Understand LNG Fire Hazards

An ioMosaic Corporation Whitepaper

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I. Introduction

Potential hazards resulting from intentional or accidental spilling of large quantities of LNG include thermal radiation from vapor cloud fires (also referred to as flash fires) and pool fires.

There is general agreement among LNG experts regarding the following aspects of potential LNG fire and explosion hazards:

1. Vapors from large, un-ignited spills of LNG cannot travel far into developed areas without finding an ignition source, igniting, and burning back to the source.

2. Once delayed ignition of the vapor cloud occurs, and provided that the cloud is unconfined and rich in methane, the LNG vapors will burn in the form of a vapor cloud fire.

3. A vapor cloud traversing over commercial and/or residential terrain will almost certainly encounter an ignition source early in its downwind drift and the resulting vapor cloud fire will burn back to the source.

4. The vapor cloud fire will burn back to the source and cause a pool fire at the source if the release is a continuous release and the release duration is longer than the time it takes the cloud to find an ignition source.

5. If the vapor cloud is confined and/or the vapors contain large amounts of heavier hydrocarbons (C2+), then the flame can accelerate and result in an explosion. The magnitude of the explosion and explosion damage will depend on several factors including the amount of vapors above the lower flammable limit, the presence of obstacles and degree of confinement, the composition of the vapor cloud, and the strength of the ignition source.

6. If immediate ignition occurs, a pool fire will result. The extent of the pool spreading (diameter) and flame height will depend on several factors including the flow rate of LNG, the spill surface type (water or land), the spill surface geometry, spill surface roughness, release composition, release temperature, ambient wind speed, ambient temperature, and ambient relative humidity.

7. If the liquid pool is unconfined and the inventory of LNG is large, the fire will continue to burn until all the fuel is exhausted by the pool fire. It is not practical or even possible to extinguish large LNG pool fires resulting from large spills of LNG unless the flow of LNG feeding the pool can be stopped.

The maximum vapor cloud fire hazard area is typically estimated by calculating a downwind dispersion distance to the lower flammable limit (LFL)[1] and a cross-wind dispersion distance to ½ LFL at low wind speed and stable atmospheric conditions. This maximum fire hazard zone is very unlikely to be experienced in any situation where the cloud drifts over populated areas. As indicated in point 3 above, the cloud will soon encounter an ignition source and burn back to the source well before the maximum hazard area is reached.

Only the outdoor population present within the flammable boundaries of the vapor cloud is assumed to perish due to (a) short exposure to very high thermal radiation fluxes from the vapor cloud fire, (b) direct flame contact, (c) secondary fires of clothing, and (d) inhalation of hot combustion products. It is assumed that people inside buildings at the time of the flash fire will not be injured or killed[2]. It is also assumed that people inside buildings which are ignited by flash fire or a pool fire will be able to escape from the burning structure without direct thermal impact injuries. This is because the flash fire will ignite buildings from the outside and it will take some time for the fires to penetrate inside.

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[1] If heavy gas box dispersion models are used, it is recommended that the downwind distance be estimated to ½ LFL to account for peak to mean concentration averaging and pocketing. If well validated CFD models are used, than a downwind distance to LFL provides an adequate representation of the extent of dispersion downwind. The cross-wind distance should be computed to ½ LFL in both cases.

[2] Although it is possible for people in buildings to be exposed to thermal radiation through windows.

A. Issues Surrounding Potential Damage from LNG Fires

Published thermal radiation damage criteria often associate a level of damage with a heat flux value or an integrated heat flux value for short duration events such as fireballs. Typical values used and their observed effects are provided by CCPS[3]:

Table 1: Thermal Radiation Flux

Thermal Radiation Flux. kW/m^2	Observed Effect
37.5	Sufficient to cause damage to process equipment
25.0	The minimum energy required to ignite wood at indefinitely long exposure (nonpiloted)
12.5	The minimum energy required for piloted ignition of wood, and melting of plastic tubing. This value is typically used as a fatality number
9.5	Sufficient to cause pain in 8 seconds and 2nd degree burns in 20 seconds.
4.0	Sufficient to cause pain to personnel if unable to reach cover within 20 seconds. However, blistering of skin (second degree burns) is likely; 0% lethality
1.6	Will cause no discomfort for long exposure

There is general disagreement among LNG experts pertaining to the extent of thermal radiation hazard zones resulting from large LNG pool fires due not only to uncertainties regarding flame emissive power but also the limiting thermal radiation impact criteria.

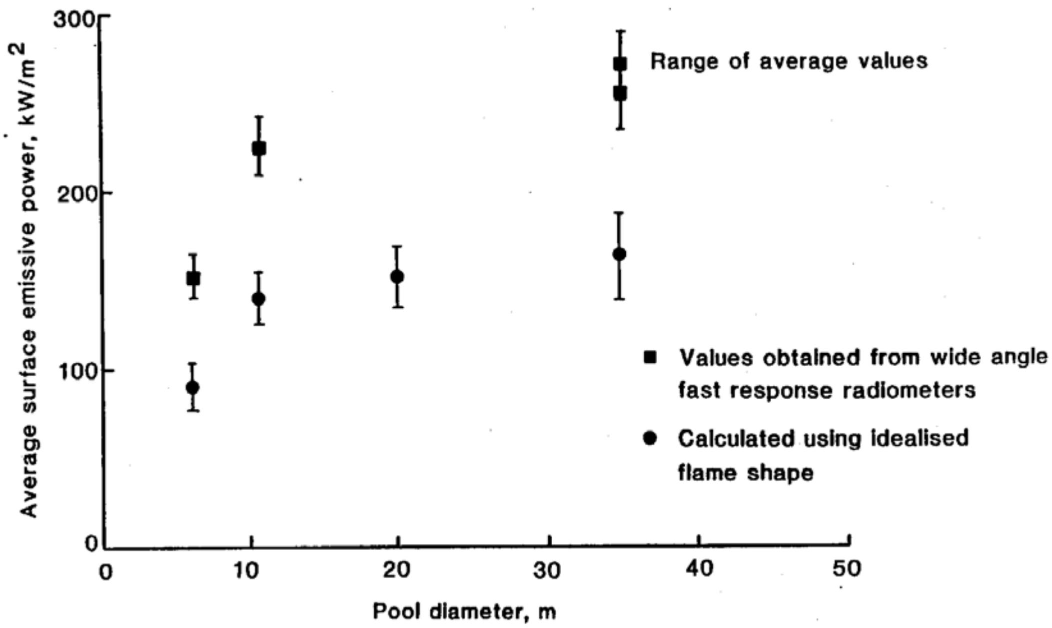
[3] "Guidelines for Chemical Process Quantitative Risk Analysis", Second Edition, page 269, American Institute of Chemical Engineers Center for Chemical Process Safety (CCPS), 2000.

