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Report to Congressional Requesters

February 2007

MARITIME SECURITY

Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification

GAO

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GAO-07-316

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Highlights

Highlights of GAO-07-316, a report to congressional requesters

February 2007

MARITIME SECURITY

Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification

Why GAO Did This Study

The United States imports natural gas by pipeline from Canada and by tanker as liquefied natural gas (LNG) from overseas. LNG—a supercooled form of natural gas—currently accounts for about 3 percent of total U.S. natural gas supply, with an expected increase to about 17 percent by 2030, according to the Department of Energy (DOE). With this projected increase, many more LNG import terminals have been proposed. However, concerns have been raised about whether LNG tankers could become terrorist targets, causing the LNG cargo to spill and catch on fire, and potentially explode. DOE has recently funded a study to consider these effects; completion is expected in 2008.

GAO was asked to (1) describe the results of recent studies on the consequences of an LNG spill and (2) identify the areas of agreement and disagreement among experts concerning the consequences of a terrorist attack on an LNG tanker. To address these objectives, GAO, among other things, convened an expert panel to discuss the consequences of an attack on an LNG tanker.

What GAO Recommends

GAO recommends that the Secretary of Energy ensure that DOE incorporates into its LNG study the key issues identified by the expert panel.

In reviewing our draft report, DOE agreed with our recommendation.

www.gao.gov/cgi-bin/getrpt?GAO-07-316.

To view the full product, including the scope and methodology, click on the link above. For more information, contact Jim Wells at (202) 512-3841 or wellsj@gao.gov.

What GAO Found

The six unclassified completed studies GAO reviewed examined the effect of a fire resulting from an LNG spill but produced varying results; some studies also examined other potential hazards of a large LNG spill. The studies' conclusions about the distance at which 30 seconds of exposure to the heat (heat hazard) could burn people ranged from less than 1/3 of a mile to about 1-1/4 miles. Sandia National Laboratories (Sandia) conducted one of the studies and concluded, based on its analysis of multiple attack scenarios, that a good estimate of the heat hazard distance would be about 1 mile. Federal agencies use this conclusion to assess proposals for new LNG import terminals. The variations among the studies occurred because researchers had to make modeling assumptions since there are no data for large LNG spills, either from accidental spills or spill experiments. These assumptions involved the size of the hole in the tanker; the volume of the LNG spilled; and environmental conditions, such as wind and waves. The three studies that considered LNG explosions concluded explosions were unlikely unless the LNG vapors were in a confined space. Only the Sandia study examined the potential for sequential failure of LNG cargo tanks (cascading failure) and concluded that up to three of the ship's five tanks could be involved in such an event and that this number of tanks would increase the duration of the LNG fire.

GAO's expert panel generally agreed on the public safety impact of an LNG spill, but believed further study was needed to clarify the extent of these effects, and suggested priorities for this additional research. Experts agreed that the most likely public safety impact of an LNG spill is the heat hazard of a fire and that explosions are not likely to occur in the wake of an LNG spill. However, experts disagreed on the specific heat hazard and cascading failure conclusions reached by the Sandia study. DOE's recently funded study involving large-scale LNG fire experiments addresses some, but not all, of the research priorities identified by the expert panel. The leading unaddressed priority the panel cited was the potential for cascading failure of LNG tanks.

LNG Tanker Passing Downtown Boston on Its Way to Port

Source: GAO.

Contents

Abbreviations

BLEVE	boiling liquid expanding vapor explosion
DOE	Department of Energy
DOT	Department of Transportation
FERC	Federal Energy Regulatory Commission
kW/m^2	kilowatts per square meter
LNG	liquefied natural gas
LPG	liquefied petroleum gas
m^2	square meters
m^3	cubic meters
m/s	meters per second
RPT	rapid phase transition
WSA	Waterway Suitability Assessment

United States Government Accountability Office
Washington, DC 20548

February 22, 2007

The Honorable John D. Dingell
Chairman
The Honorable Joe Barton
Ranking Member
Committee on Energy and Commerce
House of Representatives

The Honorable Bennie G. Thompson
Chairman
The Honorable Peter King
Ranking Member
Committee on Homeland Security
House of Representatives

The Honorable Edward J. Markey
House of Representatives

Worldwide, over 40,000 tanker cargos of liquefied natural gas (LNG) have been shipped since 1959, and imports of LNG are projected to increase over the next 10 years. LNG is a supercooled liquid form of natural gas—a crucial source of energy for the United States. Natural gas is used in homes for cooking and heating and as fuel for generating electricity, and it accounts for about one-fourth of all energy consumed in the United States each year. Prices for natural gas in the United States have risen over the past 5 years as demand for natural gas has increased faster than domestic production. To make up for the domestic shortfall, the United States imports some natural gas in pipelines from Canada. However, most reserves of natural gas are overseas and cannot be transported through pipelines. Natural gas from these reserves has to be transported to the United States as LNG in tankers. Because of the projected increase in LNG tankers arriving at U.S. ports, concerns have been raised about whether the tankers could become terrorist targets.

LNG—primarily composed of methane—is odorless and nontoxic. It is produced by supercooling natural gas to minus 260 degrees Fahrenheit at atmospheric pressure, thus reducing its volume by more than 600 times. This process makes transport by tankers feasible. The tankers are double-hulled, with each tanker containing between four and six adjacent tanks heavily insulated to maintain the LNG's supercool temperature. Generally, these ships can carry enough LNG to supply the daily energy needs of over 10 million homes. Importing LNG requires specialized facilities—called regasification terminals—at ports of entry. At these terminals, the liquid is reconverted into natural gas and then injected into the pipeline system for consumers. Currently, the United States has a total of five LNG import terminals—four are considered onshore terminals, that is, they are located within 3 miles of the shore; one is an offshore terminal located 116 miles off the Louisiana coast in the Gulf of Mexico.[1]

The United States imports about 3 percent of its total natural gas supply as LNG in recent years, but by 2030, LNG imports are projected to account for about 17 percent of the U.S. natural gas supply, according to the Department of Energy's (DOE) Energy Information Administration. To meet this increased demand, energy companies have submitted 32 applications to build new terminals for importing LNG in 10 states and five offshore areas. Figure 1 shows the locations of LNG terminals that are operational, approved, and proposed.

[1]The onshore facilities are near Boston, Massachusetts; Cove Point, Maryland; Savannah, Georgia; and Lake Charles, Louisiana. The United States also has one LNG export facility in Kenai, Alaska, that ships LNG to Japan.

Figure 1: Existing, Approved, and Proposed LNG Terminals in the United States, as of October 2006

Sources: FERC and GAO.

As of October 2006, the Federal Energy Regulatory Commission (FERC)[2]—responsible for approving onshore LNG terminal siting applications—and the U.S. Coast Guard[3]—responsible for approving offshore LNG terminal siting applications—had together approved 13 of these applications. In addition, the Coast Guard contributes to FERC's review of onshore LNG facilities by reviewing and validating an applicant's Waterway Suitability Assessment (WSA) and reaching a preliminary conclusion as to whether the waterway is suitable for LNG operations with regard to navigational safety and security considerations. The WSA includes a security risk assessment to evaluate the public safety risk of an LNG spill from a tanker following an attack. The security risk assessment analyzes potential types of attacks, their probability, and the potential consequences. The WSA also identifies appropriate strategies that can be used to reduce the risk posed by a terrorist attack on an LNG tanker, either by reducing the probability of an attack, or by reducing its consequences. If the WSA deems the waterway suitable for LNG tanker traffic, the Coast Guard provides FERC with a "Letter of Recommendation," which describes the overall risk reduction strategies that will be used on LNG tankers traveling to the proposed terminal. The Coast Guard is the lead federal agency for ensuring the security of active LNG import terminals and tankers traveling within U.S. ports.

As figure 1 shows, six new facilities have been proposed for the northeastern United States, a region that faces gas supply challenges. The Northeast has limited indigenous supplies of natural gas, and receives most of its natural gas either through pipelines from the U.S. Gulf Coast or Canada, or from overseas via tanker as LNG. The pipelines into the Northeast currently run at or near capacity for much of the winter, and demand is projected to significantly increase over the next 5 years, exceeding available supply by 2010. To meet the increasing demand, new supplies of natural gas must reach the Northeast by expanding existing pipeline capacity, constructing new pipelines, or constructing new LNG terminals—all of which have risk associated with them. Difficulties siting LNG facilities in the Northeast could lead to higher natural gas prices

[2]Under the Natural Gas Act, as amended, FERC has exclusive authority to approve or deny an application for the siting, construction, or operation of onshore LNG terminals, including pipelines, and offshore facilities in state waters—that is, generally within 3 miles of shore.

