oxygen concentrations will carry some risk to the population, because there will always be sensitive individuals. These probably include people with pulmonary or heart disease. On the basis of the references that were reviewed, it appears that minimal permanent injuries or deaths should occur in a physically fit and medically qualified population from a transient release of methane, if oxygen concentrations do not drop below 12.5% at sea level. If concentrations do not drop below 14% oxygen at sea level, the frequency of permanent injuries or deaths in the general population should be minimal as well. Of greater issue will be the potential for a fire from ignition of an LNG cloud.

3 CRYOGENIC SHIP DAMAGE: POTENTIAL AND IMPACTS

As noted in Appendix B, a range of LNG cargo tank breaches were calculated from the analysis of credible accidental and intentional breaching events. The size and location of potential breaches were used as a basis for the analysis of the potential for cryogenic damage to the structural steel of an LNG ship from a spill in the absence of a fire. 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].

A review of the structural steel used in LNG ship fabrication shows extensive use of ABS-Class A, B, and C structural ship steel [Linsner 2004]. In discussions with the U.S. Coast Guard, ABS Class E and F structural steels are also being used in some newer LNG ships. Selected material properties for ABS Class B steel include [Wellman 1983] room temperature yield strength equal to $37x10^3$ psi., coefficient of thermal expansion equal to $8.3x10^{-6}$ in/in °F, Young's modulus (E) equal to $30x10^6$ psi. As with all low alloy carbon steels, A131 class B and C transition from ductile to brittle behavior with decreasing temperature. Lower shelf (brittle) behavior starts at about 32°F. For these steels, the fracture toughness (Kc) decreases approximately linearly from $90x10^3$ psi√in at -60°F to $20x10^3$psi√in at –260°F.

This is approximately the lower bound of fracture toughness for all low alloy carbon steels at LNG cryogenic temperatures, as shown in the table below. Fracture toughness is a major influence on the structural integrity of steels that come in contact with cryogenic fluids. The lower the fracture toughness, the higher potential for damage that could be expected. Because fracture toughness data at LNG-type temperatures for steel used in ship construction is limited, the use of correlations and extrapolations from available fracture toughness data can provide useful estimates of fracture toughness for many of these steels. Two approaches were used to estimate expected fracture toughness values at LNG cryogenic temperatures for ship steels.

One method of estimating fracture toughness makes use of the "Barsom-Rolfe" two-step correlation between Charpy V-Notch (CVN) data and fracture toughness [Barsom and Rolfe 1987]. ABS – E and ABS – F steels have CVN values of 14 ft-lbs and 17-20 ftlbs respectively. Using the Barsom-Rolfe two-step correlation, this equates to a 46 ksi√in fracture toughness value for ABS E and a 55 ksi√in value for ABS F steel. Data suggests that for low alloy carbon steels well into the lower shelf behavior, the slope of the fracture toughness versus temperature curve can be taken to be 1 ksi√in/°F, down to a lower bound of 20 ksi√in. Using this correlation, both of theses steels approach the lower bound Kc of 20 ksi√in at -260 °F. This is the same value of Kc for ABS Class B steels.

An alternate approach to estimation of fracture toughness can be appropriated from the nuclear pressure vessel industry [Barsom and Rolfe 1987]. Here, a reference curve (K_{IR}) has been constructed from an extensive database of fracture testing on low alloy carbon steels with

yield strength of less than 50 ksi. Fracture toughness as a function of temperature for steels typical of this class of materials is shown in Figure 12.

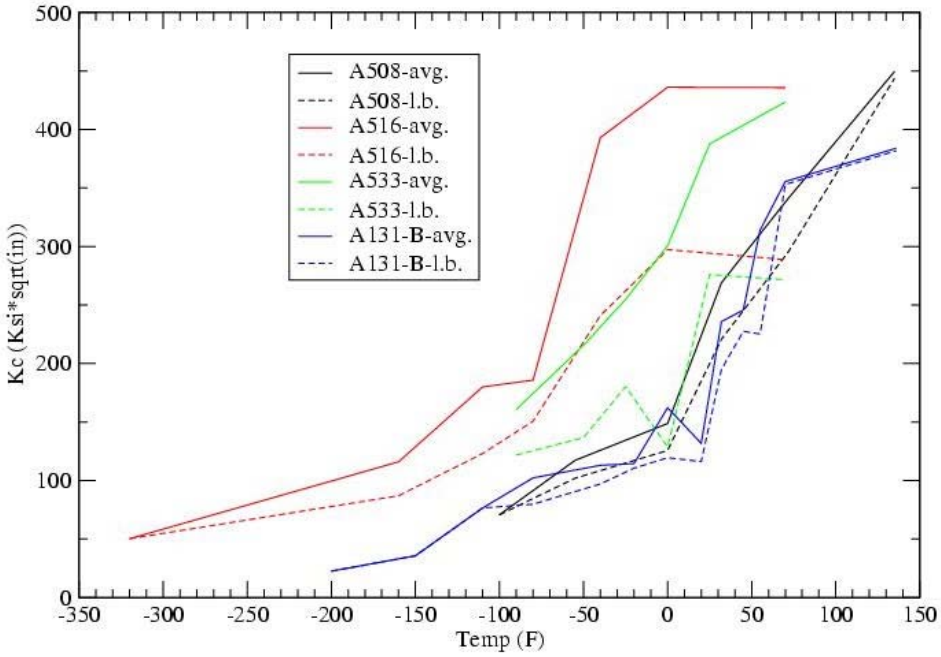


Figure 12. Fracture Toughness of Low Alloy Carbon Steels

This curve is represented by the following equation:

$$K_{IR} = 26.777 + 1.223e^{(0.0145[T-\{RT_{ndt}-160\}])}$$

The basis of this equation is that all the fracture toughness data can be represented by a single curve with a temperature shift. That is, reference nil-ductility temperature, RT_{ndt}, for the steel of interest is the key to using this K_{IR} curve. The nil-ductility temperature is determined through drop weight testing. Alternately, it can be determined by CVN testing. RT_{ndt} is 40 ºF lower than the lowest temperature at which all CVN results have more than 40 mils lateral expansion. Unfortunately, neither of these data sets is available for ABS – E or ABS – F steels. In the absence of better data, a reasonable estimate for RT_{ndt} might be taken to be the temperature at which the steel has 15 ft-lbs of absorbed energy in a CVN test. For ABS – E, this is about - 40 ºF. For ABS F, this is about –80 ºF. Therefore, using the K_{IR} approach, the fracture toughness of ABS – E steel is estimated to be 27 ksi√in and ABS – F steel is 28 ksi√in. Note, in the K_{IR} equation above, the lower bound fracture toughness is taken to be 26.777 ksi√in rather than the 20 ksi√in assumed earlier. The fundamental conclusion is reinforced however. That is, at LNG cryogenic temperatures, all the ABS low alloy carbon ship hull steels are very near the lower bound fracture toughness for low alloy carbon steel.

Therefore, based on these two types of fracture toughness estimation techniques, regardless of steel type, all low alloy carbon steels approach this lower fracture toughness bound at

LNG cryogenic temperatures. This lower bound value was used to estimate potential thermal stress states in the ship structural steel for different types of breach and spill events.