B. Flame Emissive Power

Some experts argue that very large LNG pool fires such as those resulting from a terrorist attack on an LNG tanker will produce sooty flames and the flame emissive power is expected to be much less than 220 kW/m^2. The main argument is that the pool center will be starved from oxygen.

An opposite view which is more likely to be the correct one, is that fuel that does not burn at the center of the pool due to oxygen starvation will rise due to thermal buoyancy and burn at a higher elevation as it contacts oxygen there. As a result, the flames will be taller and the associated thermal radiation hazard footprints may be higher[4]. In addition, in large scale pool fires field data such as the Montoir field trials emissive power values of approximately 300 kW/m^2 were reported (see Figure 1).

Figure 1: LNG Pool Fires – Measured Flame Emissive Power[5]



[4] Delichatsios, M. A., "Air Entrainment into Buoyant Jet Diffusion Flames and Pool Fires", Combustion and Flame, Volume 70, Pages 33-46, 1987.
[5] Nedelka, D., Moorhouse, J., and Tucker, R., "The Montoir 35-m Diameter LNG Pool Fire Experiments", Paper 3 Session III of International Conference on Liquefied Natural Gas: LNG 9 Proceedings, Nice, France, 1989.

C. Limiting Thermal Radiation Damage Criteria

Some experts argue that a 20-second 5 kW/m^2 limiting thermal radiation exposure criterion is sufficient to establish safe separation distances for the general public. The main argument here is that a typical person will sense pain quickly and can run away fast enough and take shelter. This criterion is adopted for example by NFPA-59 without reference to exposure duration.

An opposite view argues that these criteria cannot be applied to sensitive population or critical areas/infrastructures. Elderly and the very young for example, constitute sensitive populations that may not be able to take cover within 20 seconds when outdoors. "Critical areas" include unshielded areas of critical importance where people without protective clothing can be expected or required at all time including during emergencies. "Critical infrastructure" includes buildings or places that are difficult to evacuate on short notice such as sport stadiums, hospitals, schools, play grounds, theaters, etc. As a result a lower criteria is adopted by EN-1473[6] (1.5 kW/m^2), the US Department of Housing and Urban Development (450 BTU/ft2/hr or 1.4 kW/m^2), API-521[7] (1.58 kW/m^2), and the society of fire protection engineers (SFPE Handbook) recommends a level of (2.5 kW/m^2) as a public tolerance limit.

We must recognize that in the specific case of LNG terminals large quantities of LNG will be stored in bulk storage tanks and frequently arriving by ship. Under the right scenario, loss of containment can yield very large pool fires and the extent of the potential hazard zones must be accurately determined in order to establish a prudent estimate of a safe separation distance.

We must also recognize that there are some uncertainties associated with the application of several of the models used to establish safe thermal radiation separation zones. For example, the flame height correlations have not been validated against pool fires that are several hundred meters in diameter.

There are two practical approaches to addressing the issues of thermal radiation damage criteria, assuming we can all agree on what to use as a reasonable value of flame emissive power:

1. Be prudent and conservative. Set the value low enough such that anyone that is continuously exposed will not suffer irreversible injuries.

2. Evaluate the risk accurately. Consider both the exposure duration and the exposure flux (dosage), and consider the demographics of the current and projected population density nearby the proposed facility to be sited, i.e. what fraction of the people will be outdoor, what fraction is sensitive, where the critical locations are, etc. This approach will require a risk tolerability criterion that is acceptable to the community tolerating the risk in lieu of some economic benefit.

[6] Value excludes solar flux.
[7] Value is at any location where personnel with appropriate clothing are continuously exposed. Note that this value includes solar flux.

The NFPA-59 thermal radiation criteria should not be confused with and/or considered as a risk acceptability criteria. Hazards are just one aspect of risk. Other important aspects of risk management include operational, economic, social, political, and environmental factors as well as the probability of the occurrence of the hazard itself.

The 5 kW/m^2 limiting criterion does not adequately represent the risks presented by an LNG facility to sensitive population and/or critical areas/buildings. Dosage must be considered as mentioned in item 2 above. The most widely recognized and used methods for establishing the impact of thermal radiation on people are those developed by TNO[8] in the Green Book. These methods are referred to as thermal radiation probits or vulnerability models.

[8] CPR-16E, "Methods for the determination of possible damage to people ad objects resulting from releases of hazardous materials", First Edition, 1992, published by TNO.

D. Thermal Radiation Damage Probits

Probits are used to relate level of injury and exposure duration to a hazardous event of a given intensity. Hazardous events of interest in consequence modeling include dispersion leading to exposure to toxic chemicals, fires leading to exposure to thermal radiation, and explosions leading to exposure to overpressure and flying fragments.

The method of probit analysis[9] was first introduced between 1940 and 1950. A probit (probability unit, Y) is a normally distributed random variable with a mean of 5 and a standard deviation of 1 (see Figure 1).

The mortality response (percent fatality) is expressed as:

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\inf}^{Y-5} \exp - \left(\frac{u^2}{2} \right) du = \frac{1}{2} + \frac{1}{2} \operatorname{erf} \left(\frac{Y-5}{\sqrt{2}} \right) \tag{1}$$

For mortality response to a toxic exposure of concentration C and duration t, Y is given by:

$$Y = A + B \ln \left[C^N t \right] \tag{2}$$

If C varies with time, then Y can be expressed as:

$$Y = A + B \ln \left[\int C^N dt \right] \tag{3}$$

Here, the integral containing concentration represents a dose factor. Probit analysis can also be applied to thermal radiation hazards:

$$Y = A + B \ln tI^{4/3} \tag{6}$$

Where, A and B are the probit parameters established from measurements and/or critically evaluated scientific data (see Table 1), I is the radiation intensity in $\mathrm{W/m^2}$, and t is the exposure time in seconds.

