From:	phil brooke
To:	Public Involvement (UTC)
Subject:	Docket 151663-PSE LNG
Date:	Thursday, October 20, 2016 4:44:48 PM
Attachments:	lng siting rules in us faulty havens venart DEIS comment 2015.pdf lng bunkering.jpg nfpa59a europe us probs research.pdf

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Dear UTC Commissioners:
Thank you again for allowing the opportunity for public comment on this docket.

For the record, please find attached two papers on current US LNG siting deficiencies & insufficient disaster model reqs. Neighbors of this refinery have watched demonstrations of the same and similar modeling software, which suggests a 3 mile exclusion zone, yet, all PSE did was model releases they designed. **Society** of International **Gas** Tanker and **Terminal** Operators (SIGTTO), the affinity group for LNG terminals, suggests generous exclusion zones for LNG facilities. Finally, I've attached a photo of the only other marine bunkering station in the United States. Notice anything in terms of both the size and location?

If MacQuarie Group wants to do this, let them assume all liability, move it somewhere remote, then spend their own money to do it. Peak shaving is only the pretext to get into our neighborhood and wallets.

Please amend or deny the proposed settlement.

Sincerely,

Phil Brooke,
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Submitted by

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Regarding the
Jordan Cove Export Terminal
Draft Environmental Impact Statement
Docket No. CP13-483

January 14, 2015

UNITED STATES LNG TERMINAL SAFE-SITING POLICY IS FAULTY

We have commented repeatedly to the Federal Energy Regulatory Commission (FERC) and the Department of Transportation (DOT) that we believe FERC is approving variances to the requirements of 49 CFR 193, Liquefied Natural Gas Facilities: Federal Safety Standards, that have not been subjected to adequate science based review and appear to provide inadequate fire and explosion exclusion zones to protect the public.

This submission focuses on the Draft Environmental Impact Statement (DEIS) for the Jordan Cove Export (JCE) Terminal Project. We believe the JCE DEIS fails to provide for protection of the public from credible fire and explosion hazards. The conversion of the Jordan Cove facility for export, including provision of gas treatment technology utilizing mixed hydrocarbon refrigerants for liquefaction and removal of heavy hydrocarbons from the natural gas feed to the plant, presents hazards to the project more serious (on a unit weight basis) than with LNG. We believe these additional hazards have been discounted without sufficient scientific justification in spite of multiple international reports during the last decade of catastrophic accidents involving unconfined (hydrocarbon) vapor cloud explosions. It is clear that the increased hazards due to the presence of significant amounts of heavier-than-methane hydrocarbons, for which there is considerably more extensive research and accident experience than for LNG-ONLY projects, and which are “game-changing” in importance, have been seriously under-estimated in this DEIS. We believe the hazards attending the proposed operations at the Jordan Cove export facility could have the potential to rise, as a result of cascading events, to catastrophic levels that could cause the near-total and possibly total loss of the facility, including any LNG ship berthed there. Such an event could present serious hazards to the public well beyond the facility boundaries.

We also believe there remains significant potential for cascading fire and explosion events attending “LNG only” storage and handling that have not been sufficiently addressed, particularly regarding the worst-possible case events that should be considered on the shore side storage tanks and marine side (ship related), either by accident or terrorist activity. Instead of considering the findings of extensive LNG Safety research conducted at the direction of Congress during the last decade that might influence the judgment of the acceptability (to the public) of the worst case events that should be considered for this proposed terminal, the present JCE DEIS appears to largely ignore those findings.

The JCE DEIS focuses principally on arguments directed to meeting the “letter” of the federal regulations governing a single index of public safety - mathematical modeled exclusion zones (safe separation distances) intended to keep the public out of harm’s way. But this DEIS relies, for prediction of exclusion zone distances, on the use of mathematical models which have not been subjected to adequate (open for public inspection) validation requirements either by comparison with experimental data or independent scientific peer review. Furthermore, the calculations of the exclusion distances for vapor dispersion and vapor-cloud-explosion hazards do not provide any evidence of applicability in near calm conditions coupled with reliance on impermeable (concrete) vapor fences designed to retard vapor cloud travel. Until there is produced by the applicant meaningful evidence of the accuracy and applicability-for-purpose of these modeling techniques, and that information is made available for public evaluation and oversight, it must be considered that the potential hazards of storage, handling, and shipping of such massive quantities of energy as are involved in this project could have been seriously underestimated.

The Jordan Cove Export Terminal DEIS Section 4 (Environmental Analysis), which contains the section on Reliability and Safety, comes to nearly twelve hundred pages, much of which is technically complex and therefore unlikely to be very helpful to the public. In view of shortcomings in the DEIS that we will identify, we believe it is particularly timely to summarize the hazards that require careful address for the proposed export terminal, as well as provide DOT and FERC with our independent assessment of the current state of scientific knowledge, including limitations thereof, upon which proper quantification of the risks and consequences of credible accidental or intentional events should be based.

We believe the present methodology of regulating LNG Terminal (import and export) hazards-to-the-public are overdue for careful review and assessment. During the brief (six-decade) history of LNG trans-ocean transport, LNG Storage and Handling Facilities have increased in size by an order of magnitude (factor 10). At the same time, it appears that the regulatory guidelines have not been continually reviewed and updated in consideration of extensive research programs required by Congress to better provide for public safety from LNG import terminals or the ships that service them. Most importantly, the regulations that are being applied to the proposed JCE Terminal appear to give only cursory attention to the additional hazards that will be involved by the proposed expansion of the terminal for export service. For this reason alone, we believe it is important for the public to consider “how we got here”. We have prepared a short history of the development of the current LNG Facility Siting-for-Safety regulations which we believe would be helpful for all involved (public and regulators alike) to consider. However, in order to focus on the concerns that we believe require immediate address in the JCE Terminal DEIS, we have placed that historical appendix at the end of our comments. We recommend it to the reader.