Three cryogenic spill scenarios were computed for thermal stress, each of which can be related to a different type of breach event.

Scenario 1 (Small Spill)

The first scenario is a circular, through-thickness cold spot in a large, flat plate. This case could result from a spill of cryogenic material on one face of the plate while the other face is sensibly insulated (air or other lower heat transfer medium). The portion of the plate outside the cold spot provides constraint such that the region of the plate inside the cold spot is subjected to tensile stress to accommodate the thermal contraction due to the reduced temperature. The stress inside the cold spot can be computed from: [Goodier 1937]

$\sigma = 0.5 \bullet \alpha \bullet \Delta T \bullet E$ where σ = stress
α= coefficient of thermal expansion
ΔT= change in temperature
E= modulus of elasticity

Here, the resulting thermal stress is approximately 40×10^3 psi or roughly equivalent to the yield strength.

Fracture can be determined by equating the fracture toughness (K_c) with the fracture driving force (stress intensity: K_I). Stress intensity can be calculated from [Barsom and Rolfe 1987]:

$K_I = \sigma\sqrt{\pi a}$, where '*a*' is the flaw size and σ is the stress level.

Rearranging this equation, the critical flaw size can be computed as:

$$a_{cr} = \frac{K_c^{\,2}}{\pi\sigma^2}$$

The critical flaw size thus computed is about 0.1 inch. A crack-like defect of 0.1 inch would be rare in base metal plate material. However, in ship construction welding, such a flaw size could be relatively common. Once initiated, a flaw could be expected to propagate to the extent of the cold region and even some distance beyond. Thus, for a large penetration of a cryogenic LNG cargo tank and associated large spill, a large section of the ship structure could be fractured from the thermal insult alone, independent of other loadings (wave, blast, or shock).

Scenario 2 (Large, Internal Spill)

The second case considered is that of an entire structure at a low temperature supported by a structure of similar stiffness at a higher temperature. A penetration in the cryogenic LNG cargo tank, with the inner hull intact, could lead to the filling of the inner hull with the cryogenic liquid. If the ship is not ballasted, the space between the inner and outer hull

would be filled with air or nitrogen, essentially an insulator. Thus, the inner hull would be at the cryogenic temperature, while the outer hull is at sea temperature. The inner and outer hulls are of comparable stiffness. The equation for computing stress in this case is identical to that for the cold spot discussed above. The thermal stresses, fracture toughness, critical flaw size, etc. are nearly identical to the case of the cold spot. The conclusion here is that a flaw could propagate through the entire inner hull, either from side-to-side or axially, from front containment bulkhead to aft containment bulkhead of the compromised compartment.

Scenario 3 (Spill Between Ship Hulls)

Finally, the third case is for a plate, stiffened such that no out-of-plane displacement (bending) can occur. The top surface is maintained at a low temperature, while the bottom surface is maintained at a higher temperature (e.g., LNG spill within the inner and outer hulls). The temperature gradient across the plate is linear. This case could result from a penetration through both the inner hull and the cryogenic tank. Leaking LNG would encounter the inside of the outer hull plate, while seawater would be in contact with the outside of the outer hull plate. The cryogenic material and the sea can be approximated as constant temperature boundary conditions. Here, the thermal stress is given by [Goodier 1937]:

$$\sigma = \frac{\alpha \bullet \Delta T \bullet E}{(1-\upsilon)}$$ where 'υ' is Poisson's ratio

This equation results in an elastically computed stress significantly in excess of the room temperature yield stress ($100x10^3$ psi). No attempt was made to include nonlinear material properties (plasticity). However, due to plastic deformation, the actual stresses resulting from this case will be significantly less than the elastically computed $100x10^3$ psi., but still greater than the stresses resulting from the prior two cases. The potential for cracking is similar to the prior two cases.

For all three types of cryogenic spill events considered, the potential exists for progressive structural damage due to the thermal insult of the cryogenic liquid on the structural steel of the ship. The extent of the damage will depend on the volume and rate of LNG spilled and the ship areas that will be directly contacted by the liquid LNG. Based on the postulated breach events, attempts were made to estimate the potential level for ship damage from both accidental and intentional events. These are presented in the table below.

Table 40: Estimated LNG Ship Damage from Potential Tank Breaches & Spills

Breach Event	Breach Size	Tanks Breached	Ship Damage[b]
Accidental collision with small vessel	None	None	Minor[b]
Accidental collision with large vessel	5 – 12 m^2 (Spill area 0.5 – 1m^2)[a]	1	Moderate
Accidental Grounding	None	None	Minor
Intentional Breach	0.5 m^2	1	Minor
Intentional Breach	2 m^2	1	Minor
Intentional Breach	2 m^2	3	Moderate
Intentional Breach	12 m^2	1	Severe[d]
Intentional Breach	5 m^2	2	Severe
Intentional Spill	Premature offloading of LNG	None	Moderate-Severe

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
d – Severe suggests significant structural damage. Ship might not be able to be moved without significant difficulty and includes potential for cascading damage to other tanks

As discussed in Appendix B, the intentional breaching events considered included attacks, sabotage, hijackings, and insider threats. Each threat is a different type and would cause spills of different sizes and in different locations. This was taken into account when assessing what parts of an LNG ship would encounter spilled LNG and the extent and duration of the contact, discussed in detail in [Hightower 2004].

Table 40 shows that, for accidental and many intentional breaching events, the cryogenic damage to the LNG vessel would probably be minor to moderate. Moderate damage, however, might impact vessel and cargo integrity; therefore, pre-planning of approaches to mitigate these consequences should be considered. Severe structural damage could occur from some of the very large spills caused by intentional breaches. This is because the volume and rate of the LNG spilled could significantly impact the ship's structural steel. A cascading failure that involves damage to additional cryogenic tanks on the ship from the initial damage of one of the LNG cargo tanks is a possibility that cannot be ruled out at the present time. Determination of the probability or likelihood of such an event depends on the breach scenario, the spill location and any implementation of prevention and mitigation strategies to prevent such an event. In areas where cascading failures might be a significant issue, the use of complex, coupled, thermal, fluid, and structural analyses should be employed to accurately determine the potential for and extent of structural damage to the LNG ship and other LNG cargo tanks from various breach and spill events.

4 LNG SPILL DISPERSION AND THERMAL HAZARDS

If ignition occurs immediately upon spillage, then non-pre-mixed combustion occurs. In industrial spills, non-pre-mixed combustion is referred to as a fire, and the fuel-air mixing rate is controlled by flow turbulence. (In laboratory settings, non-pre-mixed combustion is referred to as a diffusion flame, because mixing is controlled by diffusive processes.) Specifically for LNG spills, the fire would be referred to as a 'spill' or 'pool' fire, as the liquid spilling from the ship results in a quasi-steady-state fire. The hazard from this type of combustion is thermal, primarily driven by radiating heat flux. Other types of non-pre-mixed combustion, including jet and spray flames, are not relevant to LNG spills, due to LNG's low storage pressure and low boiling point.

If mixing occurs before ignition, then the resulting combustion is pre-mixed. In industrial accident settings, two forms of pre-mixed combustion can occur, depending upon the strength of the ignition source and geometric factors. The two forms are termed *deflagration* and *detonation*. Deflagration is the most likely mode to occur. Because the fuel is pre-mixed with air, the flames spread at a rate relative to the chemical mixture (flame speed) and the rate at which turbulent mixing can enhance the flame area. Deflagrations differ in their consequences, depending on whether they occur in confined or unconfined volumes.