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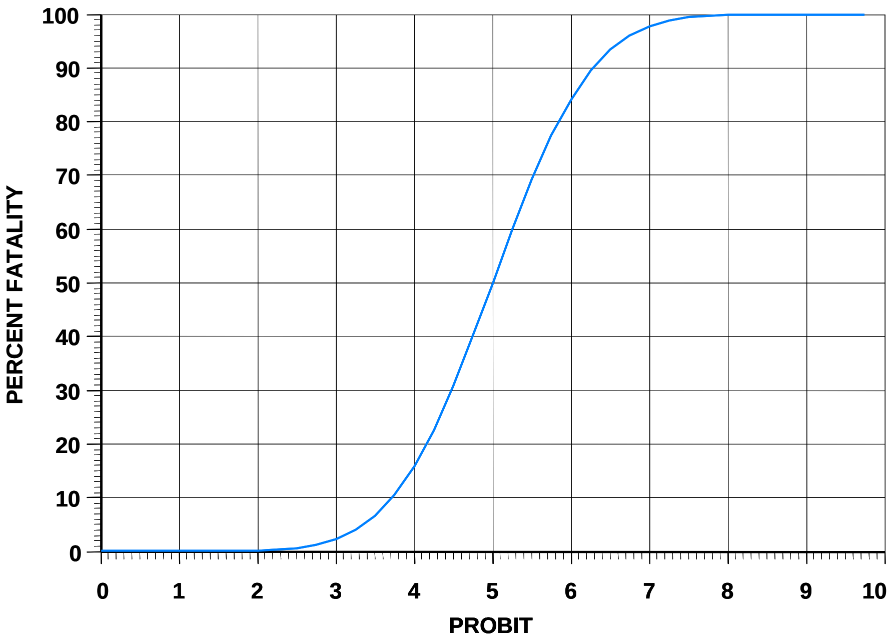
[9] D. J. Finney. *Probit analysis*. Cambridge University Press, 1977.

Figure 2: Probit Function



The TNO Green book[8] provides probit functions for first and second degree burns as well as lethality from exposure to heat radiation within the infra-red part of the spectrum (see Table 2). The last probit function reported in Table 2 accounts for clothing protective influence on fatality for humans. It assumes that 20 % of the body area remains unprotected for an average population. As a result, the fatality for protected bodies is about 14 % of the fatality for unprotected bodies.

Table 2: Typical Reaction Times to Thermal Radiation Exposure Levels[10]

Intensity (kW/m^2)	Time to react (s)
22	0.2
18	1.5
11	3.5
8	5.5
5	9.0
2.5	25.0

[10] K. Cassidy and M. F. Pantony, "Major industrial risks - a technical and predictive basis for on and off site emergency planning in the context of UK legislation," Symposium Series No. 110, 1988, pages 75-95, Institute of Chemical Engineers, Hemisphere Publishing Corporation.

The influence of running away from a location with high heat radiation to a location where the level of heat radiation is safe (approximately $1\,\text{kW/m}^2$) can also be used for the assessment of injury and fatality from heat radiation[11]. TNO considers 1 kW/m^2 as the maximum heat-flux the skin can absorb during a long time without feeling pain. The probits presented in Table 3 can be modified to take that into account by replacing the exposure time t by an effective exposure time t_e:

$$t_e = t_r + 0.6\frac{x}{u}\left[1 - \left(1 + \frac{u}{x}t_v\right)^{-5/3}\right] \tag{7}$$

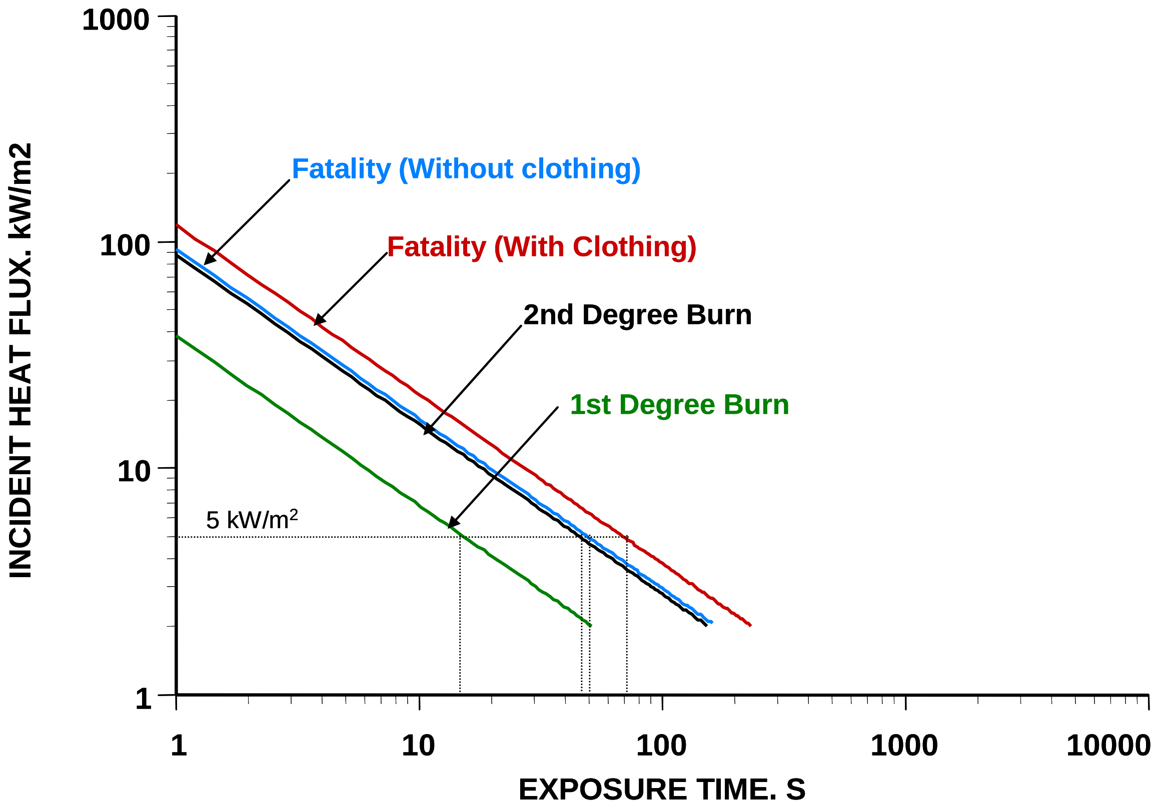
Where, t_r is the reaction time and is about 5 seconds (see Table), x is the distance to 1 kW/m^2, u is the run velocity in m/s, and t_v is the time to reach 1 kW/m^2. To illustrate the use of the TNO thermal radiation probits, we present in Figure 2 the thermal radiation dosage required to produce a 1 % probability outcome. Note that the probit equations shown in Table 2 should not be extrapolated to values less than 1 k W/m^2.

