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LNG PROPERTIES AND OVERVIEW OF HAZARDS

Liquefied natural gas (LNG) is simply a convenient form of natural gas, a cryogenic liquid condensed in volume to make storage and shipping economically feasible. Natural gas consists primarily of methane with smaller amounts of other light hydrocarbons such as ethane, propane, and butane. Natural gas occurs naturally throughout the world and has long been captured and transported to residences and industries by pipeline. Some large pipelines deliver natural gas along the ocean bottom from offshore wells and across continents.

But there are a number of large natural gas fields too remote from consumers for economic transport by pipelines. Liquefying natural gas provides an economical way to extend pipeline networks from gas fields to consumers almost anywhere in the world.

The primary uses of LNG are

- transporting natural gas by ocean transport to a market pipeline terminal;
- transporting natural gas by truck to local distribution systems (e.g., in China and in the United States);
- peak shaving storage at distribution points along natural gas pipelines; and
- power generation or home use with vaporized LNG—as natural gas.

LNG is made at a liquefaction plant and is restored to a gas at a regasification plant. Thus, the possibility of contact between LNG and the public is typically

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LNG Risk Based Safety: Modeling and Consequence Analysis, by John L. Woodward and Robin M. Pitblado

very limited except in the immediate vicinity of the plant. Truck transport of LNG provides an exception to this generalization.

In a liquefaction plant, there are several steps. The main steps, starting at the natural gas feed, include CO_2 removal, dehydration and mercury removal, initial chilling, liquefaction (including heavier hydrocarbon fractionation), nitrogen rejection, and, finally, product LNG storage. Dehydration is usually achieved by molecular sieves, and mercury removal (which is necessary to avoid subsequent aluminum corrosion) is achieved either with mole sieves or with sulfur-impregnated carbon or alumina. Chilling and liquefaction is achieved with large multistage centrifugal compressors and expanders combined with cold boxes of complex internal design. Hydrocarbon fractionation is achieved with standard distillation columns—often in the sequence deethanizer, depropanizer, and debutanizer depending on the inlet gas concentration). Nitrogen removal can be achieved in several flash stages or by stripping and reboiling. The overall heat exchange is very important, and heat transfer optimization using pinch technology approaches is now common.

A regasification plant is inherently endothermic (absorbs energy) since the LNG must be warmed to the temperature and pressure of the delivery pipeline. Since it is much more efficient to pump a liquid than to compress a gas, the LNG is pumped to pipeline pressure and then vaporized. The heat for vaporization can be provided by circulating seawater and air fin/fans or by burning part of the natural gas in heaters submersed in a water bath around LNG tubes. Again, there is inefficiency to this process, meaning some energy or, equivalently, some LNG is used for pumping and heating.

1.1 LNG PROPERTIES

The properties of LNG vary with composition, which depends on the location of the original gas as shown in Table 1.1 (U.S. Department of Energy [DOE], 2008). The original natural gas may contain many other materials including water vapor, carbon dioxide, nitrogen, and helium, some of which must be removed for liquefaction. The lightest composition is from Trinidad, which in 2005 accounted for 80% of the LNG imports to the United States. LNG with higher proportions of hydrocarbons with two and more carbon atoms is termed "rich" LNG because it has a higher specific heat of combustion than "lean" (Trinidad) LNG. The largest amount of LNG imported in 2005 was 58.6 million tons to Japan, or 30% of the world trade in LNG. A large portion of imports to Japan, as well as to South Korea and Taiwan, have been from Indonesia and the Middle East.

The critical point of methane is 190.4 K, meaning methane cannot be liquefied by pressure alone at ambient temperature. Rather, it must be cooled to liquefy. At atmospheric pressure, it must be cooled to the boiling point in Table 1.2. This is quite different from liquefied petroleum gas (LPG, largely

Table 1.1 Typical hydrocarbon composition of LNG from various locations

Component	Mole %, Source Location			
	Trinidad	Algeria[a]	Nigeria	Oman
Methane (C_1H_4)	96.9	87.93	91.692	87.876
Ethane (C_2H_6)	2.7	7.73	4.605	7.515
Propane (C_3H_8)	0.3	2.51	2.402	3.006
iso-Butane	0.1	0.50	1.301	1.603
n-Butane (C_4H_{10})	—	0.72	—	—
C5+	—	0.61	—	—
Total	100.0	100.00	100.00	100.00

[a] Skidka composition after removing nitrogen and helium.