In large open areas, the hot combustion products are buoyant and will entrain the air into the fuel mixture. The result is known as a fireball. In enclosed volumes, the combustion will result in pressure generation due to confinement of the volume expansion of the hot gases. The result is usually the failure of the enclosure. These events are loosely termed explosions. Propane leaks in houses are a typical example.

If ignition occurs sometime during mixing, not before mixing takes place and not at the end when the fuel is completely mixed, then a mixture of combustion modes will result. Generally, a pre-mixed combustion event will occur first, followed by a non-pre-mixed combustion event; and pre-mixed combustion occurs faster than most mixing events. Thus, upon ignition, a pre-mixed flame will propagate from the ignition source to the spill location. This phenomenon is known as a flashback. It can generate high pressures or result in a slow burn or fireball. The flame will anchor on the spill source and a fire will result at the spill source for the duration of the spill.

The distance and thermal damage to structures from a range of different spills was calculated based on the following selection of nominal spill conditions.

Condition 1: Spill Calculations Drainage From A Non-Pressurized Tank With A Single Hole

Note that, for all calculations, a tank with volume of 25,000 m^3 could be expected to spill approximately 12,500 m^3. An initial liquid height in the tank above the breach of 15 m and a density of 450 kg/m^3 for LNG were used.

Nomenclature:

A_t – Cross sectional area of tank
A_o - Cross sectional area of hole
m – mass of liquid in tank
ν – velocity
ν_o – effective velocity out of hole
h_t – height of the top surface of the liquid
h_i – initial height of fluid
C_d – discharge coefficient
V – volume of liquid

Basic Equations:
First apply continuity equation where:

$$\frac{dm}{dt} = (\rho A v)_{in} - (\rho A v)_{out}$$

$$(\rho A v)_{in} = 0, \quad thus$$

$$\frac{dm}{dt} = -(\rho A v)_{out} \tag{1}$$

Mass, m, can be expressed as ρV, and then $V = A_t h$. Substitute into eq. (1):

$$\frac{d(\rho A_t h)}{dt} = -(\rho A v)_{out} \tag{2}$$

The velocity of the fluid coming out of the tank can be expressed as a function of height through invoking Bernoulli's equation.

$$\frac{1}{2}\rho v_t^{\,2} + p_t + \rho g h_t = \frac{1}{2}\rho v_o^{\,2} + p_o + \rho g h_o$$

$$\rho g h_t = \frac{1}{2}\rho v_o^{\,2}$$

$$v_o = \sqrt{2 g h_t}$$

Multiply by a discharge coefficient to account for resistance of the hole:

$$v_o = C_d \sqrt{2 g h_t} \tag{3}$$

Total time of discharge:

Substitute eq. (3) into eq. (2) and integrate with initial condition, t = 0, $h=h_i$.

$t = \sqrt{\frac{2}{g}} \frac{A_t}{C_d A_o} \left(\sqrt{h_i} - \sqrt{h} \right)$, then the height of liquid throughout time can be determined.

Total time to drain is:

$$t = \sqrt{\frac{2}{g}} \frac{A_t}{C_d A_o} \left(\sqrt{h_i} \right)$$

Average flow rate:

The flow rate will be greatest at the beginning of the spill, due to the hydrostatic head having a maximum. The flow rate has a linear dependence on time, so an average flow rate was determined by dividing the maximum flow rate by 2. The maximum flow rate can be found by substituting eq. (3) into eq. (1), and using m= ρV to express in terms of volume/time. Then,

$$\left(\frac{dV}{dt} \right)_{average} = \frac{-(Av)_{out}}{2} = -\frac{C_d A_o}{2} \sqrt{2gh_i} \qquad (4)$$

Equation 4 was used for the calculations to determine the average flow rate out of the tank.

Condition 2: Spreading Equation

The diameter of the spill was determined by assuming a steady state where the mass coming in is balanced by the mass going out, due to the heat flux from the heating of the water below and from the fire above, denoted by ν_{total}. Thus,

$$(\rho A v)_{in} = (\rho A v)_{out}$$

$$\left(\frac{dV}{dt} \right)_{average} = (Av)_{out} = \frac{\pi D^2}{4} v_{total}$$

$$D = \sqrt{\frac{4}{\pi v_{total}} \left(\frac{dV}{dt} \right)_{average}} \qquad (5)$$

Equation (5) was used to determine the diameter of the spill.

Condition 3: Distance To A Specified Radiative Flux Level after Fire Ignition

Nomenclature:

q'' - radiative flux incident upon an object
E_p – Average surface emissive power (kW/m^2)
F – view factor
τ - transmissivity

A right cylinder, solid flame model was used to model the pool fire. The effect of wind on the flame was considered negligible.

The Moorehouse correlation for LNG was used to calculate flame height, found on page 3-204 of the SFPE handbook, Fire Protection Engineering, 2nd ed., (1995). The term u^* is a non-dimensional wind velocity taken to be 1 for low wind speeds.

$$H = 6.2\, D \left[\dot{m}'' / \rho_a \sqrt{gD}\right]^{0.254} u^{*-0.044} \qquad (6)$$

The radiative flux incident upon an object can be determined by:

$$q'' = E_p \tau F \qquad (7)$$

In order to determine distance to a specified, q'', Fig. 3-11.13 on page 3-210 of the SFPE handbook was used. The figure gives the non-dimensional distance from the flame axis as a function of view factor and fire height-to-radius ratio. Because q'', E_p, and τ are specified, F can be determined by eq. (7), and height-to-radius ratio from eq. (6). Then the thermal hazard distance can be determined from the figure.

Using the nominal conditions, an analysis was performed that looked at the potential ranges of spill and fire conditions available from experimental literature. Example results of this sensitivity analysis are presented in the table below.

Table 41: Sensitivity Analysis of Thermal Intensity Level Distances

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								
2	3	.6	3×10^{-4}	220	209	20	250	784
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	2×10^{-4}	220	395	8.1	454	1538
5	1	.6	3×10^{-4}	350	330	8.1	529	1652
10	1	.6	3×10^{-4}	220	467	4.1	549	1823

*nominal case

The results in Table 41 suggest that, for most of the credible accidental breach and spill scenarios, the general distance for major structural damage (high hazards where the thermal intensity is about 37.5 kW/m^2) can occur, on average, up to 250 m from a spill. The results also suggest that, for most of the credible intentional breach and spill scenarios, the general

distance for major structural damage (high hazards) can occur, on average, up to 500 m from a spill. In general, the distance to low thermal hazard levels, about 5 kW/m^2 is about 600-750 m for accidental spills and approximately 1600 m for intentional spills. For a very large, cascading spill, high hazard zones could approach 2000 m. These results were used to help quantify the hazard zone identification and hazard level identification for various breach and spill events.