Table 3: Heat Radiation Probit Parameters (taken from the TNO Green Book)[8]

Damage	Probit
First degree burns	$Y = -39.83 + 3.02\ln tI^{4/3}$
Second degree burns	$Y = -43.14 + 3.02\ln tI^{4/3}$
Fatality (Unprotected)	$Y = -36.38 + 2.56\ln tI^{4/3}$
Fatality (Protected)	$Y = -37.23 + 2.56\ln tI^{4/3}$

[11] G. Opschoor, R.O.M. van loo, and H. J. Pasman. Methods for calculation of damage resulting from physical effects of the accidental release of dangerous materials. In *International conference on hazard identification and risk analysis, human factors and human reliability in process safety*, pages 21–32. Center for Chemical Process Safety, AIChE, 1992.

Figure 3: Thermal Radiation Flux vs. Exposure Time Leading to 1 % Probability of Injury or Fatality



E. Intentional Terrorism Acts against an LNG Tanker

The potential of terrorist attacks against LNG tankers is highly debated by the media and the public. The major concern centers around the large quantity of energy stored on these large ships. New LNG supertankers now under construction will carry up to 265,000 cubic meters of LNG.

In general, and despite the large amount of energy stored on LNG tankers, they are not attractive "mass casualties" targets unless the ship is berthed in ports near highly populated areas when attacked. This is so because the hazard impact zones from a terrorist attack on an LNG tanker will be highly localized near the ship[12]. Many communities opposing the siting of LNG terminals argue that some U.S. ports represent attractive terrorism "economic targets".

We have considered numerous scenarios involving terrorism and acts of sabotage including hijacking, small boat attack, standoff weapon attack, aircraft attack, underwater diver/mine attack, placing solid explosives in the cargo hold areas, blocking the pressure relief valves, starting the pumps and unloading while the ship is berthed, etc. Based on our review we believe there is one maximum potential impact scenario that should be considered as a threat. This review will not comment on the likelihood of occurrence of this scenario but will focus on the evaluation of the maximum potential hazard zone that could be realized from this scenario. The scenario involves a fully loaded LNG ship that is berthed before cargo unloading begins.

Before describing this particular scenario in detail we begin by looking at the characteristics and dimensions of different types of existing and planned LNG tankers.

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[12] G. A. Melhem, A. S. Kalelkar, H. Ozog, and S. Saraf, "Managing LNG Risks: Separating the Facts from the Myths", ioMosaic Corporation white paper, 2006.
http://archives1.iomosaic.com/whitepapers/Managing%20LNG%20Risks.pdf

F. LNG Tanker Structural and Safety Features

At the beginning of 2005, there were 175 LNG carriers with a combined capacity of 20.68 million m^3. The principal ships in the LNG fleet range from 125,000 m^3 to 150,000 m^3. At the end of 2004, the first orders were placed for LNG carriers of more than 200,000 m^3. Carriers with a capacity of 265,000 m^3 are now under construction. Six of these carriers were ordered recently by Qatar Gas.

LNG carriers are double-hulled vessels specially designed and insulated to prevent leakage and rupture in the event of accidents such as grounding or collision.

The different types of cargo tanks utilized for shipping LNG are illustrated in Figures 4, 5, and 6. The Kvaerner-Moss system employs free standing spherical tanks fitted unto the hull. The second designs incorporate variations of a membrane type tank. In this case, the LNG cargo is contained within thin walled tanks of stainless steel. The tanks are anchored at various points to the inner hull of the double-hulled vessel, and the cargo load is transmitted to the inner hull by the intervening insulation. The world fleet is roughly divided between these two systems.

Boil-off gas during transit is limited by insulation and maximum normal boil-off is about 0.15% of cargo per day. Boil-off gas is used to supplement fuel in the ship's boilers; hence many ship propulsion systems use steam turbines. Diesel propulsion is finding favor, but for those ships onboard boil-off gas recovery systems and gas combustion units are required. Gas turbines are also being considered.

Due to the low density of the cargo, LNG carriers ride with a high freeboard. For this reason, maneuvering in port in windy conditions makes the ships susceptible to being blown to one side of the channel. Therefore, port maneuvering usually requires traffic restrictions and extra tug power for such conditions.

Table 4: Typical Modern LNG Carries Dimensions

	Membrane Carrier		Spherical Carrier	
LNG Carrier Capacity (m^3)	**145,700**	**216,000**	**125,000**	**235,000**
L - Length (m)	277.2	303.0	282.0	328.5
B - Breadth (m)	43.4	50.0	41.6	55.0
D - Depth moulded (m)	26.0	27.0	25.0	32.5
Top of tank above base line (m)	31.0	33.2	37.7	49.0
T - Draft moulded (m)	12.3	12.5	11.5	12.5
Displacement (Tonnes)	116,941	151,599	99,130	178,247
Double bottom height (m)	3.2	3.4	1.4	1.6
Double side width (m)	2.2	2.6	2.4	3.0
Outer side plate thickness (mm)	17-18	16-21	19	18-20
Inner side plate thickness (mm)	14-18	18-19	14-18	14.5-16.5
Transverse frame space (mm)	2,800	4,105	4,180	4,130
Cargo Tank Dimensions				
L - Length (m)	47.6	41.0		
H - Height (m)	27.7	29.8		
B - Breadth (m)	39.0	44.8		
Tank Diameter (m)			35	46
Approx. Volume of Tank (m^3)	43,504	48,174	22,449	50,965