There is a rich history of experience with the hazards of hydrocarbon fuels and chemicals heavier than methane (the principal component of LNG). That history describes numerous catastrophic accidents involving complete destruction of plant facilities due to fire and explosion. In the present JCE DEIS, FERC appears to have accepted extensions of arguments previously prepared for the application to build the facility as an import terminal. However, as our history (appendix) shows, the regulations regarding approval of import terminals have in the past been guided by the premise that LNG, as methane, poses significantly lesser hazards than heavier hydrocarbons routinely handled in the petroleum industry. We do not disagree with this characterization. What we find disconcerting is the extent to which the “safety” characteristics of methane have been misunderstood (and misrepresented) as the industry has expanded; today involving extremely large volumes of LNG (energy) concentrated in storage and handling facilities. After all, methane is the prize fuel that it is in that it ignites easily and burns hotly and cleanly, and those attributes entail hazards that multiply with the amounts of fuel involved. Therefore, we believe that insufficient attention has been given to the potential magnitude of the hazards that accompany the large scale storage-and-handling LNG-ONLY operations now operating and planned. But, we want to make it clear that our more serious concerns relating to the JCE Terminal result from the combined storage and handling, in gaseous and liquid forms, of methane and heavier hydrocarbons including ethylene, propane, pentane, and amines in such large amounts.

We believe the proposed JCE Terminal DEIS is a signal example of the (unwarranted) extent to which regulations designed for LNG-only handling facilities are being used as the basis for regulating large-scale projects involving heavier-than-methane hydrocarbon chemicals and fuels in volumes, particularly in combination, that involve significantly greater hazard potential than do import-only LNG terminals. With the current concerns for terrorist activity, and in view of the recent international experience of catastrophic accidental unconfined vapor cloud explosions of hydrocarbon fuels, it is time for a careful review.

Volume of Hazardous Hydrocarbons Stored at the Proposed JCE Terminal

- Hazardous Materials Tank (s) Storage Volumes, gallons
  - LNG (2) – 89,662,000
  - Ethylene (1) – 14,000
  - Propane (1) – 15,670
  - Isopentane (1) – 31,030
  - Amine (1) – 17,205
- Hazardous Materials Design Spill Volumes and Spill Impoundment Volumes, gallons
  - LNG (2) – 89,662,000 – 112,338,200 (outer tank concrete wall)
  - 36-inch Ship Load Header (at dock) – 784,600 – 785,170 (concrete sump)
  - 36-inch Ship Load Header (at tanks) – 827,740 – 833,400 (concrete sump, shared)
  - 24-inch LNG Rundown Line – 71,980 – 833,400 (concrete sump, shared)
  - 6-inch Mixed Refrigerant Line – 61,060 – 833,400 (concrete sump, shared)
  - Ethylene Storage Tank – 14,000 – 43,935 (concrete sump, shared)
  - Propane Storage Tank – 15,670 – 43,935 (concrete sump, shared)
  - Isopentane Storage Tank – 31,030 – 43,395 (concrete sump, shared)
  - Amine Makeup Tank – 17,205 – 17,245 (concrete sump)

We focus on these large hazardous materials inventories, the “design” spills that are considered, and the estimation of potential consequences which determine the safety exclusion distances for fire and explosion hazards - to provide our summary assessment of the JCE DEIS.

FAILURE TO ADEQUATELY PROVIDE FOR PUBLIC SAFETY

The JCE Terminal DEIS issued by FERC concludes that the principal regulatory requirements of 49 CFR 193: *Liquefied Natural Gas Facilities: Federal Safety Standards* providing exclusion zones to protect the public from liquid pool fire, vapor cloud dispersion, and vapor cloud explosion hazards have been met satisfactorily (with FERC-stated actions required) by the applicant’s submitted mathematical-model calculated exclusion distances.

In our opinion, the DEIS-proposed approval of the JCE Terminal, in the absence of careful address of the concerns we describe below, will not provide for sufficient separation distances (exclusion zones) to protect the public from credible events, whether by accident or intentional act. However, our principal intent is not to engage in argument regarding the details of the methodology or the accuracy of the predictions submitted by Jordan Cove to calculate the exclusion distances (we do believe there are deficiencies in that regard because sufficient evidence of the accuracy and applicability of the mathematical models and model-inputs thereto has not been presented). Most importantly, we believe that the JCE DEIS has developed too rapidly, we suspect partly due to its evolvement from the DEIS previously submitted for approval as an import (only) terminal at the Coos Bay site, and as a result has become mired in the details of exclusion zone determination using theoretical models without proper recognition of the overall potential for catastrophic hazards that must be considered for operation as an export terminal.

Our primary purpose in these comments is to state the following serious concerns which we believe require science-based adjudication prior to approval of this application-for-siting:

1. The current consequence-driven regulatory process (see appendix on history), which decides the acceptability of an LNG siting process by ensuring that the consequences of accidents will not extend offsite to affect the public), has developed similarly to that which forms the basis for nuclear plant siting approval – reliance on determination of so-called credible "design accidents" (here called "design spills") to determine the required exclusion distances (from the accident (spill) location) to the applicant's property line. The determination of these design accidents is a complex process which has developed *ad hoc*. Initially the design accident (release) was taken as the catastrophic release of the entire contents of the largest storage vessel on the site. It later was changed to the "guillotine" severance of the largest transfer line in the facility, with the release duration assumed to be ten minutes, or a shorter time if the applicant could demonstrate the ability to limit the spill duration (such as by incorporation of emergency shutdown procedures). There followed the adoption of a provision by which an alternative release rate and total amount (termed an "accidental leakage rate (ACR) spill") can be submitted by the applicant for approval. Such ACR spills are typically spills from smaller lines (such as branch or instrument lines) rather than the largest lines carrying the hazardous material. The regulation provisions now allow consideration of even smaller releases from "holes" in the selected lines. In our opinion these developments can only be understood as resulting from pressures on the applicants to seek approval of smaller and smaller required exclusion distance determinations. But the requirements placed on the applicant to demonstrate the probability or lack thereof of the different kinds of releases assumed for designation as an ACR are not sufficiently quantified – the process appears to be largely a "good-faith" decision reached jointly by the applicant and the DOT/FERC staffs. In our judgment this is not good science or engineering; it is indicative of regulation that facilitates facility approval – potentially at the expense of public safety.
2. Further compromising the effectiveness of the current regulations for public safety, the system has become dependent upon modeling methods using

complex mathematical calculations (computer programs) that are not available to the public for independent evaluation of their applicability-for-purpose; we believe this prevents a basic public right-to-know.