Table 1.2 Some properties of LNG

Property	Methane	Trinidad	Nigeria	Oman	Algeria	Gasoline
Molecular weight	16.043	16.55	17.91	18.615	18.77	100–110
Boiling point, K (°C) (bubble point)	111.67 (–161.5)	112.1 (–161.05)	112.7 (–160.4)	113.3 (–159.9)	113.25 (–159.9)	321.1 (48.0)
Liquid density (kg/m^3 at boiling point)	422.5	430.9	452.8	463.6	452.9	627.3
Vapor density (kg/m^3 at boiling point)	1.810	1.799	1.776	1.763	1.783	2.927
Vapor density (kg/m^3 at 20°C)	0.6685	0.6894	0.7459	0.7751	0.7829	3.114
Temperature at liftoff, K (293 K air)	170.1	175.1	185.9	192.4	199.0	>Ambient
Heat of combustion (higher, MJ/kg)	50.04	49.86	49.43	49.24	49.20	44.75
Carbon footprint (g CO_2/MJ)	54.8	55.3	56.3	56.8	56.9	68.4
Flammable range for vapor (mole %)	5–15	4.9–14.9	4.6–14.6	4.4–14.4	4.4–14.4	1.1–7.6
Vapor reactivity classification for explosions	Low	Low	Low	Low	Low	Medium

propane and butane) that is liquefied at ambient temperature with several bars of pressure. The safety and environmental implications of the properties of LNG are illustrated in Table 1.3.

1.2 HAZARDS OF LNG WITH RESPECT TO PUBLIC RISK

The sources of LNG hazards occur by

- liquid leaks under pressure (pump and pipe leaks),
- liquid leaks from storage tanks (the head pressure is usually atmospheric),
- rollover of an LNG storage tank,
- liquid pools evaporating to form a flammable vapor plume, and
- liquid leaks injected into water under pressure or from a moderately high elevation giving rise to a rapid phase transition (RPT) explosion.

Leaks under pressure are hazards inside processing plants (liquefaction or regasification) and from LNG transfers from storage to carriers and vice versa.

Liquid leaks can occur from land-based storage tanks and from LNG carriers. Penetrations can occur by ship collision, allision (striking a fixed object), or grounding. Corrosion is a lower-risk cause of leaks since LNG typically has low corrosivity to materials used for its handling.

An accidental release of LNG can pose the following hazards:

- radiation burns and structural weakening from flash fire, pool fire, or jet fire;
- overpressure and impulse from partially confined vapor cloud explosion;
- overpressure and impulse from confined vapor cloud explosion;
- rapid spreading, evaporation, and possibly overpressures from an RPT explosion;
- asphyxiation;
- freeze burns; and
- rollover

These events usually occur in a sequence as illustrated in Figure 1.1 (Pitblado et al., 2006). The event sequence is in chronological order from the leak to pool formation with evaporation to form a vapor cloud, vapor cloud dispersion, delayed ignition, then burn back as a flash fire to a pool fire. Modeling of these events is treated in detail in Chapters 5, 7, 8, 9, and 10. The event consequences are briefly introduced below.

Table 1.3 Safety and environmental implications of LNG properties

Property	Consequence
LNG is a cryogenic liquid.	Direct contact with skin causes freezer burns. Exposure of sufficient duration can embrittle carbon steel.
LNG evaporates completely and cleanly without a residue.	An LNG spill leaves minimal environmental impact (freezing effects only).
LNG evaporates rapidly from ground or water contact.	Vapor plume is the main hazard from spills. It can ignite, then fire is the main hazard.
The liquid density of LNG is low, less than half of that of water.	LNG tankers float high in the water. A large tank of LNG, say 30 m high, would have a liquid head of around 1.3 atmospheres. This is a comparatively low pressure to pump against.
The expansion factor in going from liquid at the boiling point to vapor at standard ambient temperature is around 600 (594–625).	This density difference provides for the economical transport and storage of natural gas as a liquid.
The molecular weight of natural gas is less than that of air (specific gravity of 0.60–0.68).	The low molecular weight of LNG vapor makes it lighter than air at ambient temperature. Natural gas rises and poses a lower threat than most hydrocarbon vapors, including gasoline, that are heavier than air.
A boiling pool produces cold vapors (at the normal boiling point).	LNG vapors at their boiling point are significantly heavier than air, by about a factor of 1.5.
Water condensation in plume creates a visible cloud.	Visibility helps in taking avoidance and escape measures.
The LFL (Lower Flammable Limit) concentration is always within the visible cloud for relative humidity above 55%.	Photographs of LNG visible plumes are useful approximations of the flammable cloud.
LNG vapors will quite quickly warm to ambient temperatures by conduction and/or by dilution with air.	By air mixing alone, the specific gravity of an evaporated LNG vapor plume approaches unity asymptotically from above by temperature warming and from below by increasing molecular weight.
LNG vapors will ultimately warm enough to become buoyant and lift off, reducing the chance of ignition.	Temperature and molecular weight have opposite effects on the vapor-specific gravity. The molecular weight effect always drives an ultimate specific gravity less than 1.0. As warming occurs by dilution and conduction, then a vapor plume from an LNG spill is likely to rise (lift off) at some point downwind of the spill.
LNG has slightly higher energy density than gasoline (10–11% higher)	LNG develops relatively high flame temperatures for small fires that are not oxygen starved.