[3]The Coast Guard, along with the Department of Transportation's Maritime Administration, has jurisdiction under the Deep Water Port Act of 1974, as amended, to approve the siting and operation of offshore LNG facilities in federal waters.

unless additional supply can be brought into the region via new, or expansion of old, pipelines.

Scientists and the public have raised concerns about the potential hazards that an LNG spill could pose. When LNG is spilled from a tanker, it forms a pool of liquid on the water. Individuals who come into contact with LNG could experience freeze burns. As the liquid warms and changes into natural gas, it forms a visible, foglike vapor cloud close to the water. The cloud mixes with ambient air as it continues to warm up and eventually the natural gas disperses into the atmosphere. Under certain atmospheric conditions, however, this cloud could drift into populated areas before completely dispersing. Because an LNG vapor cloud displaces the oxygen in the air, it could potentially asphyxiate people who come into contact with it. Furthermore, like all natural gas, LNG vapors can be flammable, depending on conditions.[4] If the LNG vapor cloud ignites, the resulting fire will burn back through the vapor cloud toward the initial spill. It will continue to burn above the LNG that has pooled on the surface—this is known as a pool fire. Experiments to date have shown that LNG fires burn hotter than oil fires of the same size. Both the cold temperatures of spilled LNG and the high temperatures of an LNG fire have the potential to significantly damage the tanker, causing multiple tanks on the ship to fail in sequence—called a cascading failure. Such a failure could increase the severity of the incident. Finally, concerns have been raised about whether an explosion could result from an LNG spill.

Although LNG tankers have carried over 40,000 shipments worldwide since 1959, there have been no LNG spills resulting from a cargo tank rupture. Some safety incidents, such as groundings or collisions, have resulted in small LNG spills that did not affect public safety. In the 1970s and 1980s, experiments to determine the consequences of a spill examined small LNG spills of up to 35 meters in diameter. Following the terrorist attacks of September 11, 2001, however, many experts recognized that an attack on an LNG tanker could result in a large spill—a volume of LNG up to 100 times greater than studied in past experiments. Since then, a number of studies have reevaluated safety hazards of LNG tankers in light of a potential terrorist threat. Because a major LNG spill has never occurred, studies examining LNG hazards rely on computer models to

[4]LNG vapors only ignite when they are in a 5 percent to 15 percent concentration in the air. If the LNG concentration is higher, there is not enough oxygen available for fire. If the concentration is lower, there is likewise not enough fuel for fire.

predict the effects of hypothetical accidents, often focusing on the properties of LNG vapor fires. The Coast Guard uses one of these studies, conducted in 2004 by Sandia National Laboratories,[5] as a basis for conducting the security risk assessment required in the WSA for proposed onshore LNG facilities.[6] Access to accurate information about the consequences of LNG spills is crucial for developing accurate risk assessments for LNG siting decisions. While an underestimation of the consequences could expose the public to additional risk in the event of an LNG spill, an overestimation of consequences could result in the use of inappropriate and costly risk mitigation strategies. DOE recently funded a new study—to be completed by Sandia National Laboratories in 2008—that will conduct small- and large-scale LNG fire experiments to refine and validate existing models (such as the one used by Sandia National Laboratories in their 2004 study) that calculate the heat hazards of large LNG fires.

In this context, you asked us to (1) describe the results of recent unclassified studies on the consequences of an LNG spill and (2) identify the areas of agreement and disagreement among experts concerning the consequences of a terrorist attack on an LNG tanker.

To address the first objective, we identified eight unclassified, completed studies of LNG hazards and reviewed the six studies that included new, original research (either experimental or modeling) and clearly described the methodology used. While we have not verified the scientific modeling or results of these studies, the methods used seem appropriate for the work conducted. We also interviewed agencies responsible for LNG regulations and visited all four onshore LNG import facilities and one export facility. To address the second objective, we identified 19 recognized experts in LNG hazard analysis and convened a Web-based expert panel to obtain their views on LNG hazards and to get agreement on as many issues as possible. In selecting experts for the panel, we sought individuals who are widely recognized as having experience with one or more key aspects of LNG hazard analysis. We sought to achieve balance in representation from government, academia, consulting,

[5]Sandia National Laboratories. *Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water*. Albuquerque: 2004.

[6]DOE is also sponsoring additional research that applies the 2004 Sandia National Laboratories' methodology to LNG tankers larger than those previously studied, which is expected to be completed in July 2007.

research organizations, and industry. Additionally, we ensured that our expert panel included at least one author from each of the six unclassified studies of LNG hazards. Because some of the studies conducted are classified, this public version of our findings supplements a more comprehensive classified report produced under separate cover. A more detailed description of our scope and methodology is presented in appendix I. We conducted our work from January 2006 through January 2007 in accordance with generally accepted government auditing standards.

Results in Brief

The six unclassified studies we reviewed all examined the heat impact of an LNG pool fire but produced varying results; some studies also examined other potential hazards of a large LNG spill and reached consistent conclusions on explosions. Specifically, the studies' conclusions about the distance at which 30 seconds of exposure to the heat could burn people ranged from about 500 meters (less than 1/3 of a mile) to more than 2,000 meters (about 1-1/4 miles). The Sandia National Laboratories' study concluded that the most likely distance for a burn is about 1,600 meters (1 mile). These variations occurred because researchers had to make numerous modeling assumptions to scale-up the existing experimental data for large LNG spills since there are no large spill data from actual events. These assumptions involved the size of the hole in the tanker, the number of tanks that fail, the volume of LNG spilled, key LNG fire properties, and environmental conditions, such as wind and waves. Three of the studies also examined other potential hazards of an LNG spill, including LNG vapor explosions, asphyxiation, and cascading failure. All three studies considered LNG vapor explosions unlikely unless the LNG vapors were in a confined space. Only the Sandia National Laboratories' study examined asphyxiation, and it concluded that asphyxiation did not pose a hazard to the general public. Finally, only the Sandia National Laboratories' study examined the potential for cascading failure of LNG tanks and concluded that only three of the five tanks would be involved in such an event and that this number of tanks would increase the duration of the LNG fire.

Our panel of 19 experts generally agreed on the public safety impact of an LNG spill, disagreed with a few conclusions reached by the Sandia National Laboratories' study, and suggested priorities for research to clarify the impact of heat and cascading tank failures. Experts agreed that (1) the most likely public safety impact of an LNG spill is the heat impact of a fire; (2) explosions are not likely to occur in the wake of an LNG spill, unless the LNG vapors are in confined spaces; and (3) some hazards, such as freeze burns and asphyxiation, do not pose a hazard to the public. Experts disagreed with the heat impact and cascading tank failure conclusions reached by the Sandia National Laboratories' study, which the Coast Guard uses to prepare WSAs. Specifically, all experts did not agree with the heat impact distance of 1,600 meters. Seven of 15 experts thought Sandia's distance was "about right," and the remaining eight experts were evenly split as to whether the distance was "too conservative" or "not conservative enough" (the other 4 experts did not answer this question). Experts also did not agree with the Sandia National Laboratories' conclusion that only three of the five LNG tanks on a tanker would be involved in a cascading failure. Finally, experts suggested priorities to guide future research aimed at clarifying uncertainties about heat impact distances and cascading failure, including large-scale fire experiments, large-scale LNG spill experiments on water, the potential for cascading failure of multiple LNG tanks, and improved modeling techniques. DOE's recently funded study involving large-scale LNG fire experiments addresses some, but not all, of the research priorities identified by the expert panel.

We are recommending that DOE incorporate into its current LNG study the key issues identified by the expert panel. We particularly recommend that DOE examine the potential for cascading failure of LNG tanks.

Background

Natural gas is primarily composed of methane, with small percentages of other hydrocarbons, including propane and butane. When natural gas is cooled to minus 260 degrees Fahrenheit at atmospheric pressure, the gas becomes a liquid, known as LNG, and it occupies only about 1/600th of the volume of its gaseous state. Since LNG is maintained in an extremely cooled state—reducing its volume—there is no need to store it under pressure. This liquefaction process allows natural gas to be transported by trucks or tanker vessels. LNG is not explosive or flammable in its liquid state. When LNG is warmed, either at a regasification terminal or from exposure to air as a result of a spill, it becomes a gas. As this gas mixes with the surrounding air, a visible, low-lying vapor cloud results. This vapor cloud can be ignited and burned only within a minimum and maximum concentration of air and vapor (percentage by volume). For methane, the dominant component of this vapor cloud, this flammability range is between 5 percent and 15 percent by volume. When fuel concentrations exceed the cloud's upper flammability limit, the cloud cannot burn because too little oxygen is present. When fuel concentrations are below the lower flammability limit, the cloud cannot burn because too little methane is present. As the cloud vapors continue to warm, above minus 160 degrees Fahrenheit, they become lighter than air and will rise and disperse rather than collect near the ground.