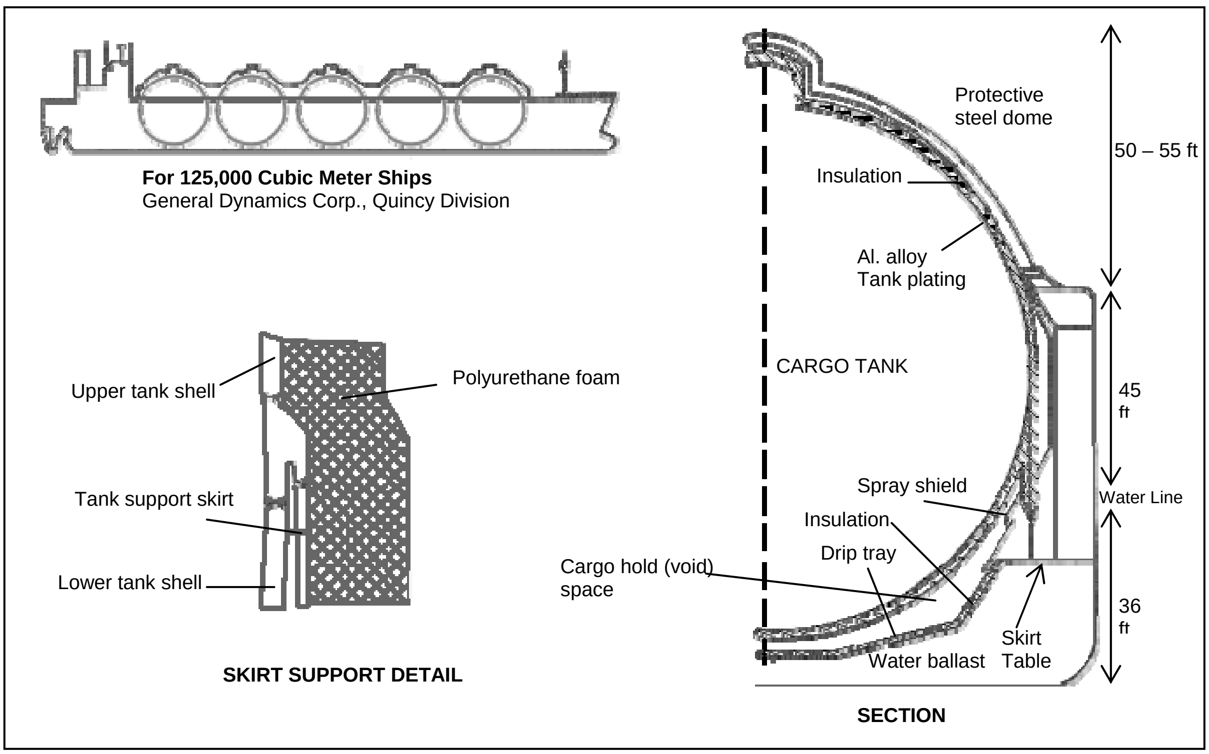
G. Spherical Tanks

The spherical tanks (see Figure 3) are supported by a cylindrical structure "skirt" attached to the sphere at approximately mid-height. The cylinder sits on the skirt table attached to the side and bottom hull. The sides and bottom are of double hull construction, with longitudinal stiffeners and spaced web frames which act to tie the inner and outer hulls into a box frame arrangement. The webs are open to allow passage of the water ballast (used on the return voyage) to move freely.

The outer hull is typically ¾" plate steel and the inner hull is ½" plate steel. The spacing between hulls is about 187 inches (220cm). The tanks are typically insulated with foam material.

Each tank is contained within water-tight bulkhead compartments. The most common ship design in use has five spherical tanks, each holding 25,000 cubic meters of LNG. Typical dimensions are length between perpendiculars of 936 ft (285m), beam of 143 ft, depth of 82 ft, and draft (constant) of 36 ft.

Figure 4: Free Standing Spherical LNG Tank[13]



[13] "Transportation of Liquefied Natural Gas", Congress of the United States Office of Technology Assessment, September 1977.

All of the ship structure comprising the hulls, bottom, bulkheads, and skirts, are fabricated from non-cryogenic steels, with minimum toughness (resistance to brittle fracture) at LNG temperatures. Thus, exposure of these structures directly to LNG is not a design criterion.

A disadvantage of the Moss system is that the spherical tanks do not fit the contour of the ship's hull and consequently a Moss design will result in a ship that is 10% longer for the same cargo capacity. Since shipyards usually specialize in one type or the other, the selection of the design will, to some extent, dictate the shipbuilder. Moss tank diameter is somewhat limited to about 40 meters due to crane lifting limitations.

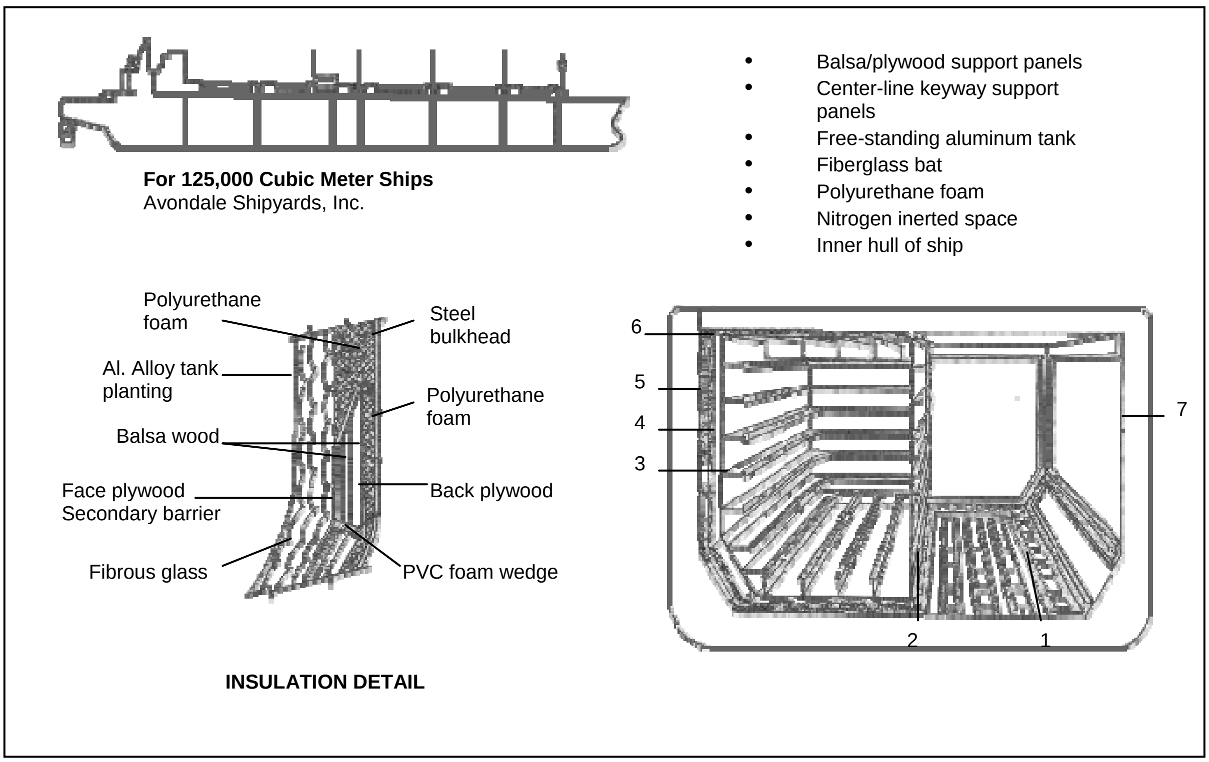
H. Membrane Tanks

The prismatic or membrane tanks are supported by insulation material backed by the inner hull and inner bottom structures (see Figure 5 and Figure 6). The sides and bottom are of double construction, with longitudinal stiffeners and spaced web frames. Watertight bulkheads separate the individual tanks. The double hull and bottom are open between bulkheads to provide space for the water ballast.