Table 1.3 *Continued*

Property	Consequence
LNG has a strong advantage over burning liquid hydrocarbons or coal in generating less CO_2 per unit of energy (81–83% as much).	LNG is preferred over liquid hydrocarbons or coal for environmental impact.
LNG liquid does not burn or explode.	As for all hydrocarbon liquids, only the vapor above the liquid burns and can explode if sufficiently confined or congested.
The vapor above LNG must mix with air to below 15% and above 5% of natural gas concentration to be flammable.	Much of the vapor cloud above an LNG spill is not in the flammable range. Only a fraction of the plume will ignite.
Methane and light composition natural gas have a relatively high lower flammability limit (LFL, 5% compared to 1% for gasoline or 0.7% for crude oil).	An LNG vapor plume contour to the LFL does not cover as large an area as an otherwise equivalent gasoline spill.
The burn rate of an LNG pool fire on land is "above the curve" for other paraffin hydrocarbons.	The higher burn rate contributes to a tall fire of shorter duration, than a corresponding amount of higher-chain hydrocarbon.
LNG pool fires produce relatively little smoke	Bright nonsmoky flames generate higher emitted radiation, and thus LNG fires radiate more heat than heavier hydrocarbons. Larger pool fires produce more smoke, so the emissive power drops off with pool size, and this is believed true for the largest LNG pool fires as well.
Applying dry chemical powder is the only way to extinguish an LNG fire. The fire will continue until all the fuel is burned.	Water will not extinguish an LNG fire. Preinstalled fire fighting foams may slow the fire. However, extinguishment does not stop liquid boiloff and hence vapor cloud formation; thus, controlled burning can be safer than extinguishment. Complete burning avoids late ignition flash fire.
LNG spills at a regasification terminal are directed to a sump, so ignition results in a pool fire at a safe location.	The terminal design can provide adequate insulation of nearby structures. Water spray systems are being evaluated to reduce radiant energy at important locations from a sump pool fire.
Unconfined or partially confined LNG vapor/air mixtures do not detonate (form a sonic velocity explosion that self-propagates as discussed later).	Considerable congestion and/or a high-energy ignition source is required to explode as a deflagration (a subsonic explosion that decays upon burning outside of a high-congestion zone).
LNG vapor has low reactivity for explosion propagation.	The flame speed of a natural gas deflagration is lower than other hydrocarbons because of its low reactivity.

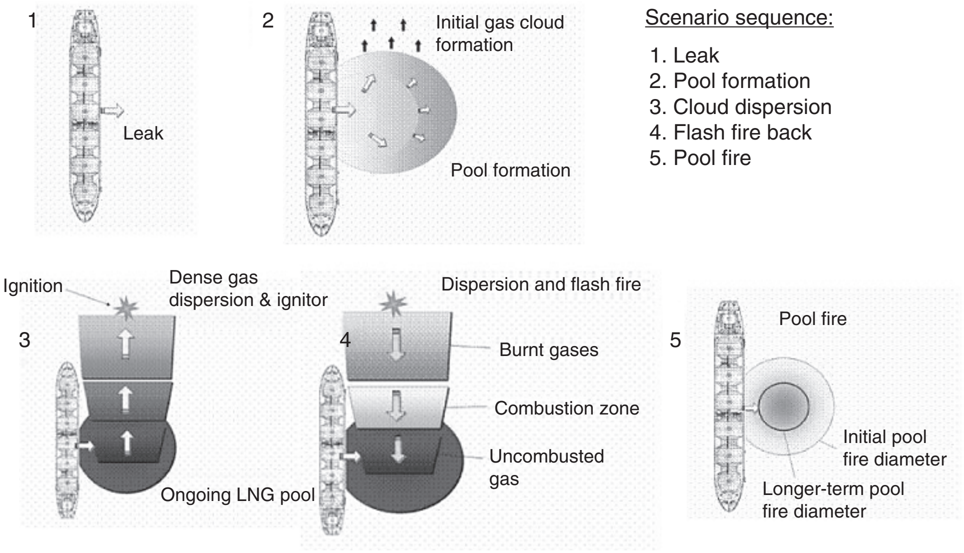

Figure 1.1 Scenario sequence for leak of LNG at sea (Pitblado et al., 2006) (reproduced by permission from Elsevier Science Publishers).

1.2.1 Flash Fire, Pool Fire, or Jet Fire

The main threat from LNG spills is a fire. Indeed, risk analyses for LNG primarily focus on the hazard of a pool fire. A jet fire requires a pressurized release that can occur in process plants but is not typically a threat to the public.

An LNG spill on land or on water would result in a rapidly evaporating pool that produces a vapor cloud driven by the wind. If any point of a vapor cloud (with dimension defined to flammable concentrations) reaches an ignition source and ignites, a flash fire would burn downwind and possibly also upwind from the ignition point. A flash fire will burn faster along the premixed (diluted by air) edges. This can create a more enveloping fire as illustrated in Chapter 10.

A flash fire is inherently transient, and exposure normally lasts no more than a few tens of seconds. While fatal to people inside the fire, the total radiation reaching an object near a flash fire is substantially lower than that from a longer-lasting pool or jet fire the same distance away. A flash fire likely does not produce secondary ignition or burns to people outside of the flaming region.