Consideration of Mass Fires and Pool Fires

All of the LNG fire studies reviewed assume that a single, coherent pool fire can be maintained for very large pool diameters (>100m). This might be unlikely due to the inability of air to get into the interior of the fire and support combustion. At some very large size, the flame envelope would break up into multiple flamelets. The heights of these flamelets are much less than the fuel bed diameter [Zukoski, Corlett, Cox and Chitty]. The break up into flamelets would result in a much shorter flame height than that assumed by the reviewed studies, which are applying height correlations far out of the diameter range for which they were developed. It is expected that the L/D (height/pool diameter) would probably be much smaller than that predicted by existing correlations.

The correlations predict an L/D ratio between one and two, while a more realistic ratio for a mass fire would be under 0.5. The view factor is very sensitive to flame height at distances not close to the fire (>1 pool diameter). View factors are used to determine how much radiative flux an object receives. Thus, if a more realistic flame height is used, lower than that which is typically calculated, then the amount of heat flux that an object receives would be less, thereby decreasing the thermal hazard zone. The zone could be decreased by a factor of two to three, depending upon the damaging heat flux levels of interest.

Various correlations for flame height have been developed for a range of pool diameters up to 30 m. The L/D correlations are typically expressed in terms of a non-dimensional heat release rate: $\dot{Q}^*$. The following figure is from Zukoski, which shows how the ratio of flame height to pool diameter varies with $\dot{Q}^*$. As pool diameter increases, $\dot{Q}^*$ decreases because it is proportional to $1/\sqrt{D}$. Zukoski states that there are different transition regions that occur, demarked by I – V in Figure 13.

For very large pool fires, region II, the flame breaks up into a number of independent flamelets as $\dot{Q}^*$ decreases, and the flame height depends on the diameter and the heat release rate. For region I, the height of the flamelets appears to become roughly independent of the source-diameter and depends only on the local heat release rate per unit area (or fuel flow per unit area). This figure is based upon pool fire tests where fuel vaporization is not affected by a substrate (such as water); water; therefore, this curve should not be used for the determination of when a pool breaks up into flamelets for LNG pool fires on water. It is unknown what the limiting diameter for break up is for LNG pool fires on water. Using an estimate of approximately 100 m, the distance to the high and lower level hazards was calculated for a range of spill conditions and is presented in Table 46.

The pool diameter and flame height suggested are speculative because experiments for large pool fires have yet to be performed. Many researchers have provided flame height correlations based on pool fires much smaller than those presently being considered [Heskestad 1998]. These results suggest LNG pool fires of as much as 8900 m in diameter before

breakup, based on results of laboratory testing on approximately 7 m by 7m wood fiberboards. Whether their results can be extrapolated to very large pool fires remains to be determined.

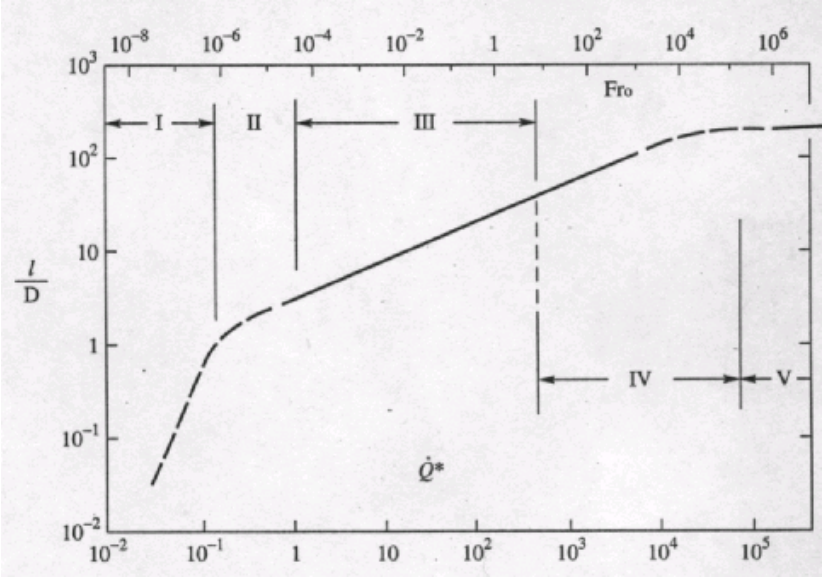


Figure 13. Flame Height/Diameter Ratio vs. Dimensionless Heat Release Rate

Taken from: [Zukoski, 1995]

The following calculations in Table 42 show the differences in the thermal hazard distances obtained using an assumption of a single, coherent pool fire for very large diameters versus the assumption of several mass fires (flamelets) with maximum diameters on the order of 100 m. 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/m^2, a transmissivity value of 0.8, and a burn rate of 3 x 10^{-4} were used. The results indicate that there is a significant increase in the distance to 5 kW/m^2 when a single coherent pool fire is assumed. The thermal hazard distances from a mass fire (flamelets), which is physically more realistic for large spills, should be considered in evaluating thermal hazards from potential large spills.

Table 42: Thermal Hazard Distance - Single Pool Fire vs. Mass Fire Assumptions

ASSUMPTION	DIAMETER	FLAME HEIGHT (m)	DISTANCE TO 37.5 kW/m^2 (m)	DISTANCE TO 5 kW/m^2 (m)
Mass Fire (flamelets)	100 m each (multiple fires comprising area of 500 m dia.)	148	400	1000
Single Pool Fire	500 m	604	575	1800

Furthermore, studies discussed in Appendix C note that the missive power decreases with increasing fire size due to smoke shielding. Values significantly lower than 220KW/m^2 are possible. As improved data are collected, improvements in hazard analysis can be

implemented. Other phenomena, such as the occurrence of fire whirls, may increase the hazard by generating large columnar flames with high emissive power. These structures most often form during non circular pool shapes exposed to light winds and rarely last more than a few seconds.

LNG Dispersion

In most of the scenarios identified, the thermal hazards from a 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, such as an intentional spill without a tank breach, an immediate ignition source might not be available and the spilled LNG could, therefore, disperse as a vapor cloud. For large spills, the vapor cloud could extend to as much as 1600 m or more, 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.

If ignited close to 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 probably burn back to the source of liquid LNG and transition into a pool fire. 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.

Experimental data and analytical estimates for vapor spreading suggest that a large vapor plume could extend to large distances, depending on atmospheric conditions. Therefore, while the impact from a vapor cloud dispersion and ignition from a large spill can potentially extend beyond 1600 meters, the area of high impact might be reduced. This suggests that LNG vapor dispersion analysis should be conducted using site-specific atmospheric conditions, location topography, and ship operations to adequately assess the potential areas and levels of hazards to public safety and property, and consideration of risk mitigation measures, such as development of approaches and procedures to ignite a dispersion cloud quickly if conditions exist that the cloud would impact critical areas.

To assess the extent of the potential dispersion from an LNG spill, we used VULCAN, a validated CFD model [Tieszen, et al. 1996]. The VULCAN fire field model under development at Sandia National Laboratories was derived from the KAMELEON Fire model in collaboration with SINTEF and Computational Industry Technologies, AS (Norway). VULCAN was developed for liquid and gaseous hydrocarbon fuels. The model has been used for a large number of heavy hydrocarbon fuel fires. VULCAN uses a Cartesian based geometry. The code runs on single or multi-processor machines. It generally parallelizes best on six processors. It runs under LINUX and UNIX operating systems.