A typical design would include 4 to 6 tanks. Typical dimensions would be a length between perpendiculars of 260 meters (850 ft), a beam of 42 meters (138 ft), a depth of 28 meters (92 ft) and a draft of 12 meters (39 ft).

All of the ship structure comprising the hulls, bottom, bulkheads, and skirts, are fabricated from non-cryogenic steels, with minimum toughness (resistance to brittle fracture) at LNG temperatures. Thus, exposure of these structures directly to LNG is not a design criterion.

Figure 5: Free Standing Prismatic LNG Tank[13]

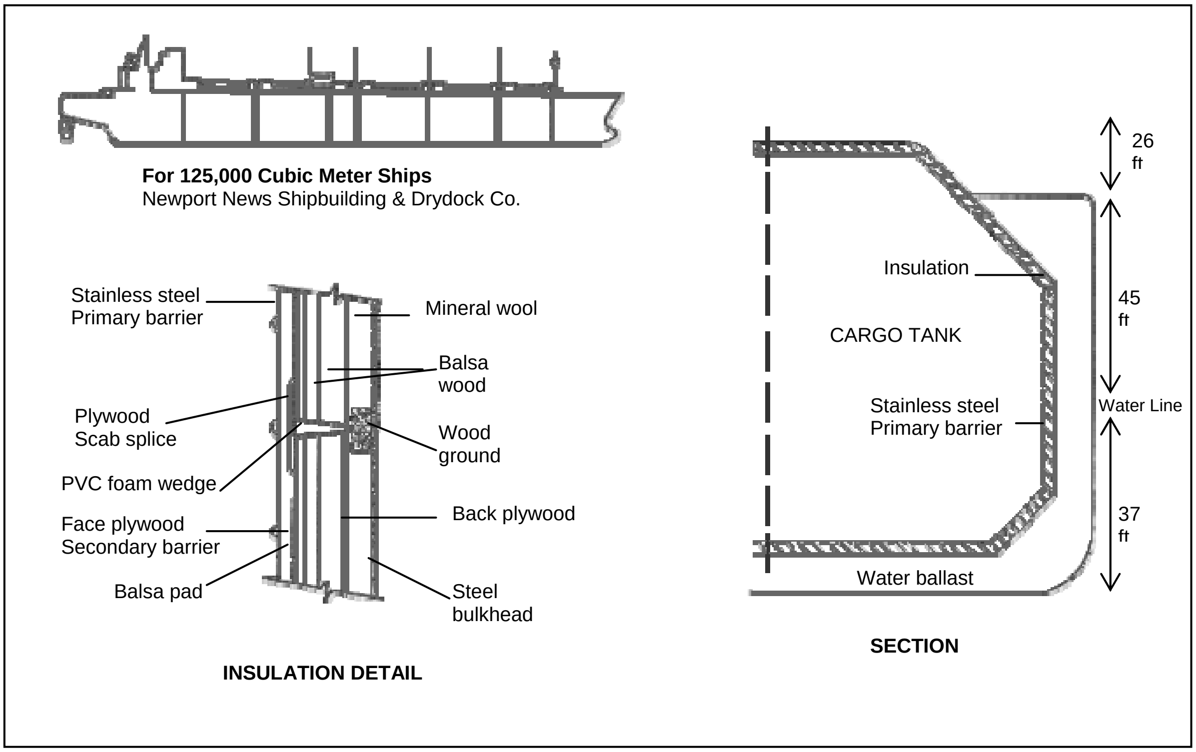


I. Storage Tanks Key Features

Table 5 provides a comparison of key characteristics of the different LNG tank systems. LNG tanks are typically operated at approximately 2 psig independent of carrier type. Membrane tanks are designed for low pressures (3.55 psig max), spherical tanks are designed for 30 psig and prismatic tanks are designed for 10 psig.

Spherical tanks are more difficult to puncture than membrane tanks unless hit at a vulnerable spot or a bigger explosive charge is used. The most vulnerable spot on a spherical tank is the tangent line which is approximately 5 ft below deck or 40 ft above the water line in a typical 125,000 m^3 vessel. In general, spherical tanks are more resilient than membrane tanks as shown in Figure 6.

Figure 6: LNG Membrane Tank[13]



Although the maximum impact scenario and the subsequent hazard footprint are developed for a 1 m diameter hole, we also evaluate the impact of larger holes on pool fire diameter and duration of the fire. We also examined the fire behavior for the case of immediate ignition as well as for delayed[14] ignition.

[14] Delayed ignition was assumed to occur after the release ended.

J. Maximum Impact Scenario Description

For this maximum impact scenario we assume that a terrorist was successful in creating a 1 m diameter hole in the center tank of an LNG tanker at (or slightly above) the water line. The tanker is berthed and fully loaded. We also assume the hole was created using an explosive charge delivered using a small aircraft or other equivalent means and as a result immediate ignition occurs leading to an unconfined pool fire on the water surface.

Table 5: Comparative Characteristics of LNG Tank Systems[13]

Characteristics	Free-Standing Tanks		Membrane Tanks
	Prismatic	Spherical	
1. System Designs	Conch Esso McMullen A.G. Weser Hitachi / Esso	Kvaerner-Moss Technigaz Gaz Transport (Cylindrical) Sener	Gaz Transport Gazocean I.H.I (semi-membrane) Bridgestone (semi-membrane)
2. Safety in event of vessel grounding / collision or other emergency	Compared with membrane system less likelihood of hull damage being transmitted to cargo tanks. More efficient use of cubic space.	Safest system in event of grounding or collision – tank structure independent of hull and most void space between vessel hull and cargo tanks. Spherical tanks can be pressurized for emergency discharge in case of cargo pump failure.	Damage to hull of vessel may be more easily transmitted to tank structure than with free-standing tanks. Membrane systems are also more liable to damage or puncture due to causes such as: ▪ surging of cargo in tank ▪ entry of tank for inspection ▪ entry of tank for repair
3. Reliability of Containment System	Most ship years operating experience and most experience without primary barrier failure. Structure can be analyzed and risk of fatigue failures minimized. Tanks can be constructed and 100% inspected prior to installation in vessel.	Tank system easiest to analyze structurally; therefore can be made most reliable.	Structure cannot easily be analyzed and therefore difficult to assure absence of fatigue failures. This could potentially lead to costly off-hire and repair time over the project life.