If the cloud vapors ignite, the resulting fire will burn back through the vapor cloud toward the initial spill and will continue to burn above the LNG that has pooled on the surface. This fire burns at an extremely high temperature—hotter than oil fires of the same size. LNG fires burn hotter because the flame burns very cleanly and with little smoke. In oil fires, the smoke emitted by the fire absorbs some of the heat from the fire and reduces the amount of heat emitted. Scientists measure the amount of heat given off by a fire by looking at the amount of heat energy emitted per unit area as a function of time. This is called the surface emissive power of a fire and is measured in kilowatts per square meter (kW/m^2). Generally, the heat given off by an LNG fire is reported to be more than 200 kW/m^2. By comparison, the surface emissive power of a very smoky oil fire can be as little as 20 kW/m^2. The heat from fire can be felt far away from the fire itself. Scientists use heat flux—also measured in kW/m^2—to quantify the amount of heat felt at a distance from a fire. For instance, a heat flux of 5 kW/m^2 can cause second degree burns after about 30 seconds of exposure to bare skin. This heat flux can be compared with the heat from a candle—if a hand is held about 8 to 9 inches above the candle, second degree burns could result in about 30 seconds. A heat flux of about 12.5 kW/m^2, over an exposure time of 10 minutes, will ignite wood, and a heat flux of about 37.5 kW/m^2 can damage steel structures.

Four types of explosions could potentially occur after an LNG spill: rapid phase transitions (RPT), deflagrations, detonations, and boiling-liquid-expanding-vapor-explosions (BLEVE).[7] More specifically:

- An *RPT* occurs when LNG is warmed and changes into natural gas nearly instantaneously. An RPT generates a pressure wave that can range from very small to large enough to damage lightweight structures. RPTs strong enough to damage test equipment have occurred in past LNG spill experiments on water, although their effects have been localized at the site of the RPT.

- *Deflagrations and detonations* are explosions that involve combustion (fire). They differ on the basis of the speed and strength of the pressure

[7]Generally, an explosion is an energy release associated with a pressure wave. Some explosions are large enough that the pressure wave can break windows or damage structures, while others are much smaller.

wave generated: deflagrations move at subsonic velocities and can result in pressures (overpressures) up to 8 times higher than the original pressure; detonations travel faster—at supersonic velocities—and can result in larger overpressures—up to 20 times the original pressure. Methane does not detonate as readily as other hydrocarbons; it requires a larger explosion to initiate a detonation in a methane cloud.

- A *BLEVE* occurs when a liquefied gas is heated to above its boiling point while contained within a tank. For instance, if a hot fire outside an LNG tanker sufficiently heated the liquid inside, a percentage of the LNG within the tank could "flash" into a vapor state virtually instantaneously, causing the pressure within the tank to increase. LNG tanks do have pressure relief valves, but if these were inadequate or failed, the pressure inside the tank could rupture the tank. The escaping gas would be ignited by the fire burning outside the tank, and a fireball would ensue. The rupture of the tank could create an explosion and flying debris (portions of the tank).

World natural gas reserves are abundant, estimated at about 6,300 trillion cubic feet, or 65 times the volume of natural gas used in 2005. Much of this gas is considered "stranded" because it is located in regions far from consuming markets. Russia, Iran, and Qatar combined hold natural gas reserves that represent more than half of the world total. Many countries have imported LNG for years. In 2005, 13 countries shipped natural gas to 14 LNG-importing countries. LNG imports, as a percentage of a country's total gas supply, for each of the importing countries ranged from 3 percent in the United States to nearly 95 percent in Japan. In 2005, LNG imports to the United States originated primarily in Trinidad and Tobago (70 percent), Algeria (15 percent), and Egypt (11 percent). The remaining 4 percent of U.S. LNG imports came from Oman, Malaysia, Nigeria, and Qatar.

LNG tankers primarily have two basic designs, called membrane or Moss (see fig. 2). Both designs consist of an outer hull, inner hull, and cargo containment system. In membrane tank designs, the cargo is contained by an Invar, or stainless steel double-walled liner, that is structurally supported by the vessel's inner hull. The Moss tank design uses structurally independent spherical or prismatic shaped tanks. These tanks, usually five located one behind the other, are constructed of either stainless steel or an aluminum alloy. LNG tankers ships are required to meet international maritime construction and operating standards, as well as U.S. Coast Guard safety and security regulations.

Figure 2: LNG Membrane Tanker

Source: GAO.

Studies Identified Different Distances for the Heat Effects of an LNG Fire

The six studies we examined identified various distances at which the heat effects of an LNG fire could be hazardous to people. The studies' variations in heat effects result from the assumptions made in the studies' models. Some studies also examined other potential hazards such as LNG vapor explosions, other types of explosions, and asphyxiation, and identified their potential impacts on public safety.

Studies Identified Various Distances That the Heat Effects of an LNG Fire Could Be Hazardous to People because of Assumptions Made

The studies' conclusions about the distance at which 30 seconds of exposure to the heat could burn people ranged from about 500 meters (less than 1/3 mile) to more than 2,000 meters (about 1-1/4 miles). The results—size of the LNG pool, the duration of the fire, and the heat hazard distance for skin burn—varied in part because the studies made different assumptions about key parameters of LNG spills and also because they were designed and conducted for different purposes. Key assumptions made included the following:

- *Hole size and cascading failure.* Hole size is an important parameter for modeling LNG spills because of its relationship to the duration of the event—larger holes allow LNG to spill from the tanker more quickly, resulting in larger LNG pools and shorter duration fires. Conversely, small holes could create longer-duration fires. Cascading failure is important because it increases the overall spill volume and the duration of the spill.

- *Waves and wind.* These conditions can affect the size of both the LNG pool and the heat hazard zone. One study indicated that waves can inhibit the spread of an LNG pool, keeping the pool size much smaller than it would be on a smooth surface, and thereby reducing the size of the LNG pool fire. Wind will tend to tilt the fire downwind (like a candle flame blowing in the wind), increasing the heat hazard zone in that direction (and decreasing it upwind).

- *Volume of LNG spilled.* The amount of LNG spilled is one of the factors that can affect the size of the pool.

- *Surface emissive power of the fire.* While the amount of heat given off by a large LNG fire is unknown, assumptions about it directly affect the results for the heat hazard zone. It is expected that the surface emissive power of LNG fires will be lower for large fires because oxygen will not circulate efficiently within a very large fire. Lack of oxygen in the middle of a large fire would lead to more smoke production, which would block some of the heat from the fire.

The LNG spill consequence studies' key assumptions and results are shown in table 1.

Table 1: Key Assumptions and Results of the LNG Spill Consequence Studies

	Key assumptions						Key results		
			Environmental conditions modeled:						
	Hole size (m^2)	Number of tanks that rupture (cascading failure	Wind speed and its effect on waves (m/s)	Wind speed and its effect on fire (m/s)	Spill volume (m^3)	Fire surface emissive power (kW/m^2)	Pool diameter (meters)	Distance to the 5kw/m^2 heat level (meters)	Duration (minutes)
Quest Consultants Inc. (Quest)[a]	19.6	1	1.5	1.5	12,500	[b]	156	497	14.3
	19.6	1	5.0	5.0	12,500	[b]	146	531	16.6
	19.6	1	9.0	9.0	12,500	[b]	110	493	28.6
Sandia National Laboratories (Sandia)	2	3	[c]	[c]	37,500	220	209	784	20
	5	3	[c]	[c]	37,500	220	572	2,118	8.1
	5	1	[c]	[c]	12,500	350	330	1,652	8.1
	5[d]	1	[c]	[c]	12,500	220	330-405	1,305-1,579	5.4-8.1
	12	1	[c]	[c]	12,500	220	512	1,920	3.4
Pitblado, et al. (Pitblado)[e]	1.77	1	[c]	3.0	17,250	[b]	171	750	32
ABS Consulting (ABSC)[f]	0.79	1	[c]	8.9	12,500	265	200[g]	650	51
	19.6	1	[c]	8.9	12,500	265	620[g]	1,500	4.2
Fay (Fay)[h]	20	1	[c]	[c]	14,300	[b]	[b]	1,900	3.3
Lehr and Simecek-Beatty (Lehr)[i]	[b]	[b]	[c]	[c]	500	200	[b]	500	2-3

Source: GAO analysis of spill consequence studies.

[a]"Modeling LNG Spills in Boston Harbor." Copyright© 2003 Quest Consultants, Inc., Norman, OK 73609; Letter from Quest Consultants to DOE (October 2, 2001); Letter from Quest Consultants to DOE (October 3, 2001).

[b]Information not available.

[c]Not included in the model.

[d]The study examined multiple scenarios of 5m^2. The ranges listed summarize the highest and lowest values for those scenarios.