VULCAN is a validated CFD fire model that uses a standard RANS formulation of the equations of motion, where the turbulence is averaged across all time scales using a k-ε turbulence model. A buoyant, vorticity generation sub-model of turbulence is included for turbulence length scales below the scale of the grid. VULCAN uses Magnussen's Eddy Dissipation Concept combustion model to relate mechanistically the local fuel, oxygen, energy, and turbulence levels to consumption of species. Soot is modeled using Magnussen's soot model to describe mechanistically the soot formation and destruction process.

VULCAN uses Leckner's model for gas band radiation. The transport of thermal radiation is calculated using the Discrete Transfer Method of Shah to solve the radiative transport equation.

Either the evaporation of a liquid pool is modeled using a user-specified evaporation rate, or by allowing the code to calculate its own evaporation rate based on heat transfer into the fuel pool. VULCAN also has a rudimentary liquid spreading model based on lubrication theory. This model predicts spreading of fuel on a horizontal surface, and is capable of modeling the dripping/draining of fuel vertically (e.g., from floor to floor in a building).

In order to obtain LNG dispersion distances to LFL for accidental events, 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 the 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 LFL to be reached was approximately 20 min. for each calculation. Two cases were analyzed, one for the nominal case of a 5 m^2 hole and one tank breach, and the other for a 5 m^2 hole and three tanks breached at once. This last case is the largest expected spill; hence, it should give an upper bound of the LFL for vapor dispersion for intentional events. The results are summarized in the table below.

Table 43: Dispersion Distances to LFL for Potential Spills

HOLE SIZE (m^2)	TANKS BREACHED	POOL DIAMETER (m)	SPILL DURATION (min)	DISTANCE TO LFL (m)
Accidental Events				
1	1	148	40	1536
2	1	209	20	1710
Intentional Events				
5	1	330	8.1	2450
5	3	572	8.1	3614

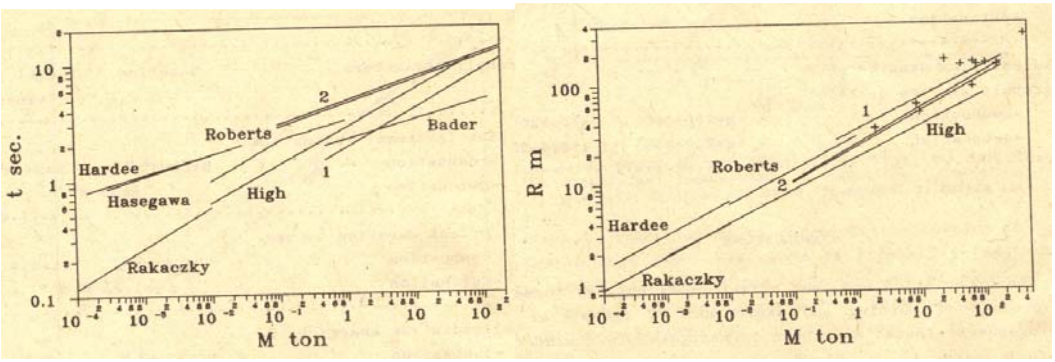
As noted above, the chances of a large vapor dispersion from either an accidental or intentional breach is rather unlikely because of the high probability that an ignition source will be available for most of the events identified. Although, the significant distances though of potential vapor dispersion, especially for a large intentional breach, suggest that LNG vapor dispersion analysis and risk mitigation measures should be carefully considered. Location-specific environmental conditions should be carefully evaluated and appropriate safety measures implemented to ensure that public health and safety, and critical facilities and infrastructures, are adequately protected.

4.1 Fireballs Resulting from an LNG Spill

A fireball will result from an LNG spill only if some mixing of the fuel and air occurs prior to ignition. Thus, if ignition occurs immediately upon release, no fireball will result. For a fireball to occur there must be fuel release, spread, vaporization, and ignition after significant premixing. If all these events have occurred, a fireball is the most benign form of

combustion that can result. The hazards are principally short-time thermal damage high in the air and away from structures and people.

Large-scale fuel-air fireballs and explosions were studied in Russia in the late 1980's [Dorofeev et al. 1991]. In their study, fireballs were created from the dispersal of 0.1 to 100 metric tons of hydrocarbon fuels (gasoline, kerosene, and diesel fuel). Because the fuels used in the experiments have significantly lower vapor pressure than LNG, mixing was created by explosively dispersing and igniting the mixture in a fuel-rich state. In spite of these differences, the results are directly relevant to fireballs that might result from a delayed ignition of vaporized LNG.



(a) (b)

Figure 14. Fireball Duration and Radius as a Function of Fuel Mass

[Dorefeev et. al. 1991]

Figure 14 shows the duration (in seconds) of combustion within the rising fireball and the maximum radius (in meters) of the fireball as a function of the fuel mass (in metric tons; i.e., per 1000kg). For example, a fireball from a 100-ton fuel release is about 11 seconds duration and has a radius of about 115 meters. Also shown in Figure 13 are the results of earlier studies, providing a measure of the uncertainty in the available data. Dorofeev fit the data to a curve and provided the following correlations:

The duration of the fireball from combusting clouds is given as

$$t = 4.6M^{0.2}$$

in which the fuel mass, M, is in metric tons and the time, t, is given in seconds.

Similarly, the maximum radius of the fireball is given as:

$$R = 23M^{0.35}$$

in which the fuel mass, M, is in metric tons and the radius, R, is given in meters.

The thermal flux from the fireballs was also measured. Peak fluxes for combusting gasoline were in the 150 – 330 kW/m^2 range. LNG would be expected to have similar behavior.

These flux levels are of the same order of magnitude as those from a pool fire. Unlike a pool fire, however, the fireball is of short duration (in the order of seconds to tens of seconds), depending upon the mass of fuel in the air. The fireball will entrain and burn all flammable vapors and provide an ignition source to the underlying liquid spill. The overall threat from a fireball is typically not of primary concern if a long duration pool fire follows it.

4.2 Thermal Damage on Structures

The potential for damage to other vessels or structures from an LNG spill and fire needs to be considered to determine the overall risk. As noted in Appendix C, the potential for fire damage from spills can be relatively extensive. The six spills projected in Appendix B would take anywhere from 10 – 20 minutes to release up to 50% of the LNG in an individual tank for a large spill and up to one hour for a small spill, depending on the location.

The thermal radiation that will damage structures is approximately 37 kW/m^2 for durations of more than 10 minutes. Damage can be expected to the vessel and nearby steel structures, because steel strengths are reduced to 60 – 75% of their room temperature values at 800º K. Further reduction in strength will result for temperatures above 800º K. Steel will melt at approximately 1800º K and is generally considered to have no strength at half the melt temperature, or 900º K. The calculations suggest that these temperatures could exist at a spill from an LNG cargo tank from 30 minutes to an hour and, therefore, potentially damage nearby steel and other structures.

Of even greater importance is the possibility that a large spill could cause a cascading set of LNG cargo tank failures. In this instance, significant long-term fire damage could result to a nearby steel structure, unloading terminal, or unloading platform. Positive operational and risk management measures can be taken to try to prevent these types of issues. This could include redundant or multiple offloading capabilities or moorings, fire protection systems, etc., as identified in Section 6.