Figure 7 illustrates the impact of hole size on pool fire diameter from a nominal 25,000 m^3 spherical tank. There are three important observations to be made:

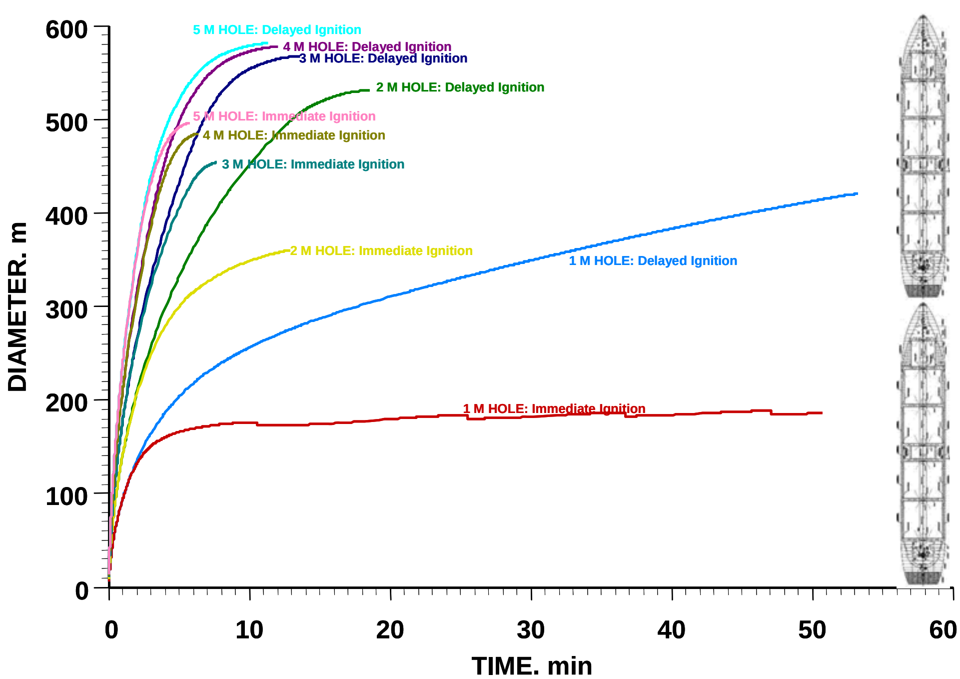
1. Immediate ignition[15] results in smaller pools,
2. As the hole size increases, the maximum pool fire diameter will asymptote,
3. The pool fire resulting from a 1 m diameter hole or larger will be big enough to engulf one entire side of the LNG tanker if the hole is in the center tank.

[15] 60 seconds.

This pool fire will be large enough so that it cannot be extinguished. It is prudent to assume that the pool will continue to burn until the LNG supply is exhausted. For a typical 125,000 m^3 Moss spherical vessel the tank inside diameter will be 37.5 m and 9.5 meters will be below the water line. As a result, the release duration from 1 m diameter hole will be approximately 1 hour, and therefore the pool fire will last approximately 1 hour. The associated flame height will be in excess of 200 meters, well above the height of the ship.

If the tanker is a spherical tanker, the cargo hold space will fill with LNG. The hold space is open and the LNG will distribute in the bottom. For either ship design, if the LNG spills into the double sidewall of the hull (ballast areas[16]) and into the water, the tanker might tilt, exposing more of the ship's top to the flames. It is possible for the ship to roll and end up on its side or even sink if enough LNG inventory has been depleted (say 50 %). The initial spill into the hull structure or the cargo hold area would likely produce a brittle fast fracture of the hull steel plates, causing local failure of the hull, the bulkheads, and subsequently the bottom structure.

Figure 7: Impact of Hole Size on Pool Fire Diameter from a 25,000 m^3 Tank[17]



Concurrently, the fire, impinging on the hull, and radiating onto the top of the ship would be expected to significantly heat the metal structure and cause it to lose its structural integrity. A 20 mm metal plate, the outer hull steel, is calculated[17] to lose 80 % of its tensile strength after approximately five minutes of exposure. Transverse web frames will conduct heat into the

[16] Note the ballast areas have little water in them when the ship is fully loaded. Water is pumped into the ballast tanks as LNG is discharged to prevent the tanker from rising and stressing the loading arms.
[17] G. A. Melhem and Henry Ozog, "Managing LNG Risks Training Manual", ioMosaic Corporation, February 2006.

inner hull and will create distributed hot spots on the inner hull. This will cause high thermal stress.

It is important to note that for this pool fire engulfment scenario, the relief valves for a typical LNG tank are undersized by at least a factor of 20 if the insulation is not damaged. If the insulation gets damaged by the fire or gets wet then the relief valves would be undersized by a factor of 200. Note that older ships contain non-fire proof insulation. For spherical tankers, the relief valves in the hold space will lift and discharge to the top of the dome/protective cover. These relief valves are only sized for thermal expansion. For either design, the main tank relief valves will also discharge. The discharge will catch on fire causing additional flame radiation contribution being experienced by the top of the tanks.

The bottom of the ship will see cryogenic temperatures while one side of the ship and the top of the ship will see close to flame temperatures.

In this scenario, the failure mechanisms would be expected to propagate along the ship, causing failure of, and spillage from, ALL the adjacent tanks (three or four tanks[18]) near simultaneously. For membrane tankers the center tanks typically contain 60 % of the cargo.

Our expectation is that this complete failure of the ships containment system and of the ship itself would develop quickly, of the order of 5 to 10 minutes due to the initial brittle fracture and to the extreme temperatures from the pool fire.

The insulation on the tanks would not be expected be provide much protection from the intense fire, acting only to prolong the time to failure of the adjacent tankage and of the ship from a few minutes to the expected 5 to 10 minutes stated above.