After a flash fire burns back to the LNG pool, or if ignition begins at the pool, the result is a pool fire. An example is seen in Figure 1.2 (Sandia, 2009). Figure 1.2 is a bright fire with no smoke. Larger fires on land (e.g., 35-m diameter) become oxygen limited and smoky. Larger fires on water are expected

Figure 1.2 Example of a large 23-m diameter LNG pool fire on water (Sandia, 2009).

to exhibit similar smokiness, and Sandia is carrying out larger scale experiments than in the figure in 2009 to confirm this. While the LNG outflow continues, an unconfined burning LNG pool tends to either increase or decrease in size toward achieving a final steady-state size. This is the size for which the burn-off rate equals the discharge rate. The steady-state pool size is smaller for a burning pool than for a nonburning pool. So, if ignition is not immediately after a spill begins, the burning pool will retreat significantly compared to its original size.

Jet fires and pool fires are treated in detail in Chapter 9. Flash fire and fire balls or boiling liquid expanding vapor explosions (BLEVEs) are discussed in Chapter 10.

1.2.2 Outdoor Vapor Cloud Explosions

Experiments have confirmed that an outdoor vapor cloud explodes only under conditions of partial confinement and/or in congested regions. Congested regions are defined by a high density of obstacles such as piping, pumps, and other such equipment. Congested regions can be found in LNG liquefaction plants and terminals. LNG spills at sea, even if caused by colliding ships, are not in a confined or congested environment. The upper decks of modern LNG vessels may offer limited congestion with reliquefaction equipment, but this will be well above any dense cloud on the sea surface. LNG spills from a docked tanker can occur beside the side of a tanker, but this is considered a 3-D expansion zone and congestion is limited to the presence of posts supporting the dock. Another factor that mitigates against a possible outdoor explosion of LNG vapors is the low reactivity of natural gas. Detonation explosions are virtually ruled out by low reactivity. A deflagration explosion from an outdoor spill of LNG in an LNG terminal is a low probability event.

1.2.3 Enclosed Vapor Cloud Explosions

Explosions occur with noticeable frequency from a buildup of natural gas vapors indoors or inside any enclosed space. Commonly, such explosions result from leaking natural gas lines in a building. LNG is held at a temperature within a few degrees of the normal boiling point. The atmosphere inside an LNG storage tank, truck, or marine carrier is 100% boil-off vapor with no oxygen content. Even a worst case vacuum breaker valve opening would not allow sufficient air ingress for the vapor space to become flammable.

Vapor from a passing LNG cloud could leak into or be induced into a building. LNG delivery lines at regasification or liquefaction plants are not allowed inside buildings. Air intakes into buildings are usually elevated above most LNG dense vapor clouds, and the circumstances for vapor induction into a building are rare. For these reasons, a confined LNG vapor cloud explosion is a very unlikely threat. Chapter 10 further discusses unconfined LNG explosions and vapor intrusion into buildings.

1.2.4 Asphyxiation

For asphyxiation, the LNG vapors must dilute the oxygen concentration in the breathing zone of people below 15% oxygen for impaired behavior, below 10% for nausea and vomiting, or below 6% oxygen for death. The concentration of LNG vapor required to reach these end points is 28.2%, 52.2%, and 71.3%, respectively, and the higher concentrations would also be associated with freeze burns. These concentrations exist only near the spill for an outdoor release. The normal variations in the wind direction and evasive measures by any individual so near a vapor plume make it very unlikely that asphyxiation will occur outdoors. The public is extremely unlikely to be near the point where LNG vapor concentrations are above 28.2%.

A spill into an occupied confined space is also very unlikely because of industrial safety practices regarding confined space entry. These rules require the presence of a second person, the use of a rescue harness, air testing, and such precautions that mitigate any potential for an asphyxiation event, and the presence of LNG operations make it even less likely that confined space work would be ordered.

1.2.5 Freeze Burns

A single incident occurred in which LNG accidentally leaked under pressure near enough to a person to cause a freezer burn. This was in 1977 at Arzew, Algeria during a ship-loading operation when a large-diameter valve ruptured and the worker was sprayed with part of 1500–2000 m^3 released LNG

(CHIV, 2003). The valve was made of aluminum. Current practice requires valves to be made of stainless steel. This is a recognized hazard for industrial workers, but not for the public. Further details of asphyxiation and freeze burns are discussed in Chapter 10.

1.2.6 RPT Explosions

An RPT explosion is a physical explosion and is due to the sudden boiling or phase change from liquid to vapor that has occurred upon occasion when LNG is spilled onto water, usually in a way that the LNG penetrates into and mixes well with water. No injuries have occurred from an RPT of LNG, but equipment has been damaged. The overpressures developed by an RPT have not been measured well enough yet, but observations indicate that the overpressures have not been high enough to cause personnel injury. RPTs are discussed in Chapter 7 and are included in issues that require further research in Chapter 12.

1.2.7 Roll Over

Early in the development of LNG, the importance of mixing LNG stored in tanks was not realized. It is now understood that LNG tanks can stratify upon standing. The bottom layers always exist under the pressure of hydraulic head and can, therefore, be at pressure equilibrium at a temperature quite a few degrees higher than the top layers. Since liquid density of the upper layer can increase over time due to boiloff of methane increasing the percentage of heavier components, at some point the layers can invert. This would bring the lower layer to the surface, and without the hydrostatic pressure above it, a small fraction would immediately flash. Since the expansion ratio of liquid to vapor is 600:1, even a small flash can generate a large volume of gas. The sudden increase in tank pressure can exceed the capacity of pressure relief valves that are designed for fire exposure and threaten roof or even wall failure. This is primarily a hazard to personnel at an LNG export or import terminal, although a complete tank failure would be a large event that could extend beyond plant boundaries. Rollover is treated in Chapter 6.