[e]R. M. Pitblado, J. Baik, G. J. Hughes, C. Ferro, and S. J. Shaw. "*Consequences of Liquefied Natural Gas Marine Incidents*." *Process Safety Progress* 24 no. 2 (June 2005).

[f]ABS Consulting Inc. *Consequence Assessment Methods for Incidents Involving Releases from Liquefied Natural Gas Carriers*. May 13, 2004. FERC "Staff's Responses to Comments on the Consequence Assessment Methods for Incidents Involving Releases from Liquefied Natural Gas Carriers," June 18, 2004.

[g]ABS Consulting modeled pool size as a semicircle and reported the radius of that semicircle in the study. The reported radii were used to calculate the diameter of the semicircle so the study results could be compared with the other studies.

[h]J.A. Fay. "Model of Spills and Fires from LNG and Oil tankers." *Journal of Hazardous Materials* B96 (2003): 171-188.

[i]William Lehr and Debra Simecek-Beatty. "Comparison of Hypothetical LNG and Fuel Oil Fires on Water." *Journal of Hazardous Materials* 107 (2004): 3-9.

In terms of the studies' results, we identified the following three key results:

- *Pool size* describes the extent of the burning pool—and can help people understand how large the LNG fire itself will be.
- *Heat hazard distance* describes the distance at which 30 seconds of exposure could cause second degree burns.
- *Fire duration* of the incident describes how long people and infrastructure will be exposed to the heat from the fire. The longer the fire, the greater potential for damage to the tanker and for cascading failure.

Although all the studies considered the consequences of an LNG spill, they were conducted for different purposes. Three of the six studies—Quest, Sandia, and Pitblado—specifically addressed the consequences of LNG spills caused by terrorist attacks. Two of these three studies—Quest and Sandia—were commissioned by DOE. The Quest study, begun in response to the September 11, 2001, attacks, was designed to quantify the heat hazard zones for LNG tanker spills in Boston Harbor. Only the Quest study examined how wind and waves would affect the spreading of the LNG on the water and the size of the resulting LNG pool. The Quest study based its wind and wave assumptions on weather data from buoys near Boston Harbor. The Quest study found that, while the waves would help reduce the size of the LNG pool, the winds that created the waves would tend to increase the heat hazard distance downwind. To simplify the modeling of the waves, the Quest study considered "standing" waves (rather than moving waves) of various heights and, therefore, did not consider the impact of wave movement on LNG pool spreading. The ABSC study expressed concern that Quest's standing wave assumption resulted in pool sizes that were too small because wave movement might help spread the LNG.

The 2004 Sandia study was intended to develop guidance on a risk-based analysis approach to assess potential threats to an LNG tanker, determine the potential consequences of a large spill, and review techniques that could be used to mitigate the consequences of an LNG spill. The assumptions and results in table 1 for the Sandia study refer to the scenarios Sandia examined that had terrorist causes. According to Sandia, the study used available intelligence and historical data to develop credible and possible scenarios for the kinds of attacks that could breach an LNG tanker. Sandia then modeled how large a hole each of the weapon scenarios could create in an LNG tanker.[8] Two of these intentional breach scenarios included cascading failure of three tanks on an LNG tanker. In these cases, the LNG spill from one tank, as well as the subsequent fire, causes the neighboring two tanks to fail on the LNG tanker, resulting in LNG spills from three of the five tanks on the tanker. After considering all of its scenarios, Sandia concluded that, as a rule-of-thumb, 1,600 meters is a good approximation of the heat hazard distance for terrorist-induced spills. However, as the table shows, one of Sandia's scenarios—for a large spill with cascading failure of three LNG tanks—found that the distance could exceed more than 2,000 meters and that the cascading failure would increase the duration of the incident.

Finally, the stated purpose of industry's Pitblado study was to develop credible threat scenarios for attacks on LNG tankers and predict hazard zones for LNG spills from those types of attacks. The study identified a hole size smaller than the other studies that specifically considered terrorist attacks.

The other studies we reviewed examined LNG spills regardless of cause. FERC commissioned the ABS Consulting study to develop appropriate methods for estimating heat hazard zones from LNG spills. FERC uses these methods, in conjunction with the Sandia study, to examine the public safety consequences of tankers traveling to proposed onshore LNG facilities before granting siting approval. The two scenarios in the ABSC study illustrate how small holes could result in longer fires, which have a higher potential to damage the tanker itself. One scenario used a hole size of 0.79 square meters and the other a hole size of about 20 square meters. The difference in duration is striking—it takes 51 minutes and 4.2 minutes, respectively, for the fire to consume all the spilled LNG.

Finally, the Lehr and Fay studies compared the fire consequences of LNG spills with known information about oil spills and fires. Although most

[8]Please note that the information used to develop Sandia's terrorist scenarios is classified and will be discussed in GAO's classified report.

studies made similar assumptions about the volume of LNG spilled from any single LNG tank, Lehr examined a much smaller spill volume—just 500 cubic meters of LNG, compared with a range of 12,500 to 17,250 cubic meters.

Some Studies Examined Other Potential Hazards and Identified Their Impact on Public Safety

Three of the studies also examined other potential hazards of an LNG spill, including LNG vapor explosions, other types of explosions, and asphyxiation.

LNG vapor explosions. Three studies—Sandia, ABSC, and Pitblado—examined LNG vapor explosions, and all agreed that it is unlikely that LNG vapors could explode and create a pressure wave if the vapors are in an unconfined space. Although the three studies agreed that LNG vapors could explode only in confined areas, they did not conduct modeling or describe the likelihood of such confinement after an LNG spill from a tanker. The Sandia study stated that fire will generally progress through the vapor cloud slowly and without producing an explosion with damaging pressure waves. The study did suggest, however, that if the LNG vapor cloud is confined (e.g., between the inner and outer hull of an LNG carrier), it could explode but would only affect the immediate surrounding area. The ABSC study and the Pitblado study agreed that a confined LNG vapor cloud could result in an explosion.

Other types of explosions. Three studies—Sandia, ABSC, and Pitblado—examined the potential for RPTs. The Sandia study concluded that, while RPTs have generated energy releases equivalent to several pounds of explosives, RPT impacts will be localized near the spill. Sandia also noted that RPTs are not likely to cause structural damage to the vessel. The ABSC study noted that their literature search suggested that damage from RPT overpressures would be limited to the immediate vicinity, though it noted that the literature did not include large spills like those that could be caused by a terrorist attack. Only one study, Pitblado, discussed the possibility of a BLEVE. According to our discussions with Dr. Pitblado, an LNG ship with membrane tanks could not result in a BLEVE, but he said that Moss spherical tanks could potentially result in a BLEVE. A BLEVE could result because it is possible for pressure to build up in a Moss tanker. A 2002 LNG tanker truck incident in Spain resulted in an explosion that some scientists have characterized as a BLEVE of an LNG truck. Portions of the tanker truck were found 250 meters from the accident itself, propelled by the strength of the blast.

Asphyxiation. Only the Sandia study examined the potential for asphyxiation following an LNG spill if the vapors displace the oxygen in the air. It concluded that fire hazards would be the greatest problem in most locations, but that asphyxiation could threaten the ship's crew, pilot boat crews, and emergency response personnel.

Experts Generally Agreed That the Most Likely Public Safety Impact of an LNG Spill Is Fire's Heat Effect, but That Further Study Is Needed to Clarify the Extent of This Effect

Our panel of 19 experts generally agreed on the public safety impact of an LNG spill and disagreed with a few of the conclusions of the Sandia study.[9] The experts also suggested priorities for future research—some of which are not fully addressed in DOE's ongoing LNG research—to clarify uncertainties about heat impact distances and cascading failure. These priorities include large-scale fire experiments, large-scale LNG spill experiments on water, the potential for cascading failure of multiple LNG tanks, and improved modeling techniques.

Experts Agreed That the Heat from an LNG Fire Was Most Likely to Affect Public Safety, but That Explosions from an LNG Spill Are Unlikely

Experts discussed two types of fires: vapor cloud fires and pool fires. Eighteen of 19 experts agreed that the ignition of a vapor cloud over a populated area could burn people and property in the immediate vicinity of the fire. While the initial vapor cloud fire would be of short duration as the flames burned back toward the LNG carrier, any flammable object enveloped by the vapor cloud fire could ignite nearby objects, creating secondary fires that present hazards to the public. Three experts emphasized in their comments that the vapor cloud is unlikely to penetrate very far into a populated area before igniting. Expanding on this point, one expert noted that any injuries from a vapor cloud fire would occur only at the edges of a populated area, for example, along beaches. One expert disagreed, arguing that a vapor cloud fire is unlikely to cause significant secondary fires because it would not last long enough to ignite other materials.

[9] We considered experts "in agreement" if more than 75 percent of experts indicated that they completely agreed or generally agreed with a given statement. Not all experts commented on every issue discussed.