4.3 Analysis of Fire Damage to LNG Cargo Tank Insulation

The insulation used in LNG ships varies considerably, from rigid foams to bulk zeolite-type materials. The susceptibility of these insulation materials to either burning or thermal degradation also varies considerably. Many LNG vessels use foam insulation materials that include polystyrene, polyurethane, phenolic resin, and hybrid foam systems. [Kawasaki 2003] [Kvaerner-Masa 2003,2004] [OTA 1977] These foams are considered combustible to slightly combustible; meaning, they will burn when exposed to an open flame, as might occur in a breach with a resulting fire. Of greater importance, though, is that these foams will begin to decompose at temperatures of about 550º K. Because an LNG fire can be expected to burn at temperatures of approximately 3000°F, thermal loading on the LNG vessel from an engulfing fire, if suffieient in duration, could lead to heat transfer through the structure, decomposition of the foam, and an increase in the LNG volatilization rate in an impacted cargo tank. This could lead to rupture or collapse of the tank, additional damage to the LNG vessel, and greater hazards to both the public and property.

Foam used to insulate LNG is enclosed within a steel weather cover, or within the inner hull of the LNG tanker. Extensive burning of the foam is not expected, given the lack of sufficient air to support combustion in these regions, even in cases with limited damage to the

hull or weather cover. Based on the foam being located within an enclosure, thermal decomposition of the LNG foam insulation is more likely. Heat transfer will result in thermal decomposition of the foam insulation, the products of which will burn if vented to the air, or cause an increase in the pressure in the region between the steel and the inner container.

From the spills calculated and discussed in this section, accidental spills with general pool fire diameters of 200 m might be possible. The flame height for such a spill might approach 150 m, high enough to engulf the top of an LNG tanker. For this size of fire, at least some portions of adjacent LNG cargo tanks would probably be exposed to the fire. As calculated in other sections of the report, a fire from a spill could last from five to twenty minutes.

We estimated the consequence of a fire from an LNG spill on the insulation of an undamaged LNG cargo tank. Initial modeling of the thermal response and decomposition of 12 lb per cubic foot density polyurethane foam in above-deck areas was conducted using one-dimensional heat transfer models and polyurethane foam thermal degradation data. The above deck location was chosen as a severe condition, due to the presence of only a single, steel cover and air gap protecting the foam insulation. The calculations were conducted with a tank configuration of a steel cover and air gap overlaying eight inches of foam insulation over an aluminum LNG cargo tank. Using a thermal radiation intensity of 220 kW/m^2 for the fire, as observed from several LNG fire tests, the analysis suggests that heat transfer through the steel shell and air gap could fully degrade eight inches of polyurethane type foam in about five minutes. The maximum volumetric production of LNG vapor calculated in the LNG cargo tank was about 0.8 m^3/s per square meter of tank wall exposed to the fire.

For several reasons, the analysis probably provides a lower bound for the time required for a fire from an LNG spill to degrade the thermal insulation of an adjacent cargo container. First, the analysis did not take into consideration the thermal retardation benefits of the fire suppression systems on LNG cargo tankers, which can provide up to 10 liters/m^2 per minute of water to exposed cargo tanks and decks, as established by the International Gas Carrier Code. Second, many LNG carrier designs have up to 36 inches of thermal insulation, which probably increases the time for damage to occur to an adjacent LNG cargo tank. Third, the thermal decomposition rate and decomposition temperature of insulating foams differ, depending on the foam material and properties. These additional factors all could increase the time required for full thermal degradation of the insulating foam on an adjacent LNG cargo tank.

The results, though, do suggest that damage to adjacent containers from an LNG spill and fire cannot be ruled out and should be carefully considered, especially in operations in high-consequence areas. Based on our analysis, it appears that one to two adjacent LNG cargo tanks might be affected at any one time from an LNG spill and fire. Efforts to manage the hazards from the impact of an LNG fire on adjacent cargo tanks should consider a combination of risk management approaches. These should include consideration of LNG cargo vessel designs, consideration of the designs of LNG cargo tank insulation and thermal degradation properties, consideration of operations and safety management improvements or upgrades, and consideration of both public safety and property consequences for site-specific locations. These efforts, when implemented as a system, could produce an integrated protection and risk management approach that provides an appropriate level of both public safety and property and reduces potential damages from a fire.

5 LNG – AIR COMBUSTION TO GENERATE DAMAGING PRESSURE

Two types of combustion modes might produce damaging pressure, deflagration, and detonation. Deflagration is a rapid combustion that progresses through unburned fuel-air mixture at subsonic velocities, whereas detonation is an extremely rapid combustion that progresses through an unburned fuel-air mixture at supersonic velocities.

In order for deflagration to occur, the fuel-air concentration must be above the minimum flammable limit (lean limit) and below the maximum flammable limit (rich limit). For LNG, these limits are 3.8% – 17% fuel by volume. If the fuel concentration is within these limits and encounters an ignition source, it will ignite and burn. Because of the moderate flammability range, the amount of time lapse between dispersal and ignition is limited. For low reactivity fuels such as natural gas, combustion will usually progress at low velocities and not generate overpressure. Certain conditions, however, might cause an increase in burn rate that does result in overpressure. If the fuel-air cloud is confined, is very turbulent, or progresses through obstacles, a rapid acceleration in burn rate might occur [Benedick et al. 1987]. In extreme cases, the burn rate might increase to supersonic velocities. This is known as deflagration-to-detonation transition (DDT).

Under specialized conditions, pre-mixed combustion can result in a detonation. This mode is not common and is generally considered to be very unlikely (but not impossible) to occur in most industrial accident situations, such as an LNG spill. Detonations have the highest power density of any combustion mode and, thus, result in the highest pressures and most damage. In a detonation, the combustion front typically travels at Mach 5 and, for hydrocarbons, has a peak pressure about 15 times the initial pressure. A detonation can be directly initiated in a fuel and air mixture from high initiation pressures or, under very limited circumstances, it can transition from a deflagration to a detonation (called DDT, or deflagration to detonation transition in the pre-mixed combustion literature) under conditions involving confinement. In industrial accidents, detonations are also sometimes called 'unconfined vapor cloud explosions.' In military literature, gas phase detonations are termed fuel-air explosions (FAE).

Detonation is the most violent form of fuel-air combustion. For detonation to occur, the fuel-air mixture must be within the minimum and maximum detonation limits. These limits are much narrower than flammability limits. To ignite a fuel-air mixture within the limits of detonation, shock initiation is necessary. Shock initiation can be produced by "igniting" the fuel-air cloud with an explosion or by the deflagration-to-detonation transition involving confinement described above.

For low reactivity fuels, the initiation energies are quite large and unlikely to occur in an accidental breach, but might be possible in an intentional breach or tank rupture scenario. Spilled LNG could become trapped between the inner and outer hulls which, if ignited, could lead to an explosion. In general, large releases will involve sufficient LNG for this space to be fuel rich. Of greater concern are small leaks where a flammable mixture could develop.