3. The calculations supporting the exclusion zone distance for the LNG “tanktop” fire chosen by the applicant as the controlling “design spill” fire do not consider potential cascading failure hazards to the public that could follow such a fire. We believe such failures have the potential to lead to structural failures of the LNG tank(s) which could lead to catastrophe.
4. There are numerous potential hazards from fires and explosions that could result in cascading events involving the liquefaction trains at the facility as well as LNG ships berthed at the facility. We realize the ship is not FERC’s responsibility; however, the worst-case hazard potential for the marine side of the proposed terminal should be considered before approval in view of the public concerns recently addressed in research required by Congress.
5. The methods used to determine vapor-cloud exclusion zones, particularly the use of “mitigation” methods such as gas-impervious concrete fences to prevent advance of vapor clouds beyond the applicant’s property lines, could increase the potential for serious, even catastrophic, vapor cloud explosions. The JCE Terminal DEIS appears to ignore international experiences of catastrophic unconfined vapor cloud explosions (UVCE), at least four of which occurred in the last decade, destroying the facilities involved as a result of cascading events.

- **<u>Design Spill Accident Selection</u>**

The design spill specified for the ship's cargo unloading line for the Jordan Cove Export facility has been designated as a guillotine break of a 36 inch line with a ten minute duration spill of 827,740 gallons. Havens’ 2009 review[1] of eleven LNG import terminal environmental impact statements indicates approvals for ship unloading line design spills ranging from 28,900 gallons (Keyspan, not approved) to 812,000 gallons (Trunkline, approved). FERC provided no quantitative justification for approving such large variations for these eleven spills, which resulted in large variations in the extent of vapor cloud exclusion zones. Since the vapor cloud zone determinations are directly related to the amount of LNG spilled, this lack of consistency in the design spills selected for analysis by the various applicants has the appearance of simply determining the size of the spill that the applicant’s property line distance will allow. None of these widely varying approvals appear to have been supported by quantitative science-based analysis.

The Jordan Cove Export (JCE) DEIS illustrates the potential for misunderstanding in the current design-spill-selection process. The JCE DEIS specifies a ship unloading line (SUL) spill of more than 827,000 gallons into a concrete impoundment basin. To our knowledge this JCE SUL spill is the largest specified by any terminal applicant to date. To the reader uninitiated in the complexities of this process, this choice of design spill might be viewed as conservative (assuming a worst case spill of nearly a million gallons of LNG). However, current scientific knowledge concerning such events ensures that the applicant would have no hope of guaranteeing that the vapor cloud from such a large spill could be maintained within their property boundary *without incorporating extreme*

[1] Havens, J., Consequence Analyses for Credible LNG Hazards, Second Annual AICHE/CSCHE Topical Conference, Montreal, Quebec, August 2009

measures. The extreme measures proposed to contain the cloud on the JCE's property are vapor-impervious concrete fences, some forty feet tall, which prevent the advance of a vapor cloud in selected directions. We believe this provision could result in defeating the purpose of the exclusion zones for ensuring public safety - by introducing additional severe hazards of vapor cloud explosion.

There are other serious problems with the design spill quantities and vapor dispersion (vapor cloud formation) predictions. The vapor dispersion model predictions presented assume maximum wind speeds (presumably at 10 meters elevation) of 1-2 m/s. Near the ground (one to five meters elevation) the wind direction fluctuation (as well as the speed) is very uncertain in near-calm wind conditions. There are proven scientific reasons to expect that low-wind speed (near-calm) conditions combined with the high density stratification of the cold LNG vapor cloud near the spill can increase the potential for damaging vapor cloud explosions. In such conditions the advance of the LNG vapor cloud is determined primarily by gravity forces on the cloud; typical cloud advance speeds would be around one (or even a fraction of one) meter per second. As a consequence, mixing of LNG vapor with air would be exceptionally "slow", and some degree of partial "containment of the cloud" would result due to the vapor fences' holdup effect. Finally, we expect that since the fences do not surround the property (there are gaps where the gas could get through) it is likely that simulations of the vapor dispersion, even with the presently specified fences, might not predict containment of the flammable gas cloud boundaries at higher wind speeds.

- **Vapor Dispersion Models are Proprietary and are not Available for Public Vetting**

The vapor dispersion models (also used for the damaging explosion-overpressure predictions) are not available for independent inspection or evaluation. While the models are presumably available to anyone requesting such services, the cost would probably be prohibitive to the public. This is a very significant development in government regulation policy; previously such models (DEGADIS and FEM3A) were available to the public at no cost. We believe this situation should be reviewed; it has the potential to undermine confidence in the entire process.

At least two new vapor dispersion models have been approved, for a total of four; DEGADIS, FEM3A, and two new ones, PHAST and FLACS. In contrast to DEGADIS and FEM3A, the development of which were paid for with public funds and which were (and still are) freely available for use and independent evaluation, the new models are privately held (proprietary), prohibitively expensive to the public, and they are not freely available for evaluation of applicability and accuracy. To our knowledge PHAST and FLACS are the only models which have been used since they were approved, and they are the only (vapor dispersion) models used for the preparation of the JCE Terminal DEIS.

- **The Fire Radiation Design Spill Ignores the Potential for Severe Cascading Effects**

The controlling fire radiation exclusion zone distance calculated using LNGFIRE3 and presented in the JCE DEIS barely falls within the applicant's property boundaries. We believe that the application of the LNGFIRE3 model to such a tank-top scenario requires assumptions which are erroneous to describe the wind speed and flow patterns at the top of the tank and that these deficiencies could result in non-conservative predictions of exclusion zones. However, as we want to prioritize our concerns regarding hazards with severe (catastrophe) potential, we focus here on our concern that such a fire (tank-top), if it were to occur in a nearly full LNG tank, could burn for a protracted time period, perhaps twenty to thirty hours, and there would be no practicable way to extinguish it.