1.3 RISK ANALYSIS REQUIRES ADEQUATE MODELING

Experience with transporting and using LNG so far has been highly favorable, as is discussed in Chapter 2. No incidents, such as groundings or ship collisions, have resulted in spills of LNG cargo. Following the terrorist attacks of September 11, 2001, however, experts recognized that an attack on an LNG carrier could result in a large spill, that is, a volume up to 100 times greater than studied in past experiments. Because a major LNG spill has never occurred, studies evaluating LNG hazards must rely on computer models to predict the effects of potential accidents and attacks. This approach sometimes requires extrapolation of experiments into the range where the underlying mechanisms may change.

An example is discussed in Chapter 9 concerning the extrapolation of the flame height from pool fires. Pool fire experiments so far have ranged to pool diameters up to 35 m for LNG on land. The resulting flame for small LNG fires is usually bright, indicating that adequate air reaches the burning fuel. Large pool fires, though, become smoky, indicating the onset of oxygen-limited burning. Extrapolating to LNG pools of possibly 100+ m diameter poses the question of whether the fire will break up into smaller segments, fed by cells of alternating updraft and downdraft. If so, the flame height might be much shorter than extrapolations for a single united flame indicate. A shorter flame height would decrease the exposure angle for radiation flux and would produce a much lower radiation hazardous zone than is predicted from a single, very high (up to 350 m high) flame.

Other examples of the limitations inherent in projecting beyond our current testing experience are covered in this book. Errors in overpredicting catastrophic effects can be as costly to the public's best interest as can errors in underprediction. The objectives of this book are to clearly state what test data establish, what models predict, and what uncertainties remain.

1.4 FLAMMABILITY

Pure methane has flammability limits of 5–15% (volume or mole) in air, but as LNG is composed of multiple light-ends including noncombustible nitrogen, its actual flammable range can vary somewhat from the range quoted for pure methane. The ignition likelihood is also affected by the ignition energy as shown in Figure 1.3 from Zabetakis (1965). While this might imply narrower flammability limits, in practice, many common ignition sources found in LNG terminals and in surrounding urban or suburban locations can be strong ignition sources such as fired heaters, open flames, or motor vehicles. Even area classification rules (e.g., API 500, IP 15) include a probability aspect and weak ignition sources can be sited at normally nonflammable locations (Class 1, Division 2), which could be reached by a rare major spill. Strong ignition sources can be located beyond the Class 1, Division 2 zone.

Typical flammable limit ranges for common LNG components are readily available from many sources (Lees, *SFPE Handbook*, etc.), and these are shown in Table 1.4.

Rules are available in these references for estimating the flammable concentrations of mixtures. Smaller LNG spills will flash off sufficiently quickly that the cloud concentration will be close to that of the total LNG composition. However, large spills of LNG will boil off progressively with the lighter ends preferentially boiling first followed by heavier materials. Large spills may take many minutes to hours to entirely boil off and significant

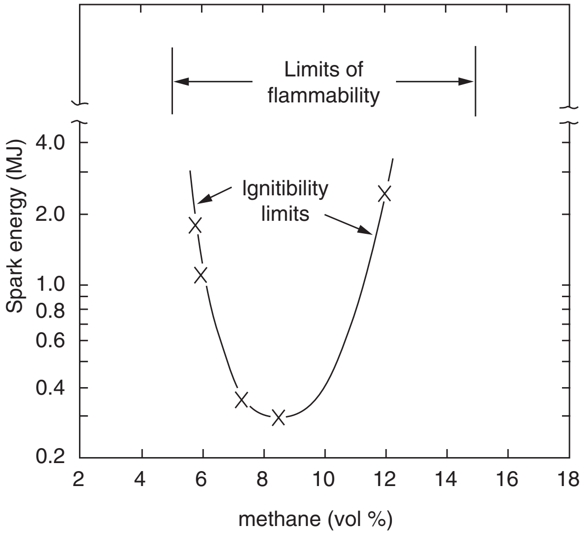

Figure 1.3 Flammable limits and ignition energies for methane (Zabetakis, 1965).

Table 1.4 Flammable limits for common LNG components

Material	Specific Gravity (Air = 1)	Lower Flammable Limit (Vol %)	Upper Flammable Limit (Vol %)
Methane	0.55	5.0	15.0
Ethane	1.04	3.0	12.4
Propane	1.52	2.1	9.5
n-Butane	2.01	1.8	8.4

concentration variations would be expected with time. The earliest boiloff will tend to be at the highest rate on land (as the LNG has not yet fully cooled the soil beneath) and concentration will be richer in methane; thus, the largest cloud distance will be methane rich, and the conventional 5–15% flammability range is the most relevant, even if a subsequent boiloff may have heavier components that might reduce the lower flammable limits. Spills on the sea typically do not reduce in boil-off rate as the cool-down effect on land does not occur on sea, as chilled seawater sinks and is replaced by fresh warm seawater, but lighter ends will still preferentially boil sooner. Further details are in Section 7.2.6.