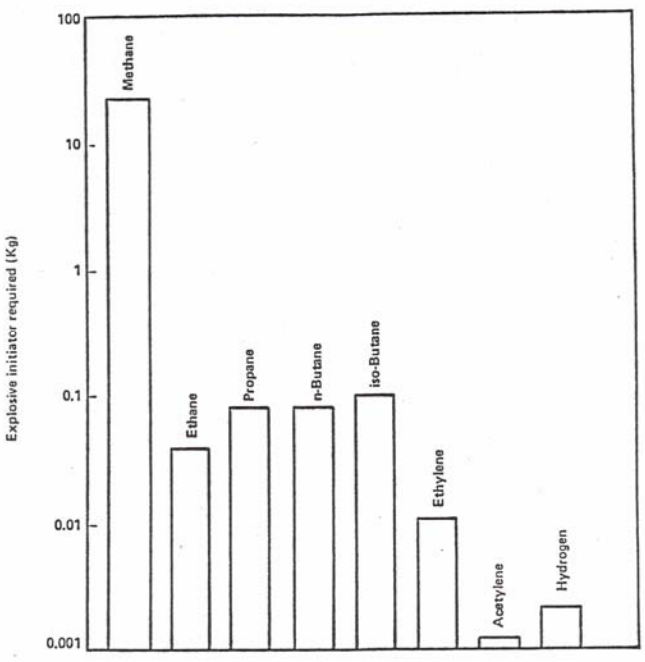


Figure 15. Relative Detonation Properties of Common Fuels

[Benedick et al 1986]

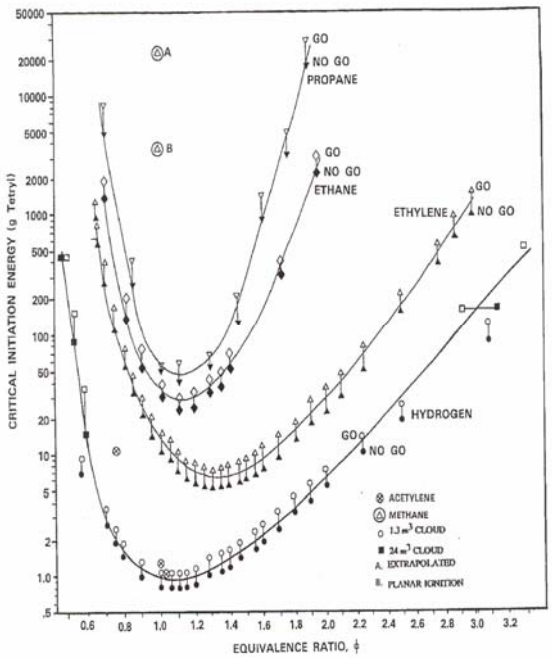


Figure 16. Initiation Energy Required to Detonate Common Fuels at Various Fuel-Air Ratios.

[Moen 1993]

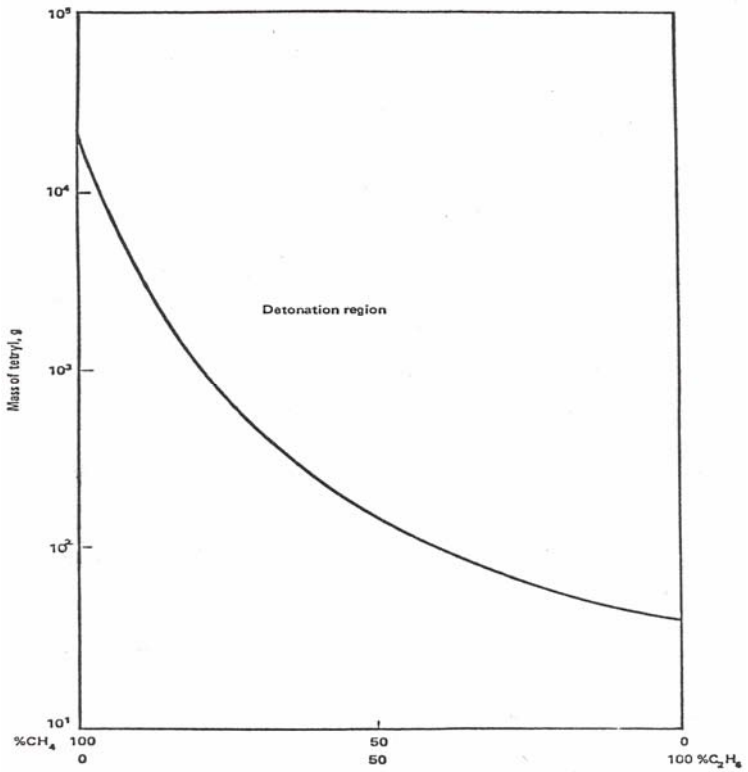


Figure 17. Effect of Ethane Concentration on the Detonability of Methane

[Moen 1993]

Another potential for an explosion is if LNG is spilled without an ignition source, such as an intentional spill from premature offloading of LNG. In this scenario, there could be extensive volumes of LNG that can be spilled either onto the ship or onto the water surface without and ignition source. These type of approaches have been considered and used and are very sensitive to environmental and meteorological conditions [Tieszen 1991]. Therefore, the potential for this type of event exists, but actually getting an explosion can be difficult.

Figures 16 – 17 show the relative detonation properties of several common fuels; and Table 44 provides some physical and chemical properties of hydrocarbon fuels. As Figure 15 shows, methane does not detonate as readily as other hydrocarbons, making it a safer fuel. Further, all fuels become less able to detonate if they are not perfectly mixed to stoichiometric proportions, as shown in Figure 16. It is unlikely for this correct stoichiometric proportion to be obtained around or in a ship during a cryogenic liquid spill. For many sources, refined LNG has a high percentage of methane at the wellhead compared to natural gas. Figure 17 shows that the level of refinement of natural gas stored as LNG can have an effect on detonation sensitivity, with a less processed product being more sensitive to detonation.

Table 44: Properties of Common Hydrocarbon Fuels

[AICE 1994] [Baker 1991]

FUEL	FORMULA	FLAMMABLE LIMITS, VOL %	HEAT OF COMBUSTION, kJ/g	IGNITION TEMP, °C	BOILING POINT, °C
Methane	CH_4	5.5 – 14	55.5	650	-161
Ethane	C_2H_6	3 – 12.5	51.9	472	-89
Ethylene	C_2H_4	2.7 – 36	50.3	490	-104
Acetylene	C_2H_2	2.5 – 82	49.9	305	-84
Propane	C_3H_8	2.2 – 9.5	50.3	450	-42
Propylene	C_3H_6	2.4 – 10.1	48.9	455	-48
Propyne	C_3H_4	2.1 – 12.5	48.3	NA	-23
Octane	C_8H_{18}	1 – 6.5	47.9	NA	126

5.1 Magnitude of LNG-Air Explosion Overpressure

In order to estimate the overpressure at a given distance from a fuel-air explosion, several parameters must be defined. First, the mass of fuel within the flammability limits must be determined. To find the energy released, the mass of fuel within flammability limits is then multiplied by the heat of combustion. Finally, the velocity of combustion, or flame Mach number (Mf), must be estimated. For explosively initiated detonations, a value of 5.2 should be used for Mf.

Once the total energy release and combustion velocity are known, the scaled overpressure versus scaled distance curve given in Figure 18 can be used to estimate an overpressure at a specific distance. Within Figure 18, the curve assumes a spherical cloud geometry and single point initiation. This is not quite accurate for LNG vapor clouds, which are more disk shaped.