Professor Venart's study of this fire scenario raises serious questions regarding the possibility of massive failure of a full-containment LNG tank due to severe, long-term, fire heat exposure to the tank with such a fire atop it. We believe that if this Design Spill Fire is to be used to determine the fire-radiation exclusion zone, there must also be considered the potential for such a fire to cause catastrophic failure of the tank (or tanks), resulting in the rapid release (spill) of perhaps half a million gallons of burning LNG. Should that occur, the fire radiation distances from the earthen-berm tertiary containment provided would surely extend the estimated fire radiation exclusion zone requirements to provide for public safety well beyond the facility property lines, to say nothing of the potential for catastrophic damage to the entire facility. We present below excerpts from Venart's presentation to DOT's Pipeline and Hazardous Materials Safety Administration (PHMSA)[2] that illustrate our concerns for cascading failures following such a tank-top-fire-scenario.

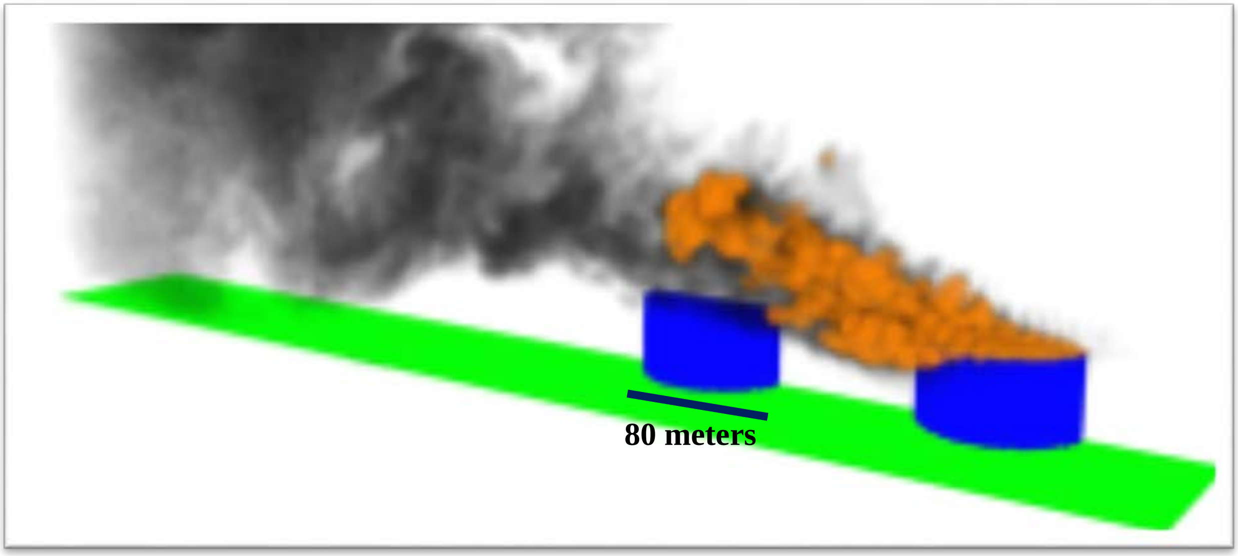
Description of full-containment LNG tanks

- Very large – 80 > 90 meters diameter, 40 > 50 meters tall
- Post tensioned reinforced concrete, walls 0.7 m thick, roof 0.5 m thick
- Post tension; steel, vertical and circumferential through buttresses and tendons
- Concrete shell outer layer, inner layers, vapor barrier (steel), insulation (perlite) Nickel-steel LNG containment
- Plumbing, in and out, through the tank top

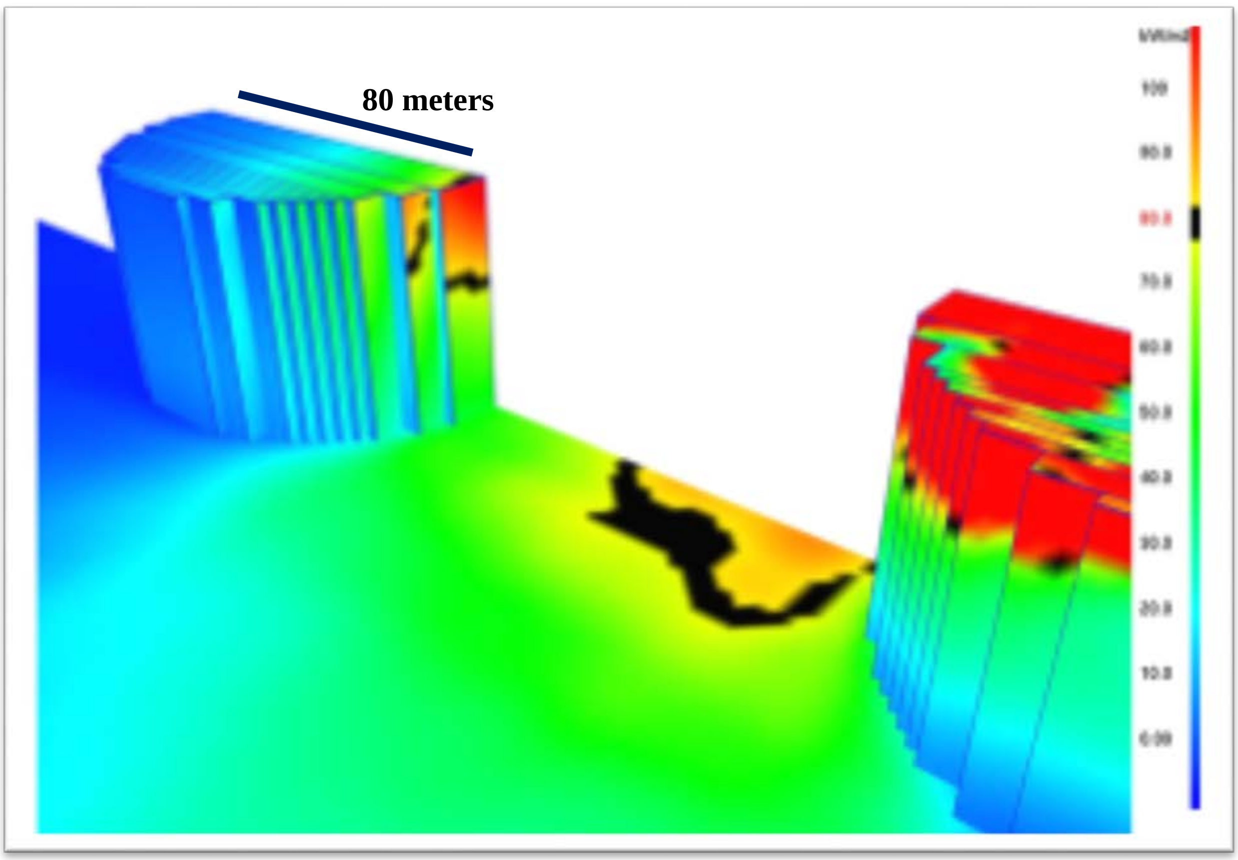
Typical Tank(s)