Experts agreed that the main hazard to the public from a pool fire is the heat from the fire but emphasized that the exact hazard distance depends on site-specific and scenario-specific factors. Furthermore, a large, unconfined pool fire is very difficult to extinguish; generally almost all the LNG must be consumed before the fire goes out. Experts agreed that three of the main factors that affect the amount of heat from an LNG fire are the following:

- *Site-specific weather conditions*. Weather conditions, such as wind and humidity, can influence the heat hazard distances. For example, more humid conditions allow heat to be absorbed by the moisture in the air, reducing heat hazard distances.
- *Composition of the LNG*. The composition of the LNG can also affect the distance at which heat from the fire is felt by the public. In small fires, methane, which comprises between 84 percent and 97 percent of LNG, burns cleanly, with little smoke. Other LNG components—propane and butane—produce more smoke when burned, absorbing some of the fire's heat and reducing the hazard distance. As the fire grows larger, the influence of the composition of LNG is hypothesized to be less pronounced because large fires do not burn efficiently.
- *Size of the fire*. The size of the fire has a major impact on its surface emissive power; the heat hazard distance increases with pool size up to a point but is expected to decrease for very large pools, like those caused by a terrorist attack.

Experts also discussed the following hazards related to an LNG spill:

- *RPTs*. Experts agreed that RPTs could occur after an LNG spill but that the overpressures generated would be unlikely to directly affect the public.
- *Detonations and deflagrations*. Experts made a key distinction between these types of explosions in confined spaces as opposed to unconfined spaces. For confined spaces, they agreed that it is possible, under controlled experimental conditions, to induce both types of explosions of LNG vapors; however, a detonation of confined LNG vapors is unlikely following an LNG spill caused by a terrorist attack. Experts were split on the likelihood of a confined deflagration occurring after a terrorist attack: eight thought it was unlikely, four thought it likely, and five thought neither likely nor unlikely.[10] For unconfined spaces, experts were split on

[10]Two experts did not comment.

whether it is possible to induce such explosions; however, even experts who thought such explosions were possible agreed that deflagrations and detonations in unconfined spaces are unlikely to occur following an LNG spill caused by a terrorist attack.

- *BLEVE*. Experts were split on whether a BLEVE is theoretically possible in an LNG tanker. Of the ten experts who agreed it was theoretically possible, six thought that a BLEVE is unlikely to occur following an LNG spill caused by a terrorist attack on a tanker.[11]

- *Freeze burns and asphyxiation*. Experts agreed that freeze burns do not present a hazard to the public because only people in close proximity to LNG spill, such as personnel on the tanker or nearby vessels, might come into contact with LNG or very cold LNG vapor. For asphyxiation, experts agreed that it is unlikely that an LNG vapor cloud could reach a populated area while still sufficiently concentrated to pose an asphyxiation threat.

Experts Disagreed with a Few Key Conclusions of the Sandia National Laboratories Study

Experts disagreed with heat hazard and cascading failure conclusions of the Sandia study. Specifically, 7 of 15 experts thought Sandia's heat hazard distance was "about right," and the remaining 8 experts were evenly split as to whether the distance was "too conservative" (i.e., larger than needed to protect the public) or "not conservative enough" (i.e., too small to protect the public). Experts who thought the distance was too conservative generally listed one of two reasons. First, the assumptions about the surface emissive power of large fires were incorrect because the surface emissive power of large fires would be lower than Sandia assumed. Second, Sandia's hazard distances are based on the maximum size of a pool fire. However, these experts pointed out that once a pool fire ignites, its diameter will begin to shrink, which will also reduce the heat hazard distance. Experts who thought Sandia's heat hazard distance was not conservative enough listed a number of concerns. For example, Sandia's distances do not take into consideration the effects of cascading failure. One expert suggested that a 1-meter hole in the center tank of an LNG tanker that resulted in a pool fire could cause the near simultaneous failure of the other four tanks, leading to a larger heat hazard zone.

[11]Three experts said that BLEVEs were "neither likely nor unlikely," and one expert thought that BLEVEs were likely.

Officials at Sandia National Laboratories and our panel of experts cautioned that the hazard distances presented cannot be applied to all sites. According to the Sandia study authors, their goal was to provide guidance to federal agencies on the order of magnitude of the hazards of an LNG spill on water. As they pointed out in interviews and in their original study, further analysis for specific sites is needed to understand hazards in a particular location. Six experts on our panel also emphasized the importance of site-specific and scenario-specific factors. For instance, one expert explained that the $5kW/m^2$ hazard distance depends on the size of the tanker and the spill scenario, including factors such as wind speed, timing of ignition, and the location of the hole. Other experts suggested that key factors are spill volume and the impact of waves. Additionally, two experts explained that there is no "bright line" for hazards—that is, 1,599 meters is not necessarily "dangerous," and 1,601 meters is not necessarily "safe."

Only 9 of 15 experts agreed with Sandia's conclusion that only three of the five LNG tanks on a tanker would be involved in cascading failure. Five experts noted that the Sandia study did not explain how it concluded that only three tanks would be involved in cascading failure. Three experts said that an LNG spill and subsequent fire could potentially result in the loss of all tanks on board the tanker.

Twelve of 16 experts agreed, however, with Sandia's conclusion that cascading failure events are not likely to greatly increase (by more than 20 to 30 percent) the overall fire size or heat hazard ranges. The four experts who disagreed with Sandia's conclusion about the public safety impact of cascading failure cited two main reasons: (1) Sandia did not clearly explain how it reached that conclusion and (2) the impact of cascading failure will partly depend on how the incident unfolds. For instance, one expert suggested that cascading failure could include a tank rupture, fireball, or BLEVE, any of which could have direct impacts on the public (from the explosive force) and which would change the heat hazard zones that Sandia identified.

Finally, experts agreed with Sandia's conclusion that consequence studies should be used to support comprehensive, risk-based management and planning approaches for identifying, preventing, and mitigating hazards from potential LNG spills.

Experts Suggest Future Research Priorities to Determine the Public Safety Impact of an LNG Spill

In the second iteration of the Web-based panel, we asked the experts to identify the five areas related to the consequences of LNG spills that need further research. Then, in the final iteration of the Web-based panel, we provided the experts with a list of 19 areas—generated by their suggestions and comments from the second iteration—and asked them to rank these in order of importance. Table 2 presents the results of that ranking for the top 10 areas identified and indicates those areas that are funded in the DOE study discussed earlier.

Table 2: Expert Panel's Ranking of Need for Research on LNG

Rank	Research area	Funded in DOE's study
1	Large fire phenomena	√
2	Cascading failure	
3	Large-scale spill testing on water	√
4	Large-scale fire testing	√
5	Comprehensive modeling: interaction of physical processes	
6	Risk tolerability assessments	
7	Vulnerability of containment systems (hole size)	
8	Mitigation techniques	
9	Effect of sea water coming in as LNG flows out	
10	Impact of wind, weather, and waves	

Source: GAO.

Note: A rank of 1 is the highest rank, and a rank of 10 is the lowest. Panel members ranked 19 areas of research from 1 to 19; a score was calculated for each area based on this ranking. Only the 10 areas with the highest scores are presented in this table.

As the table shows, two of the top five research areas identified are related to large LNG fires—large fire phenomena and large-scale fire testing. Experts believe this research is needed to establish the relationship between large pool fires and the surface emissive power of the fire. Experts recommended new LNG tests for fires between 15 meters and 1,000 meters. The median suggested test size was 100 meters. Some experts also raised the issue of whether large LNG fires will stop behaving like one single flame but instead break up into several smaller, shorter flames. Sandia noted in its study that this behavior could reduce heat hazard distances by a factor of two to three.

Experts also ranked research into cascading failure of LNG tanks second in the list of priorities. Concerning cascading failure, one expert noted that, although the consequences could be serious, there are virtually no data looking at the hull damage caused by exposure to extreme cold or heat.

As table 2 shows, DOE's recently funded study involving large-scale LNG fire experiments addresses some, but not all, of the research priorities identified by the expert panel. For DOE, Sandia National Laboratories plans to conduct large-scale LNG pool fire tests beginning with a pool size of 35 meters—the same size as the largest test conducted to date. Sandia will validate the existing 35-meter data and then conduct similar tests for pool sizes up to 100 meters. The goal of this fire testing is to document the impact of smoke on large LNG pool fires. Sandia suggests that these tests will create a higher degree of knowledge of large-scale pool fire behavior and significantly lower the current uncertainty in predicting heat hazard distances.

According to researchers at Sandia National Laboratories, some of the research our panel of experts suggested may not be appropriate. Sandia indicated that comprehensive modeling, which allows various complex processes to interact, would be very difficult to do because of the uncertainty surrounding each individual process of the model. One expert on our panel agreed, noting that while comprehensive modeling of all LNG phenomena is important, combining those phenomena into one model should wait for experiments that lead to better understanding of each individual phenomenon.