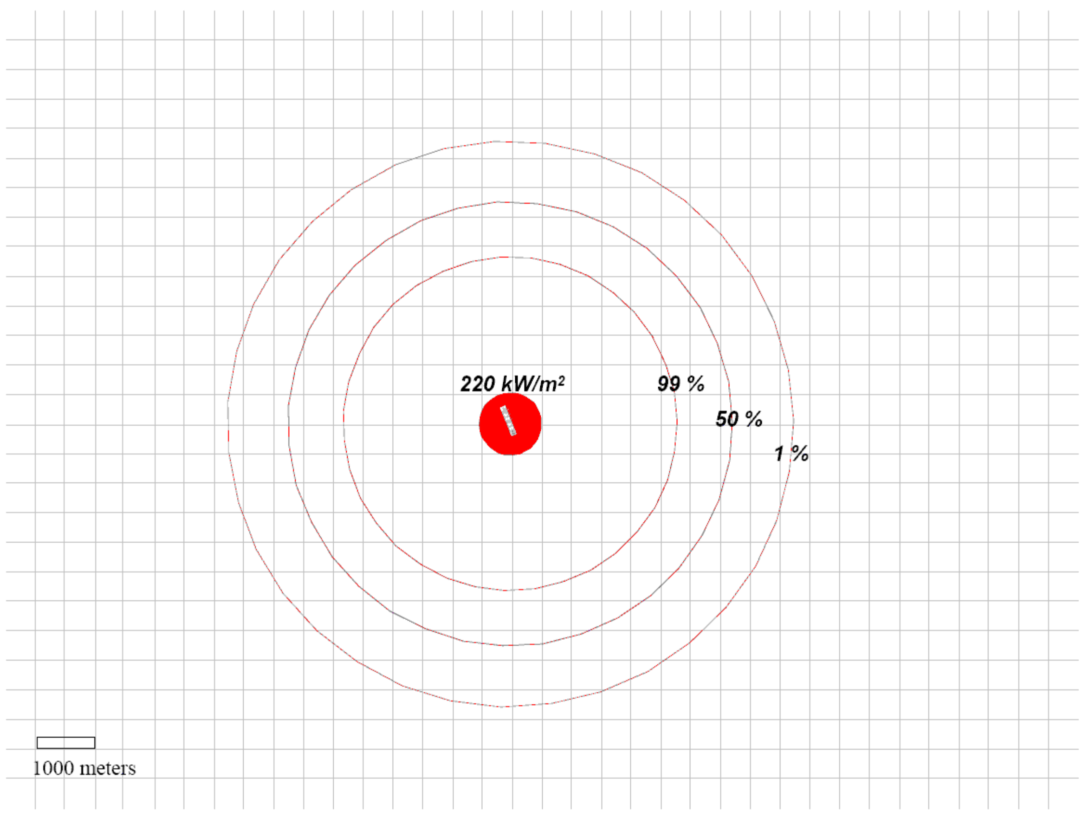
[18] Some new LNG ships with membrane tanks only contain four tanks.

K. Hazard Footprint Estimates for a Typical 200,000 m^3 LNG Ship

We estimate that the maximum impact hazard footprint for this scenario will result from a pool fire fueled by the simultaneous failure of three or four tanks, releasing approximately 150,000 m^3 of LNG from a 200,000 m^3 tanker. These hazard footprints were estimated assuming a 5 minutes release of 150,000 m^3. The results are shown graphically in Figure 8.

Figure 8: Hazard Impact of a Terrorist Attack on a 200,000 m3 LNG Tanker Leading to Pool Fire on Water.

Thermal Radiation Hazard Zones expressed using Probits in Percent Fatality.



A flame emissive power of 220 kW/m^2 leads to a distance of 3.7 km to the 50 % fatality limit excluding the contribution of solar flux.

II. Consideration by Regulatory Agencies (NRC, FERC) for Utilizing a Portfolio Approach to Permitting

Most United States regulatory agencies charged with regulating potentially hazardous facilities have a tendency to evaluate each new applicant on a case by case basis. Each new facility that is approved by the agency causes an incremental additional risk to its environment and to the jurisdiction of the regulatory agency. The Nuclear Regulatory Commission was the first regulatory agency to examine risks presented by nuclear power plants and express risk in the form of F-N curves to examine the overall risk for general acceptability. They further had the foresight to anticipate that there may be as many as 100 nuclear plants in the United States and developed design basis criteria and other standards and guidelines so that the risk presented by 100 operating nuclear power plants as measured by F-N curves would be acceptably low. Their pioneering analysis is reported in the Reactor Safety Study (WASH-1400)[19]. Today there are 104 operating nuclear operating units at 65 power plant locations in the United States[20].

At present FERC does not require a quantitative, F-N style, risk analysis to evaluate applications for onshore LNG facilities, especially those close to highly populated areas. Further, FERC has not, to our knowledge, embarked on an evaluation of what is the total risk presented to the United States from all existing peak shaving and importation LNG facilities and how it changes with each new import terminal that is approved.

A quantitative risk analysis approach to siting approval should be explored. FERC may wish to consider moving from a case by case approval process to considering all anticipated applications for LNG terminals (and peak shaving facilities, if any) and treating them as a portfolio of risk which require management rather than individual projects.

[19] WASH 1400, Reactor Safety Study, Appendix III-Failure Data, WASH-1400 (NUREG-75/014). United States Nuclear Regulatory Commission. October 1975. Referred to as WASH-1400.
[20] Energy Information Administration, DOE, Nuclear Plants Operating in the United States, September, 30, 2005. http://www.eia.doe.gov/cneaf/nuclear/page/nuc_reactors/reactsum.html.

III. Conclusions

Despite the issues raised in this paper regarding the value of flame emissive power, flame height, and pool size for large LNG pool fires, prudent estimates of safe separation distances can be developed for both intentional and accidental LNG release scenarios.

The NFPA-59 thermal radiation criteria should not be confused with and/or considered as a risk acceptability criteria. Hazards are just one aspect of risk. Other important aspects of risk management include operational, economic, social, political, and environmental factors as well as the probability of the occurrence of the hazard itself.

The 5 kW/m^2 limiting criterion does not adequately represent the risks presented by an LNG facility to sensitive population and/or critical areas/buildings. Recognized and peer reviewed vulnerability and/or probit models for establishing the impact of thermal radiation such as those developed by TNO represent a better alternative.