[2] Venart, J., LNG Tank-top Fires: Radiation Exclusion Zones, Presented to DOT PHMSA, Washington, DC, May 30, 2013.

LNG tank-top fire (high wind speed) FDS model results by Venart



Smoke and Fire Development for Two Tanks



Down-wind tank being exposed to an up-wind tank-top fire
Boundary heat flux for two tanks at 1 minute after fire initiation.
Incident heat flux exposures to both tanks in excess of 80 kW/m^2, wind 7.5 m/s.

Conclusions regarding tank-top fire and cascading failure scenario

- LNGFIRE3 has NOT been validated for the size of LNG fires anticipated for tank-top fires. Its use to establish conservative thermal exclusion zones is suspect.
- If not extinguished such a tank-top fire could possibly burn for 20-30 hours.
- NIST FDS CFD and experimental studies establish that the wind flowing around the sides of the tank tends to drag the flame down over the edge of the tank towards the ground. This exposes the concrete containment to high temperatures, radiant fluxes greater-than-design and thus thermal stresses with a potential for spalling, cracking, and other failure modes, thus loss of support to the interior mild steel moisture barrier and the insulating perlite.
- Thermal stresses to this complex system over the many hours of fire exposure could possibly cause collapse of the downwind edges of the Nickel steel primary containment and loss of LNG into the Perlite, a situation perhaps sufficient to result in total collapse of the containment system due to thermal stress. Under such conditions escalation of the event would be inevitable.
- The extent of the pool fire could now increase to the edges of any berm-impoundment surrounding the tank area, if provided, and a very much larger pool fire could result (of shorter duration).
- With two tanks, if one tank did not collapse, its adjacent neighbor would be exposed to heat fluxes greater than 80 kW/m^2 should the prevailing wind result in its flame exposure. Due to the increased fire size, plant processing areas could be adversely affected and the public radiation exclusion zone substantially increased.

- **Potential for Cascading Events Increases with Heavier-than-Methane Hydrocarbons**

The JCE DEIS pays little attention to the potential for boiling liquid expanding vapor explosions (BLEVEs) and UVCEs involving the liquefaction facilities. There appears to be a lack of coordination between the federal agencies (FERC and EPA[3] in this instance) in consideration of hydrocarbon explosion potential. We suspect that this is due to past emphasis of the regulations on LNG-only facilities. We quote from the Executive Summary of EPA 744-R-94-002:

> **This report assesses the potential consequences of accidents involving flammable chemicals to support the evaluation of whether such chemicals may warrant addition to the list of extremely hazardous substances (EHSs) under section 302 of Title III of the Superfund Amendments and Reauthorization Act (SARA). EPA's analysis included identification and evaluation of existing listing and classification systems, along with any applicable criteria; review of existing regulations and codes dealing with flammable materials; analysis of histories of accidents involving flammable substances; and modeling potential consequences of fires and explosions of flammable substances. …**
>
> **A review of accident history indicates that flammable substances have been involved in many accidents, and, in many cases, fires and explosions of flammable**

[3] Flammable Gases And Liquids And Their Hazards, United States Environmental Protection Agency, EPA 744-R-94-002, February 1994

substances have caused deaths and injuries. Accidents involving flammable substances may lead to vapor cloud explosions, vapor cloud fires, boiling liquid expanding vapor explosions (BLEVEs), pool fires, and jet fires, depending on the type of substance involved and the circumstances of the accident.

Vapor cloud explosions produce blast waves that can potentially cause offsite damage and kill or injure people. EPA reviewed the effects of blast wave overpressures to determine the level that has the potential to cause death or injury. High overpressure levels can cause death or injury as a direct result of an explosion; such effects generally occur close to the site of an explosion. EPA's analysis of the literature indicates that people also could be killed or injured because of indirect effects of the blast (e.g., collapse of buildings, flying glass or debris); these effects could occur farther from the site of the blast. A vapor cloud may burn without exploding; the effects of such a vapor cloud fire are limited primarily to the area covered by the burning cloud. The primary hazard of BLEVEs, pool fires and jet fires is thermal radiation; the potential effects of thermal radiation generally do not extend for as great a distance as those of blast waves. In addition, the effects of thermal radiation are related to duration of exposure; people exposed at some distance from a fire would likely be able to escape. BLEVEs, which generally involve rupture of a container, can cause container fragments to be thrown substantial distances; such fragments have the potential to cause damage and injury. Fragments and debris may also be thrown out as a result of the blast from a vapor cloud explosion.