Conclusions

It is likely that the United States will increasingly depend on the importation of LNG to meet the nation's demand for natural gas. Understanding and resolving the uncertainties surrounding LNG spills is critical, especially in deciding on where to locate LNG facilities. Because there have been no large-scale LNG spills or spill experiments, past studies have developed modeling assumptions based on small-scale spill data. While there is general agreement on the types of effects from an LNG spill, the results of these models have created what appears to be conflicting assessments of the specific consequences of an LNG spill, creating uncertainty for regulators and the public. Additional research to resolve some key areas of uncertainty could benefit federal agencies responsible for making informed decisions when approving LNG terminals and protecting existing terminals and tankers, as well as providing reliable information to citizens concerned about public safety. Although DOE has recently funded a study that will address large-scale LNG fires, this study will address only 3 of the top 10 issues—and not the second-highest ranked issue—that our panel of experts identified as potentially affecting public safety.

Recommendation for Executive Action

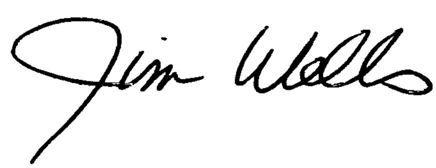
To provide the most comprehensive and accurate information for assessing the public safety risks posed by tankers transiting to proposed LNG facilities, we recommend that the Secretary of Energy ensure that DOE incorporates the key issues identified by the expert panel into its current LNG study. We particularly recommend that DOE examine the potential for cascading failure of LNG tanks in order to understand the damage to the hull that could be caused by exposure to extreme cold or heat.

Agency Comments and Our Evaluation

We requested comments on a draft of this report from the Secretary of Energy (DOE). DOE agreed with our findings and recommendation. In addition, DOE included technical and clarifying comments, which we included in our report as appropriate.

As agreed with your offices, unless you publicly announce the contents of this report earlier, we plan no further distribution until 30 days from the report date. At that time, we will send copies to interested congressional committees, the Secretary of Energy, and other interested parties. We also will make copies available to others upon request. In addition, the report will be available at no charge on the GAO Web site at http://www.gao.gov.

If you or your staff have any questions regarding this report, please contact me at (202) 512-3841 or wellsj@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. Key contributors to this report are listed in appendix IV.



Jim Wells
Director, Natural Resources
and Environment

Appendix I: Scope and Methodology

To address the first objective, we identified eight unclassified, completed studies of liquefied natural gas (LNG) hazards and reviewed the six studies that included new, original research (either experimental or modeling) and clearly described the methodology used. While we have not verified the scientific modeling or results of these studies, the methods used seem appropriate for the work conducted based on conversations with experts in the field and our assessment. We also discussed these studies with their authors and visited all four onshore LNG import facilities and one export facility. We attended a presentation on LNG safety and received specific training on LNG properties and safety. We also conducted interviews with officials from Sandia National Laboratories, Federal Energy Regulatory Commission, Department of Transportation, Department of Energy, and the U. S. Coast Guard. During our interviews, we asked officials to provide information on past LNG studies and plans for future LNG spill consequences work.

To obtain information on experts' opinions of the public safety consequences of an LNG spill from a tanker, we conducted a three-phase, Web-based survey of 19 experts on LNG spill consequences. We identified these experts from a list of 51 individuals who had expertise in one or more key aspects of LNG spill consequence analysis. In compiling this initial list, we sought to achieve balance in terms of area of expertise (i.e., LNG experiments, modeling LNG dispersion, LNG vaporization, fire modeling, and explosion modeling). In addition, we included at least one author of each of the six major LNG studies we reviewed, that is, studies by Sandia National Laboratories; ABS Consulting; Quest Consultants Inc.; Pitblado, et al.; James Fay (MIT); and William Lehr (National Oceanic and Atmospheric Administration). We gathered resumes, publication lists, and major LNG-related publications from the experts identified on the initial list.

We selected 19 individuals for the panel. One or more of the following selection criteria were used: (1) has broad experience in all facets of LNG spill consequence modeling (LNG spill from hole, LNG dispersion, vaporization and pool formation, vapor cloud modeling, fire modeling, and explosion modeling); (2) has conducted physical LNG experiments; or (3) has specific experience with areas of particular importance, such as LNG explosion research. In addition, we included: (1) at least one author from each of the major LNG studies and (2) representatives from private industry, consulting, academia, and government. All 19 experts selected for the panel agreed to participate. The names and affiliations of panel members are included in appendix II.

To obtain consensus concerning public safety issues, we used an iterative Web-based process. We used this method, in part, to eliminate the potential bias associated with group discussions. These biasing effects include the potential dominance of individuals and group pressure for conformity. Moreover, by creating a virtual panel, we were able to include more experts than possible with a live panel.

For each phase in the process, we posted a questionnaire on GAO's survey Web site. Panel members were notified of the availability of the questionnaire with an e-mail message. The e-mail message contained a unique user name and password that allowed each respondent to log on and fill out a questionnaire but did not allow respondents access to the questionnaires of others.

In the questionnaires, we asked the experts to agree or disagree with a set of statements about LNG hazards derived from GAO's synthesis of major LNG spill consequence studies. Prior to the first iteration, we had an LNG spill consequence expert who was not a part of the panel review each statement and provide comments about technical accuracy and tone. Experts were asked to indicate agreement on a 3-point scale (completely agree, generally agree, do not agree) and to provide comments about how the statements could be changed to better reflect their understanding of the consequences of LNG spills.

If most experts agreed with a statement during the first iteration, we did not include it in the second iteration. If there was not agreement, we used the experts' comments to revise the statements for the second iteration. The second iteration was posted on the Web site, using the same protocol as used for the first. Again, panel members were asked to agree or disagree and provide narrative comments. We revised the statements where there was disagreement and posted them on the Web site again for the third iteration. At the end of the third iteration, at least 75 percent of the experts agreed or generally agreed with most of the ideas presented.

Because some of the studies conducted are classified, this public version of our findings supplements a more comprehensive classified report produced under separate cover. We conducted our work from January 2006 through January 2007 in accordance with generally accepted government auditing standards.

Appendix II: Names and Affiliations of Members of GAO's Expert Panel on LNG Hazards

Myron Casada	ABS Consulting
T.Y. Chu	Sandia National Laboratories
Philip Cleaver	Advantica
Bob Corbin	U.S. Department of Energy
John Cornwell	Quest Consultants, Inc.
James Fay	Massachusetts Institute of Technology
Louis Gritzo	FM Global
Jerry Havens	University of Arkansas
Benedict Ho	BP
Greg Jackson	University of Maryland
Ron Koopman	Hazard Analysis Consulting
Bill Lehr	National Oceanic and Atmospheric Administration
Georges Melhem	ioMosaic Corporation
Gordon Milne	Lloyd's Register
Robin Pitblado	Det Norske Veritas
Phani Raj	Technology and Management Systems, Inc.
Velisa Vesovic	Imperial College
Harry West	Texas A&M University
John Woodward	Baker Engineering and Risk Consultants, Inc.

Appendix III: Summary of Expert Panel Results

For each question below, we show only those responses that were selected by at least one expert. The number of responses adds up to 19—the total number of experts on the panel. Percentages may not add to 100% due to rounding.

Introduction

Large LNG spills from a vessel could be caused by an accident, such as collision or grounding, or by an intentional attack. While large accidental LNG spills are highly unlikely given current LNG carrier designs and operational safety policies and practices, these spills do pose a hazard to the public if they occur in or near a populated area. **What is your level of agreement with this paragraph?** (Finalized in the second iteration.)

Count	Percentage	Label
8	42.11%	Completely agree
11	57.89%	Generally agree

LNG Hazards

Overall Hazards

LNG is a cryogenic liquid composed primarily of methane with low concentrations of heavier hydrocarbons, such as ethane, propane, and butane. LNG is colorless, odorless, and nontoxic. When LNG is spilled, it boils and forms LNG vapor (natural gas). The LNG vapor is initially denser than ambient air and visible; LNG vapor will stay close to the surface as it mixes with air and disperses. LNG and LNG vapor pose four possible hazards: freeze burns, asphyxiation, fire hazard, and explosions. **What is your level of agreement with this paragraph?** (Finalized in the second iteration.)

Count	Percentage	Label
5	26.32%	Completely agree
12	63.16%	Generally agree
2	10.53%	Do not agree

LNG Hazards-Freeze Burns

LNG poses a threat of freeze burns to people who come into contact with the liquid or with very cold LNG vapor. Since LNG boils immediately and vaporizes after it leaves an LNG tank and LNG vapor warms as it mixes with air, only people in close proximity to the release, such as personnel on the tanker or nearby escort vessels, might come into contact with LNG or LNG vapor while it is still cold enough to result in freeze burns. Freeze burns do not present a direct hazard to the public. **What is your level of agreement with this paragraph?** (Finalized in the second iteration.)