The initial flash will primarily be pure methane. Reid (1980) provides a graph showing the evaporation sequence ("trajectory") for a mixture of 85% methane, 10% ethane, and 5% propane in Figure 1.4. While the graph shows the residual liquid concentration, the vapor concentration can be inferred by the straight line decline at uniform ethane–propane residual concentration in

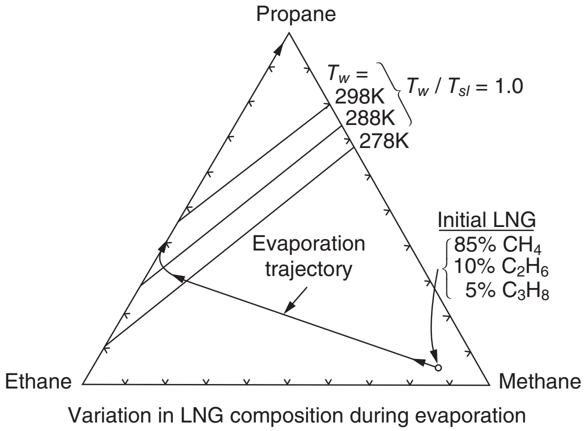

Figure 1.4 LNG boil-off sequence showing residual liquid concentration (Reid, 1983) (reproduced by permission of Elsevier Science Publishers).

the liquid that the boiloff is essentially pure methane until almost all the methane is evaporated. The authors have confirmed the initial boiloff is essentially 100% methane using the PHAST consequence model.

1.5 REGULATIONS IN SITING ONSHORE LNG IMPORT TERMINALS

Regulations in the United States, Europe, and Asia establish separation distances based on consequence analysis or risk assessment and other requirements for LNG import terminals, as summarily covered below. These regulations affecting risk analysis are covered in Chapter 6.

1.5.1 U.S. Marine LNG Risk and Security Regulation

The United States Coast Guard (USCG) is the lead federal agency for maritime security in the United States. It derives its risk and security responsibilities under the Ports and Waterways Safety Act of 1972 (P.L. 92-340) and the Maritime Security Act of 2002 (P.L. 107-295). Under the latter act, the USCG also has siting approval authority for offshore LNG terminals. USCG regulations cover waterways, the jetty, and the pipework up to the first valve at the receiving storage tank.

The USCG determines the suitability of waterways to transport LNG safely and requires a waterway suitability assessment (WSA) for operations on proposed waterways. The WSA describes the LNG carrier escort plans, local emergency response capabilities, ship speed limits, and the like. The USCG requires operations and emergency manuals be submitted for each port where ships will operate. It creates safety rules for specific ports to minimize the chance for accidents (IELE, 2003b).

"The most heavily secured LNG shipments are those bound for the Everett terminal because they pass through Boston harbor" (Parfomak, 2004). For these shipments, the USCG has had numerous security provisions, including (Greenway, 2003)

- inspecting tanker loading at the port of origin for Trinidad shipments;
- occasional on-board escort by Coast Guard "sea marshalls";
- advanced notice of arrival of an LNG tanker by 96 hours;
- advanced notification of local police, fire, and emergency agencies as well as the Federal Aviation Administration and the U.S. Navy;
- boarding of LNG tankers for inspection prior to entering Boston harbor;
- harbor escort by armed patrol boats;
- enforcement of a security zone closed to other vessels two miles ahead and one mile to each side of an LNG tanker;
- suspension of overflights by commercial aircraft; and
- additional security measures that cannot be disclosed publicly.

Parfomak (2004) cites the USCG saying that many of these security provisions are in place for other U.S. LNG terminals as well and would likely be put in place for new on-shore LNG terminals.

On October 22, 2003, the USCG issued final rules for security requirements mandated by P.L. 107-925 in Title 33 of the *Code of Federal Regulations*, Chapter 1, Subchapter H. "The rules require certain owners or operators of marine assets to designate security officers, perform security assessments, develop and implement security plans, and comply with maritime security alert levels" (ibid.).

1.5.2 U.S. Land-Based LNG Risk and Security Regulation

Federal Energy Regulatory Commission (FERC) Oversight The U.S. FERC is responsible for permitting new land-based LNG import terminals and for ensuring safe operation through subsequent inspections (18 CFR 157, 49-CFR-193). FERC requirements include security cameras, hazard detectors, and zones to protect residents and businesses surrounding an LNG terminal from

1. thermal radiation from a fire in the LNG impoundment area that holds any LNG accidentally leaked from the carrier unloading lines or the LNG storage tank and
2. flammable vapors from the LNG impoundment area that could ignite beyond the LNG terminal boundaries.

The FERC derives its siting authority under the Natural Gas Act of 1938 (15 USC 717). It has jurisdiction over all existing LNG marine terminals in the United States and, in 2004, over 15 peak shaving plants involved in interstate gas trade (Parfomak, 2004).