The probability of occurrence of vapor cloud explosions appears to be rather low, based on analysis of the literature. EPA reviewed factors that may affect the probability of occurrence of a vapor cloud explosion, including the quantity of flammable vapor in a cloud, the presence of obstacles or partial confinement, and the type of ignition source. ***Analysis of accidents indicates that vapor cloud explosions are less likely when the quantity in the cloud is less than 10,000 pounds. (emphasis added)*** **It is generally thought that some type of obstruction or confinement enhances the probability that a vapor cloud explosion, rather than a vapor cloud fire, will occur. A high energy ignition source also contributes to the probability of occurrence of a vapor cloud explosion. …**

Based on modeling and analysis of the literature, flammable gases and volatile flammable liquids appear to be the flammable substances of most concern, because they may readily form vapor clouds, with the potential for damaging vapor cloud explosions. EPA identified a number of such substances of concern. The analysis carried out by EPA for this report was intended to provide a general background on the hazards of flammable gases and liquids. The modeling results and accident data illustrate and compare the consequences of vapor cloud explosions, vapor cloud fires, BLEVEs, and pool fires. …

There have been a large number of devastating hydrocarbon explosions, particularly BLEVEs, since 1994. Finally, we note that the design spills considered in the JCE DEIS exceed the 10,000 pound figure suggested by EPA as demarcating the size below which UVCEs are "improbable" (see emphasis added text in the EPA report quoted above) by at least a factor of 10, and in the case of LNG spills, by a factor of perhaps 300.

- **<u>The Vapor Clouds Formed from the Design Spills Pose Severe Explosion Hazards</u>**

The vapor dispersion distances calculated using PHAST and FLACS, while extending in some cases slightly past the applicant's property boundaries, obviously could not have been determined by the (dispersion) models used without the applicant's provision of gas-impermeable vapor fences to retain the flammable cloud boundaries within the property boundary. The Figure below indicates the position of the proposed vapor fences; gas-impermeable concrete fences as tall as forty feet.

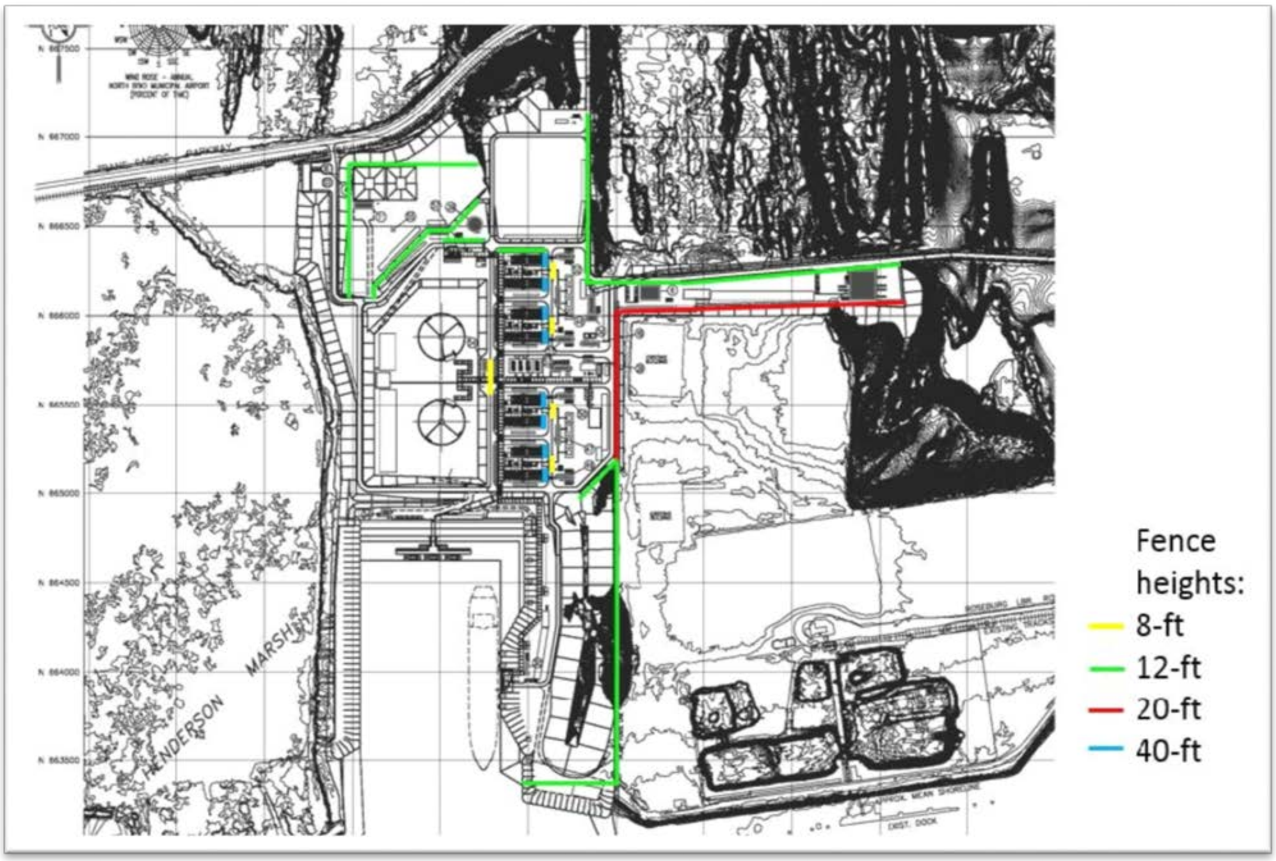


Figure 4.13-1 from DEIS
Vapor Fences at Jordan Cove Facility

Vapor Cloud Explosion hazards of LNG

The Jordan Cove Export DEIS FERC summarily dismisses the potential for methane vapor cloud explosions with the following statement:

> *The potential for unconfined LNG vapor cloud detonations was investigated by the Coast Guard in the late 1970s at the Naval Weapons Center at China Lake, California. Using methane, the primary component of natural gas, several experiments were conducted to determine if unconfined vapor clouds would*

> *detonate. Unconfined methane vapor clouds ignited with low-energy ignition sources (13.5 joules), produced flame speeds ranging from 12 to 20 mph. These flame speeds are much lower than the flame speeds associated with a deflagration with damaging overpressures or a detonation.*