Count	Percentage	Label
14	73.68%	Completely agree
5	26.32%	Generally agree

LNG Hazards-Asphyxiation

After an LNG spill, LNG vapor forms a dense, visible vapor cloud that is initially heavier than air and remains close to the surface. The cloud warms as it mixes with air and as portions of the cloud reach ambient air temperatures, they begin to rise and disperse. Asphyxiation occurs when LNG vapor displaces oxygen in the air. Asphyxiation is a threat primarily to personnel on the LNG tanker or to people aboard vessels escorting the tanker at close range. An LNG vapor cloud could move away from the tanker as it mixes with air and begins to disperse. However, it is unlikely that the vapor cloud could reach a populated area while still sufficiently concentrated to pose an asphyxiation threat to the public. **What is your level of agreement with this paragraph?** (Finalized in the second iteration.)

Count	Percentage	Label
8	42.11%	Completely agree
10	52.63%	Generally agree
1	5.26%	Do not agree

LNG Hazards-Vapor Cloud: Wind Effect

The effect of wind on an LNG vapor cloud varies with wind speed. The most hazardous wind conditions, however, are low winds, which can push a vapor cloud downwind without accelerating the LNG vapor dispersion into the atmosphere. Low wind conditions have the highest potential of allowing an LNG vapor cloud to move a significant distance downwind.

What is your level of agreement with this paragraph? (Finalized in the third iteration.)

Count	Percentage	Label
8	42.11%	Completely agree
10	52.63%	Generally agree
1	5.26%	Do not agree

LNG Hazards-Fire Hazard

Because LNG vapor in an approximately 5 to 15 percent mixture with air is flammable, LNG vapor within this flammability range is likely to ignite if it encounters a sufficiently strong ignition source such as a cigarette lighter or strong static charge. **What is your level of agreement with this paragraph?** (Finalized in the third iteration.)

Count	Percentage	Label
13	68.42%	Completely agree
6	31.58%	Generally agree

LNG Hazards-Fire Hazard: Thermal Hazard End Point

The main hazard to the public from a pool fire is the thermal radiation, or heat, that is generated by the fire rather than the flames themselves. Often this heat is felt at considerable distance from the fire. Scientific papers have used two different thresholds as end points to describe the impact of thermal radiation on the public: 5 kilowatts per square meter and 1.6 kilowatts per square meter.
Which level do you think is the appropriate end point to use to define thermal hazard zones in order to protect the public? *(Please indicate your response, then provide an explanation in the textbox below your answer.)*

Count	Percentage	Label
8	42.11%	5 kilowatts per square meter
2	10.53%	1.6 kilowatts per square meter
6	31.58%	Other
3	15.79%	I do not have the expertise necessary to respond to this question.

Of the six experts who answered “other,” two experts indicated that $5kW/m^2$ is a useful or appropriate level for measuring the impact on people. One expert suggested that dosage (a measure that combines thermal radiation and duration of exposure) is most appropriate. Another expert suggested that both thresholds are appropriate, depending on the circumstances of the analysis. (Finalized in the first iteration.)

LNG Hazards-Fire Hazard: Pool Fire

A pool fire could form in the wake of a vapor cloud fire burning back to the source or just after an LNG spill, if there is immediate ignition of the LNG vapor. A pool fire burns the vapor above a liquid LNG pool as the liquid boils from the pool. A large, unconfined pool fire is very difficult to extinguish; generally almost all the LNG must be consumed before the fire goes out. **What is your level of agreement with this paragraph?** (Finalized in the second iteration.)

Count	Percentage	Label
13	68.42%	Completely agree
5	26.32%	Generally agree
1	5.26%	Do not agree

The main hazard to the public from a pool fire is the thermal radiation, or heat, from the fire. This heat can be felt at a considerable distance from the flames themselves. Numerous factors can impact the amount of thermal radiation that could affect the public: site-specific weather conditions, including humidity and wind speed and direction, the composition of the LNG, and the size of the fire. **What is your level of agreement with this paragraph?** (Finalized in the second iteration.)

Count	Percentage	Label
13	68.42%	Completely agree
6	31.58%	Generally agree

The wind speed and direction also affect the distance at which thermal radiation from the fire is felt by the public. In high winds, the flames will tilt downwind, increasing the amount of heat felt downwind of the fire and decreasing the amount of heat felt upwind. More humid conditions allow heat to be absorbed by the moisture in the air reducing the heat felt by the public. **What is your level of agreement with the above paragraph?** (Finalized in the second iteration.)

Count	Percentage	Label
6	31.58%	Completely agree
11	57.89%	Generally agree but suggest the following clarification.
2	10.53%	I do not have the expertise necessary to respond to this section.

The composition of the LNG can also affect the distance at which thermal radiation from the fire is felt by the public. In small fires, methane, which comprises between 84 percent and 97 percent of LNG, burns cleanly, with little smoke. Cleaner-burning LNG fires, particularly those burning LNG with higher methane content, result in higher levels of thermal radiation than oil or gasoline fires of the same size because the smoke generated by oil and gasoline fires acts as a shield, reducing the amount of thermal radiation emitted by the fire. While LNG composition can have a large impact on the thermal radiation from small LNG fires, as LNG fires get larger, these effects are hypothesized to be less pronounced. **What is your level of agreement with this paragraph?** (Finalized in the third iteration.)

Count	Percentage	Label
5	26.32%	Completely agree
10	52.63%	Generally agree
3	15.79%	Do not agree
1	5.26%	I do not have the expertise necessary to respond to this section.

The size of the fire has a major impact on the thermal radiation from an LNG pool fire. Thermal radiation increases with pool size up to a point but is expected to decrease for very large pools, like those caused by a terrorist attack. **What is your level of agreement with this paragraph?** (Finalized in the second iteration.)

Count	Percentage	Label
4	21.05%	Completely agree
10	52.63%	Generally agree
4	21.05%	Do not agree
1	5.26%	I do not have the expertise necessary to respond to this section.

LNG Hazards–Vapor Cloud Fire

If an LNG vapor cloud formed in the wake of an LNG spill and drifted away from the tanker as it warmed and dispersed, the vapor cloud could enter a populated area while areas of the cloud had LNG vapor/air mixtures within the flammability range. Since populated areas have numerous ignition sources, those portions of the cloud would likely ignite. The fire would then burn back through the cloud toward the tanker and continue to burn as a pool fire near the ship, assuming that liquid LNG still remains in the spill area. Ignition of a vapor cloud over a populated area could burn people and property in the immediate vicinity of the fire. While the initial fire would be of short duration as the flames burned back toward the LNG carrier, secondary fires could continue to present a hazard to the public. **What is your level of agreement with the above paragraph?** (Finalized in the second iteration.)

Count	Percentage	Label
7	36.84%	Completely agree
11	57.89%	Generally agree but suggest the following clarification
1	5.26%	Do not agree

LNG Hazards–Vapor Cloud Fire: Burn Back Speed

After ignition of a vapor cloud that drifted away from an LNG tanker spill, how fast could the flame front travel back toward the spill site if it was unconfined or confined? (Finalized in the second iteration.)

Count	Percentage	Label
15	78.95%	Not checked
2	10.53%	I do not have the expertise necessary to respond to this section.
2	10.53%	No answer

Experts did not agree on the speed of a flame front traveling through an LNG vapor cloud in either a confined or unconfined state. Responses varied from less than 5 meters per second up to 50 meters per second in unconfined settings and from 0 meters per second to 2,000 meters per second in confined settings.

Explosions-RPT

A rapid phase transition (RPT) can occur when LNG spilled onto water changes from liquid to gas virtually instantaneously due to the rapid absorption of ambient environmental heat. While the rapid expansion from a liquid to vapor state can cause locally large overpressures, an RPT does not involve combustion. RPTs have been observed during LNG test spills onto water. In some cases, the overpressures generated were strong enough to damage test equipment in the immediate vicinity. Overpressures generated from RPTs would be very unlikely to have a direct affect on the public. **What is your level of agreement with this paragraph?** (Finalized in the second iteration.)

Count	Percentage	Label
15	78.95%	Completely agree
4	21.05%	Generally agree

Explosions-Deflagrations and Detonations

Deflagrations and detonations are rapid combustion processes that move through an unburned fuel-air mixture. Deflagrations move at subsonic velocities and can result in overpressures up to eight times the original pressure, particularly in congested/confined areas. Detonations move at supersonic velocities and can result in overpressures up to 20 times the original pressure. **What is your level of agreement with this paragraph?** (Finalized in the third iteration.)