Most structures are significantly less resistant to internal blasts than they are to external blasts. If natural gas finds it way into a structure and then ignites, severe structural damage can occur. This is a potential concern to the LNG tanker if the spilled LNG is somehow trapped on the ship or between the hulls, as well as for nearby structures or other ships where the LNG might settle and ignite. While detonations are unlikely, some type of overpressure events could occur on a ship with a large LNG spill and provisions to prevent these types of events should be considered.

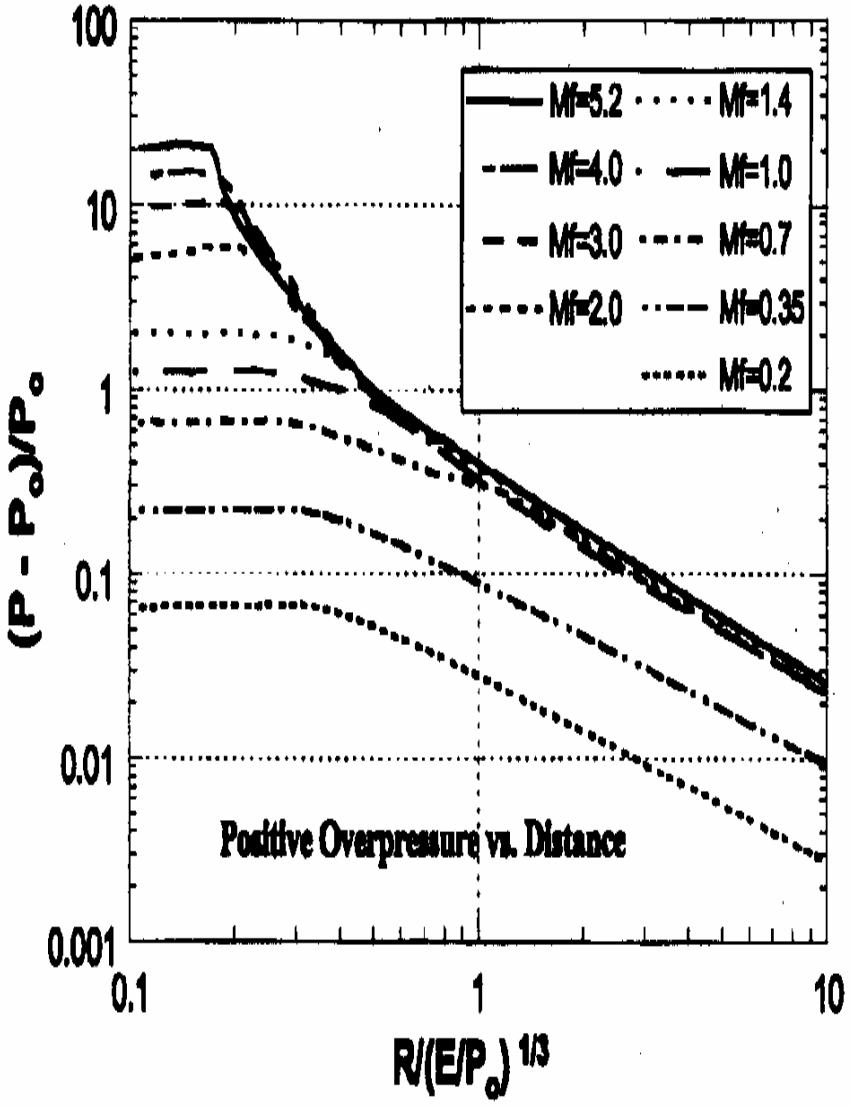


Figure 18. Scaled Blast Overpressure vs. Scaled Distance For Various Flame Mach Numbers

P = Blast overpressure, Pa
P_0 = Ambient pressure, Pa
R = Distance from explosion center, m
E = Energy released from explosion, J

[Tang 1999]

APPENDIX E
LNG PLANT EXPLOSION IN SKIKDA, ALGERIA

REPORT OF THE U.S. GOVERNMENT TEAM SITE INSPECTION OF THE SONATRACH SKIKDA LNG PLANT IN SKIKDA, ALGERIA
MARCH 12-16, 2004

EXECUTIVE SUMMARY (only)

On March 12 – 16, 2004 a six-member DOE and FERC team (U.S.G. team) visited Algeria to gain an understanding of the tragic explosion and fire at the Skikda LNG facility, which occurred on January 19, 2004.

The investigation team of the U.S. Department of Energy visited Algeria at the request of the U.S. Department of Energy and with the agreement of the Algerian Minister of Energy and Mines. A Ministry representative escorted the team to Skikda to tour the damaged facility and meet with plant management and technical staff. After returning to Algiers, the U.S.G. team met with Sonatrach Executive Vice President for Downstream Activities, Bachir Achour, who gave a broader understanding of the accident and the ongoing investigations.

Several accident investigations are ongoing. The Algerian investigation is under way, and definitive conclusions are not yet available; however, on 3/22/2004, Mr. Achour presented Sonatrach's preliminary findings at the LNG 14 conference held in Doha, Qatar. The re-insurers, including Lloyds, are also carrying out an independent investigation, and findings are not yet available.

The Skikda LNG Facility was composed of six trains; trains 40, 30, 20, and 10 are adjacent, from west to east, and are separated from trains 5 and 6, which are located remotely to the east. At the time of the accident, train 10 had been shut down for major maintenance while train 6 was shut down for regular maintenance. At the time of the accident, Train 40 had been operating at steady state for six days following routine maintenance.

A series of cascading events appear to have caused a major explosion and fire that resulted in loss of life and extensive damage. Sonatrach's preliminary hypothesis is that an undetermined hydrocarbon leak occurred in the semi-confined area between train 40's control room, boiler, and the liquefaction area. Sonatrach stated that the source of this original leak is not clear and might never be determined. The air intake to the boiler's firebox apparently ingested the fuel-air mix, causing more heat to be generated within the boiler and hence raising the internal pressure. After the boiler's pressure relief valve activated, and the operators apparently turned off the supply fuel to the boiler, the air intake fan ingested hydrocarbon/air mixture within the flammable limits. The first small explosion appears to have been in the firebox enclosure. It then breached the boiler and provided an ignition source to the external accumulation of combustible gas leading to the larger explosion.

Deaths and injuries occurred only in the plant area. Damage outside the industrial area was limited to broken windows. Most deaths and injuries were due to the impact of the major explosion and flying debris, rather than from the resulting fire. The proximity of the train 40

control room to administrative, maintenance and security/fire control buildings was a major factor in the number of injuries and fatalities.

Trains 40, 30, and 20 are virtually destroyed, although damage decreases with distance from the region between trains 30 and 40 (i.e. damage to 20 is not as severe as 40). Train 10's apparent damage was minimal (loss of aluminum insulation jacket on some process vessels), and it might be usable after further inspection. Trains 5 and 6 were not impacted except for sensitive instrumentation and detectors that must be replaced prior to resuming operation (estimated by Sonatrach to be two months). The instrumentation and electrical network on train 10 might also need to be replaced and/or rewired, as it was part of the network of instrumentation feeding data to the control room for trains 10, 20, and 30.

The U.S.G. team observations and analysis of the potential events at the plant are included in this report, as well as issues to be alert to in other plant designs and operating practices.

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