In consideration of the potential for mixtures of methane with heavier hydrocarbons that could be present at the terminal, the DEIS continues the statement immediately above with the following:

> *To examine the potential for detonation of an unconfined natural gas cloud containing heavier hydrocarbons that are more reactive, such as ethane and propane, the Coast Guard conducted further tests on ambient-temperature fuel mixtures of methane-ethane and methane-propane. The tests indicated that the addition of heavier hydrocarbons influenced the tendency of an unconfined natural gas vapor cloud to detonate. Less processed natural gas with greater amounts of heavier hydrocarbons would be more sensitive to detonation. … Although it has been possible to produce damaging overpressures and detonations of unconfined LNG vapor clouds, the Jordan Cove Project would be designed to receive feed gas with methane concentrations as low as 94 percent, which are not in the range shown to exhibit overpressures and flame speeds associated with high-order explosions and detonations.*

However there is an important scientific paper describing the Coast Guard sponsored tests at China Lake[4] which contains the following (page 13):

> *The second group of tests was designed to test a postulated accident scenario in which the vapor formed during a LNG spill is mixed with air to form a flammable mixture and then diffuses into a culvert system. The mixture in the culvert ignites and the combustion wave accelerates and transitions to a detonation. This detonation wave then exits the culvert and detonates the remaining unconfined vapor cloud. … a 6 m long culvert, 2.4 m in diameter, was buried vertically in the ground in the center of the polyethylene hemisphere. A stoichiometric mixture of methane/propane and air was introduced into the hemisphere and a detonation was initiated at the bottom of the culvert using a 3.2 mm thick layer of datasheet explosive (13 kg). In tests 1 and 3 (reported to be 85% methane and 94% methane), a strong shock wave was felt at the bunker and also in the town of Ridgecrest, 22 km from the test site. … <u>Based on the test data, it appears that in tests 1 and 3 a detonation was produced within the unconfined cloud (emphasis added)</u>.*

The Coast Guard Test No. 3 described immediately above was 94% methane, the lower limit methane concentration that Jordan Coves plans to accept as input feed to the terminal. While we acknowledge the use of a high-energy ignition source in CG Test No. 3, that is not sufficient reason to dismiss this test result as being meaningful for the Jordan Cove Export Terminal hazard assessment. The possibility of intentional use of high-explosives to ignite a vapor cloud must be considered - such methods are used routinely in the military to ignite the vapor/aerosol

[4] Parnarouskis, M., et.al., “Vapor Cloud Explosion Study”, Sixth International Congress on Liquefied Natural Gas, 1980.

hydrocarbon/air clouds formed in the use of fuel-air (FAE) weapons. There are additional factors which can add to the potential for accidental occurrence of a "boosted" ignition source in the vapor clouds that could be formed following the spills being considered at the JCE facility.

Perhaps most importantly, as vapor fences at the Jordan Cove Facility could (in addition to the spill-guidance trenches and impoundments themselves) provide a degree of partial confinement to the cloud, there is additional potential for run up to detonation, especially if the cloud contains more than a few percent ethane/propane or equivalent heavy components.

All of the figures presented in the DEIS of flammable vapor cloud travel distance for the LNG design spills illustrate simply that the vapor fences prevent travel (except in minor cases which FERC has provided exceptions for) beyond the applicant's property boundary. We believe these results entirely miss the point of the intention of the regulations – to provide for public safety. These figures appear to indicate that the authors of the application (Jordan Cove and their Consultants) believe that the hazard extent of these spills ends at the calculated lower flammable limit concentration reached by the cloud (the cloud boundaries depicted represent concentration LFL/2, as required by the regulation). However, this assumption was historically based on the fact that a reasonable limit on the fire damage from a vapor cloud fire, which would be of short duration, would not extend significantly beyond the flammable vapor concentration boundary. The parties that prepared the JCE DEIS must surely be aware of the serious potential for an unconfined vapor cloud explosion to extend well beyond the limits of the flammable cloud boundary. In the text above describing the Coast Guard's explosion tests at China Lake, we provided evidence of the potential for LNG clouds that contain small amounts of heavier-than-methane hydrocarbons to develop damaging overpressures. We focus on two of the figures presented in the JCE DEIS, both for the design spills from the LNG ship unloading line. The points we wish to emphasize are specified immediately following the figures.

Figure 4.13.5 from DEIS
LNG Spill from a Guillotine Rupture of the Ship Loading Header

The area covered by the cloud in Figure 4.13.5 is estimated to be approximately 320 meters wide and 480 meters long (top to bottom in the figure). We estimate this gas cloud would be between 2 and 4 meters deep. The cloud envelops a large portion of the liquefaction trains; these trains are dense packed equipment structures which are known to accelerate flames in such a gas cloud sufficiently to cause damaging overpressures. The cloud essentially surrounds the LNG storage tanks.

Figure 4.13-7 from DEIS

LNG Jetting and Flashing Scenario from a Rupture of the Ship Loading Header

The area covered by the cloud in Figure 4.13.7 is estimated to be approximately 400 meters wide and 720 meters long (top to bottom in the figure). We estimate this gas cloud would be between 2 and 5 meters deep. The cloud envelops the LNG shipping berth, indicating that a ship at the berth would be completely surrounded by the flammable cloud. While the dense packing of equipment seen in the previous figure associated with the liquefaction trains is not inside the cloud, there are containment factors associated with the space between the sea wall and the carrier that could cause damaging flame accelerations leading to explosions. We wonder what an LNG ship's Master would say if she were informed that a flammable cloud of hydrocarbons was about to surround her ship.

Vapor Cloud Explosion hazards of mixed refrigerant liquids (hydrocarbons C2-C5)

For brevity, we focus on only one of the figures presented in the JCE DEIS for mixed refrigerant liquids; the design spill from the rupture of the inter-stage refrigerant pump discharge piping. The points we want to emphasize are specified immediately below the figure.