Count	Percentage	Label
1	5.26%	Not checked
7	36.84%	Completely agree
10	52.63%	Generally agree
1	5.26%	Do not agree

Explosions—Deflagrations, Detonations, and BLEVEs

Please choose the response that best describes your opinion about each type of explosion of LNG vapors in each setting described. (Finalized in the third iteration.)

Answer	Deflagration with overpressure in an unconfined setting	Deflagration with overpressure in a confined setting	Detonation in an unconfined setting	Detonation in a confined setting	Boiling-liquid-expanding-vapor-explosion (BLEVE)
Under controlled experimental conditions, it is possible to induce this type of explosion in this type of setting.	7	18	4	15	11
This type of setting cannot support this type of explosion.	8	0	11	2	7
More research is necessary to answer this question.	3	0	3	0	0
I don't have the expertise necessary to answer this question.	0	0	0	1	0
No answer/not checked	1	1	1	1	1

If experts answered that "under controlled experimental conditions, it is possible to induce this type of explosion in this type of setting," they were asked to answer the following question:

What is the likelihood of a each type of explosion of LNG vapors in each setting described occurring following an LNG spill caused by a terrorist attack on a tanker? (Finalized in the third iteration.)

Answer	Deflagration with overpressure in an unconfined setting	Deflagration with overpressure in a confined setting	Detonation in an unconfined setting	Detonation in a confined setting	Boiling-liquid-expanding-vapor-explosion (BLEVE)
Highly unlikely	3	6	1	7	4
Unlikely	2	2	3	3	2
Neither likely nor unlikely	1	5	0	3	3
Likely	1	4	0	2	1
Highly likely	0	0	0	0	0
No answer/ not checked	0	1	0	0	1

LNG Hazards–Is BLEVE the Worst?

A BLEVE is the worst potential hazard of an LNG spill. It would result in the rupture of one or more LNG tanks, perhaps simultaneously, on the ship, with potential rocketing debris and damaging pressure waves. **What is your level of agreement with the above paragraph?** (Finalized in the first iteration.)

Count	Percentage	Label
2	10.53%	Completely agree
16	84.21%	Do not agree (Please explain in the textbox below.)
1	5.26%	No answer

Questions About the 2004 Sandia National Laboratories Study[1]

The Sandia report concluded that the most significant impacts to public safety exist within 500 meters of a spill, with much lower impacts at distances beyond 1,600 meters even for very large spills. **Please choose the response that best describes your opinion about these hazard distances.** (Finalized in the third iteration.)

[1]Since two of the experts were authors of the Sandia study, their responses to ALL the questions related to the study below have been excluded. For the questions related to the Sandia study, there are 17 experts responding.

Count	Percentage	Label
4	23.54%	They are too conservative (i.e., should be smaller)
7	41.18%	They are about right
4	23.53%	They are not conservative enough (i.e., should be larger)
2	11.76%	No answer

The Sandia report concluded that large, unignited LNG vapor clouds could spread over distances greater than 1,600 meters from a spill. For a nominal intentional spill, the hazard range could extend to 2,500 meters. The actual hazard distances will depend on breach and spill size, site-specific conditions, and environmental conditions. **Please choose the response that best describes your opinion about these hazard distances**. (Finalized in the third iteration.)

Count	Percentage	Label
4	23.53%	They are too conservative (i.e., should be smaller)
6	35.29%	They are about right
4	23.53%	They are not conservative enough (i.e., should be larger)
1	5.88%	Do not have the expertise to answer
2	11.76%	No answer

The Sandia report concluded that cascading damage (multiple cargo tank failure) due to brittle fracture from exposure to cryogenic liquid or fire-induced damage to foam insulation is possible under certain conditions but is not likely to involve more than two or three cargo tanks for any single incident. **What is your level of agreement with this paragraph**? (Finalized in the third iteration.)

Count	Percentage	Label
3	17.65%	Completely agree
6	35.29%	Generally agree
6	35.29%	Do not agree
2	11.76%	I do not have the expertise necessary to respond to this section.

The Sandia report concluded that cascading events are not expected to greatly increase (not more than 20-30 percent) the overall fire size or hazard ranges (500 meters for severe impacts, much lower impacts beyond 1,600 meters) but will increase the expected fire duration. **What is your level of agreement with this paragraph?** (Finalized in the third iteration.)

Count	Percentage	Label
7	41.18%	Completely agree
5	29.41%	Generally agree
4	23.53%	Do not agree
1	5.88%	No answer

The Sandia report suggested that consequence studies 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. **What is your level of agreement with this paragraph?** (Finalized in the third iteration.)

Count	Percentage	Label
8	47.06%	Completely agree
8	47.06%	Generally agree
1	5.88%	Do not agree

Commodity Comparison

In your opinion, what is the risk to public safety posed by an attack on tankers carrying each of the following energy commodities? (Finalized in the first iteration.)

Answer	Liquefied natural gas	Crude oil	Diesel	Gasoline	Heating oil	Jet fuel	Liquefied petroleum gas
Little to None	1	2	1	0	1	1	0
Little	3	10	11	5	11	6	1
Medium	6	3	3	8	3	6	4

Answer	Liquefied natural gas	Crude oil	Diesel	Gasoline	Heating oil	Jet fuel	Liquefied petroleum gas
Large	3	0	0	2	0	2	5
Very Large	2	0	0	0	0	0	5
No expertise to answer	1	1	1	1	1	1	1
No answer	3	3	3	3	3	3	3

Future Research

In the first and second survey iterations, you noted areas related to LNG spill consequences that need further research. We are interested in your thoughts on the relative level of need for research in these areas, and also the five areas you think should be of highest priority in future research.

Please indicate the degree to which further research is needed in each of the areas listed below. (Finalized in the third iteration.)

Responses to each part of this question are in the table below, which is sorted by mean score so that the highest-ranked research priorities appear first.

Type of research	Very great need (1)	Great need (2)	Moderate need (3)	Some need (4)	Little to no need (5)	Do not have the expertise to answer (6)	No answer (7)	Mean score
Large fire phenomena (impact of smoke shielding, large flame versus smaller flamelets)	9	5	3	0	1	1	0	4.17
Cascading failure	5	9	4	1	0	0	0	3.95
Large-scale LNG spill testing on water[a]	7	7	2	1	2	0	0	3.84
Large-scale fire testing[b]	7	6	3	2	1	0	0	3.84
Comprehensive modeling allowing different physical processes to interact	2	10	3	4	0	0	0	3.53
Risk tolerability assessments	5	4	3	1	3	1	2	3.44

Type of research	Very great need (1)	Great need (2)	Moderate need (3)	Some need (4)	Little to no need (5)	Do not have the expertise to answer (6)	No answer (7)	Mean score
Vulnerability of LNG containment systems, including validating hole size predictions for the double hull ship structure	5	4	3	5	2	0	0	3.26
Mitigation techniques	3	5	6	3	2	0	0	3.21
Effect of sea water pouring into a hole as LNG flows out	2	6	5	3	2	0	1	3.17
Impact of wind, weather, and waves (on pool spread size, evaporation rate, pool formation, etc.)	3	4	6	3	3	0	0	3.05
Improvements to 3-D computational fluid dynamics dispersion modeling	0	4	6	6	2	1	0	2.67
Effects of different LNG compositions (on vaporization rates, thermal radiation, explosive behavior, etc.)	2	2	4	8	3	0	0	2.58
Whether an explosive attack will result in immediate vapor cloud ignition	0	5	4	5	4	1	0	2.56
Rapid phase transitions: likelihood in various scenarios and impact	1	2	6	6	4	0	0	2.47
Effects of igniting LNG vapors in containment or ballast tanks	0	5	3	5	6	0	0	2.37
BLEVE properties of tanks on LNG ships	1	4	3	4	7	0	0	2.37
Deflagration/detonation of LNG	1	0	5	8	5	0	0	2.16
Effects of a large, unignited vapor cloud drifting from the incident site	0	0	7	5	7	0	0	2.00

Type of research	Very great need (1)	Great need (2)	Moderate need (3)	Some need (4)	Little to no need (5)	Do not have the expertise to answer (6)	No answer (7)	Mean score
Effect of clothing and obstructions on the radiant heat level received by the public	1	1	2	6	9	0	0	1.89
Other[c]	12	2	0	0	0	0	5	[d]

[a]Experts suggested pool sizes of 15 meters up to 1,000 meters, though the median response was 100 meters.

[b]Experts suggested pool sizes of 15 meters up to 1,000 meters, though the median response was 100 meters.

[c]Experts suggested frequency modeling, determination of acceptable risk to society, analysis of foam on LNG tankers, risk analysis for larger LNG tankers, CFD modeling for pool spreading and evaporation, and improvement to existing techniques used for fighting LNG fires.

[d]Not applicable.

Appendix IV: GAO Contact and Staff Acknowledgments

GAO Contact

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Staff Acknowledgments

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