To meet these objectives, the FERC regulations cite the National Fire Protection Association (NFPA) standard NFPA 59a and establish a thermal radiation exclusion distance and a vapor cloud exclusion distance. These distances, from the impoundment area to the nearest fence line, establish the required minimum area for an LNG import terminal in the United States.

Federal Pipeline Safety and Security Agencies The Office of Pipeline Safety (OPS) within the Department of Transportation has authority to regulate the safety and security of LNG peak shaving plants under the Natural Gas Pipeline Safety Act of 1968 (P.L. 90-481). The OPS regulations for peak shaving plants are found in 49 CFR 193, *Liquefied Natural Gas Facilities: Federal Safety Standards* (Subpart J—Security). The OPS regulations govern protective enclosures, communications, monitoring, lighting, power sources, warning signs, and security procedures.

Transportation Security Administration (TSA) The Pipeline Branch of the TSA is the lead U.S. federal authority for the security of the interstate gas pipeline network under the Natural Gas Pipeline Safety Act of 1968 (P.L. 90-481). This security authority was transferred to TSA from the Transportation Department's OPS under the Aviation and Transportation Security Act of 2001 (P.L. 107-71). The TSA has visited the largest pipeline operators including some with LNG plants to review their security plans based on the OPS/industry guidance circulated in 2002. However, TSA does not plan to inspect all plants because all land-based LNG plants may not be considered "nationally critical" (Parfomak, 2004).

1.5.3 European and International Regulations

The European Standard EN 1473 (2005) stipulates the requirements for the design, construction and operation of on-shore LNG facilities. Unlike the U.S. regulations and standards, which are prescriptive, the EN 1473 regulation is based on a different philosophy. It requires a risk analysis to satisfy an acceptable level of risk for "for life and property outside and inside the plant boundaries." This approach requires hazard assessment, consequence assessment, and assessment of frequencies of occurrence for events from small to large releases of LNG. This approach allows consideration of mitigation factors to reduce the magnitudes or frequency of potential events. That is, the analyst is allowed consideration of topography, shielding by trees and buildings, full or partial holdup of dispersion of vapors, thermal radiation absorption in the atmosphere, and the probability of early or late ignition.

The International Maritime Organization (IMO) followed the USCG in developing maritime security standards outside U.S. jurisdiction. These standards, the International Ship and Port Facility Security (ISPS) Code, contain detailed mandatory security requirements for shipping companies, port authorities, and governments. The code is intended to provide a standardized, consistent framework for governments to evaluate risk and "offset changes in threat with changes in vulnerability" (IMO, 2002).

1.6 REGULATION FOR SITING OFFSHORE LNG IMPORT TERMINALS

In 2004, four U.S. offshore terminals were being considered: three in the Gulf of Mexico and one offshore of Oxnard, California (Parfomak, 2004). These would be connected to land only by underwater pipelines. According to one report, they may need to overcome technical challenges with their floating designs (Shook, 2003).

The USCG reviews applications for offshore LNG import terminals, which must provide risk analysis, vapor dispersion modeling, and fire radiation exclusion zones. Further discussion is in Section 6.9 of Chapter 6.

1.7 CONTROVERSIAL CLAIMS OF LNG OPPONENTS

A number of claims made by opponents of LNG import terminals cite obsolete studies or are unsubstantiated by reliable data and facts. Some claims found on Internet websites in 2009 are listed in Table 1.5 and are compared with current substantiated technical material.

Table 1.5 Current public claims of LNG hazards vs. substantiated information

Claim	Current Substantiated Information
Claim #1. An LNG vapor cloud will be 127 mi long from an attack on an LNG carrier (Riley website and the film *The Risks and Danger of LNG*)	Obsolete models made erroneous predictions early in the history of LNG risk analysis. The errors include using an incorrect end point for the flammable limits, using incorrect air entrainment modeling, and using passive dispersion models. Subsequently, better models have been developed using information from large-scale LNG spill experiments. Modern models have "converged" and now provide much more consistent predictions as discussed in Chapter 8. The Sandia report (Hightower et al., 2004) predicts the maximum distance for an unignited LNG cloud to be 2500 m (1.55 mi). For a fire radiation of 5 kW/m^2, maximum distances are 500–1600 m (0.31–1.0 mi) (see also FERC-ABS Consulting, 2004, ABS, 2004).
Claim #2. Each gallon on LNG has several hundred times the energy potential of a gallon of gasoline.	See Table 1.1. The heat of combustion of (e.g., Algerian) LNG is 49.2 MJ/kg or 84.35 MJ/gal compared with gasoline at 44.75 MJ/kg or 106.3 MJ/gal.
Claim #3. An LNG tanker holds 3,000,000 gal (11,360 m^3) of LNG, the energy equivalent to 55 Hiroshima atomic bombs (Riley website and the film *The Risks and Danger of LNG*)	Using the same flawed reasoning, one can conclude that: • 1000 lb of wood equals 3530 lb of TNT explosive • 1000 lb of coal equals 4470 lb of TNT explosive • A 24-gal automobile gasoline tank equals 1225 lb of TNT explosive. Hazard potential depends upon both the amount of energy and the rate at which it is released. Energy released by burning LNG is relatively slow (Melhem et al., 2006).
Claim #4. (Van der Linde and Hintze, 1978) In a totally fictional prologue, the authors postulate the effects of a 50,000-t crude oil tanker being piloted up the Arthur Kill between Staten Island and the New Jersey shore. The tanker collides at 14 knots at right angle into the midsection of a docked LNG carrier (unspecified type). The authors speculate that	Rebuttal: Much of the technology cited below and detailed later in this book was not available in 1978. 1. A single tank of LNG contains 25,000 m^3 or about 10,625 t. The authors, thus, speculate that nearly the entire LNG double hull is cut open by the collision. This deep a penetration is unlikely by ship collision modeling discussed in Chapter 5. 2. The spilling LNG will flow downward from the split hole, not onto the carrier deck. In any event, cracks in an embrittled deck would be irrelevant. However, the Sandia report acknowledges that "Both the ship itself and other LNG cargo tanks could be damaged from a large spill." (Hightower et al., 2004, p. 38).

Table 1.5 *Continued*

Claim	Current Substantiated Information
1. 10,000-t spills from a single tank.	
2. The spilling LNG fractures the deck of the carrier.	
3. The spilling LNG instantly freezes the surrounding waters of the Arthur Kill.	3. It is not possible to instantly freeze a flowing body of water as large as the Arthur Kill. See discussion on heat transfer from LNG to water in Chapter 7.
4. The spilled LNG ignites and burns back to the source and causes the remaining four LNG tanks on the carrier to explode.	4. The remaining four LNG tanks are well insulated, so heat from the fire would have little influence except to increase the boiloff of vapors that would be vented by the pressure relief valve. The vented vapor would burn as a vertical plume. The concentration of LNG vapor inside the tanks would remain well above the upper flammable limit and would not ignite even as the vented vapors burn. The conditions for an explosion are absent (see Chapter 10), so the tanks would not explode. There is an issue with cryogenic damage to the carrier structural elements and Sandia National Laboratories is investigating for the DOE the potential for cascading failures from this mechanism in 2009.
5. As the four LNG tanks explode they project fragments of steel that penetrates the on-shore storage tanks at the LNG import terminal.	5. LNG storage tanks are built with an outer wall capable of withstanding fragments from an explosion, especially as far away as the docks.
6. Shock waves from the explosions flatten oil and gasoline storage tank farms.	6. There is considerable evidence from large-scale explosions at refineries and chemical plants that storage tanks have too much bulk to have more than minor damage from explosion blast waves as far away as from a neighboring plant (or dock in this case). Dents and small penetrations have been observed in the vapor space of tanks, but these do not lead to more than a minor venting of vapor.
7. Buildings are toppled by the explosions.	7. Buildings would not be toppled since there is too little congestion and confinement in the harbor area or on the water to generate an outdoor vapor cloud explosion. Modeling studies are done extensively around industrial areas and can be invoked to obtain a more realistic prediction of the size of a flammable vapor cloud from a spill of 10,000 t of LNG. The blast waves above 3 psig from a large methane release do not usually extend beyond 500 m.
8. Blocks of stone and girders rain from the sky. (This must presumably be from LNG vapors entering buildings and exploding inside a building since there would be no oil and gasoline from flattened storage tank farms.)	8. There is a considerable delay before LNG vapors passing or even surrounding a building to build up to concentrations above the lower flammable limit before an indoor explosion could be possible. This delay time is readily enhanced by turning off the heating, ventilation, and air conditioning (HVAC) systems. See Chapter 8 discussion of vapor intrusion indoors. The vapor cloud dissipates rapidly if the wind is not nearly absolutely calm.
9. The authors city an early paper by J. Fay postulating that a freeze burn area from a full tank loss of LNG would extend 12 miles.	

10. Concerning air induced into a large pool fire of LNG: “Estimates of wind speeds resulting from a large LNG fire range as high as 1,000 miles per hour.”	9. Chapter 10 lists the conditions for freeze burn and asphyxiation by LNG vapors. The vapors warm from –162°C by mixing with air at 20°C. Modern dispersion models put the distance for a plume of 10.8-t spill warming to 0°C as 1.4 mi. (wind speed 2.5 m/s) 10. This is a ridiculously high, supersonic wind speed (Mach 1.3) and is not physically possible in a fire.
Claim #5. The February 1973 accident at a Staten Island, New York LNG terminal storage tank was out of service and was being repaired. A fire developed and 37 people were killed (for details, see Chapter 2.) The claim is that “after all 37 people lost their lives at an LNG facility.”	This accident did not involve LNG, but rather was determined to be a construction accident in an empty tank. Between the mid-1960s and mid-1970s, more than 60 LNG facilities were built in the United States as peak shaving plants. Over that period, these plants have had an excellent safety record.
Claim #6. Fire burning back to an LNG tank would cause it to explode (Quillen, 2002).	Since an LNG tank is well insulated, an external fire would have a small influence on increasing LNG vaporization and release through pressure relief valves. The emitted vapors would likely ignite and generate a nearly vertical fire plume similar to a plant flare. There would be no congestion above the LNG tank to promote flame acceleration, which is a prerequisite for an explosion.