Figure 4.13-10 from DEIS
Mixed Refrigerant Release from Rupture of the Inter-stage Refrigerant Pump Discharge Piping

The area covered by the cloud in Figure 4.13.10 is estimated to be approximately 400 meters wide and 720 meters long (top to bottom in the figure). We estimate this gas cloud would be between 2 and 4 meters deep. The cloud envelops large portions of the liquefaction trains as well as at least half of the LNG shipping berth, including the space between the ship and the sea wall. We believe that an unignited MRL vapor cloud as indicated here could have the potential to cause a catastrophic UVCE that would result in severe cascading effects endangering the entire terminal.

Vapor Cloud Explosion hazards of ethylene

The DEIS presents a single vapor cloud prediction for the 14,000 gallon ethylene design spill. The wind speed is specified as 1 m/s (essentially calm). The area covered by the cloud in Figure 4.13-13 is estimated to be approximately 320 meters wide and 400 meters long (top to bottom in the figure). We estimate this gas cloud to be between 2 and 4 meters deep as well. The cloud envelops large portions of the liquefaction trains as well as all of one of the LNG tanks and about ¼ of the other one. The DEIS states that the ethylene release scenario at the refrigerant trucking area would remain within Jordan Cove's property or extend over a navigable body of water, so it would not have a significant impact on public safety with respect to flammable vapor dispersion.

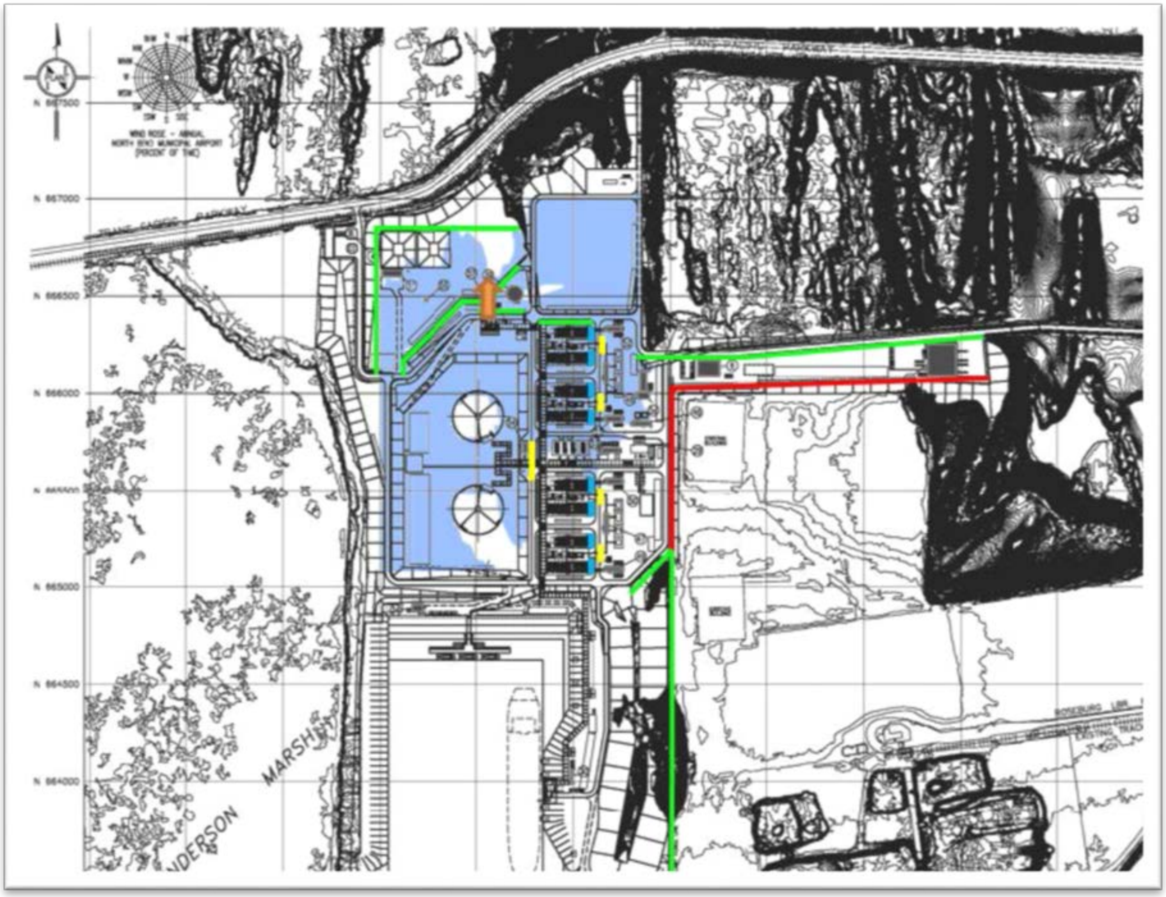


Figure 4.13-13. Ethylene Release from Rupture of the Ethylene Trucking Hose

Overpressure Analyses

The DEIS at page 4-963 states the following. "… the propensity of a vapor cloud to detonate or produce damaging overpressures is influenced by the reactivity of the material, the level of confinement and congestion surrounding and within the vapor cloud, and the flame travel distance." We add that the potential flame travel distance is the distance that can be traversed by the flame in gas/air concentrations lying within the flammable region, i.e., between the LFL and UFL. This travel distance is in turn determined by the amount of flammable gas that is mixed with air in the cloud, and thus by the amount released into the atmosphere. The implications are clear; if a very large vapor cloud can form with large distances that can be traversed by a flame burning in the flammable region, the potential for flame acceleration increases.

While the DEIS presents explosion overpressure predictions for the mixed refrigerant gases, it dismisses the (UVCE) explosion hazards for LNG. We believe this cannot be justified for the following reasons:

- The Coast Guard Tests show that with a strong igniter (high explosive), methane with about 6% propane added detonated. The DEIS states that Jordan Cove "will limit the heavier than methane hydrocarbon content in the LNG streams to 6%". This leaves no margin for safety, even if they could be certain of maintaining those levels.

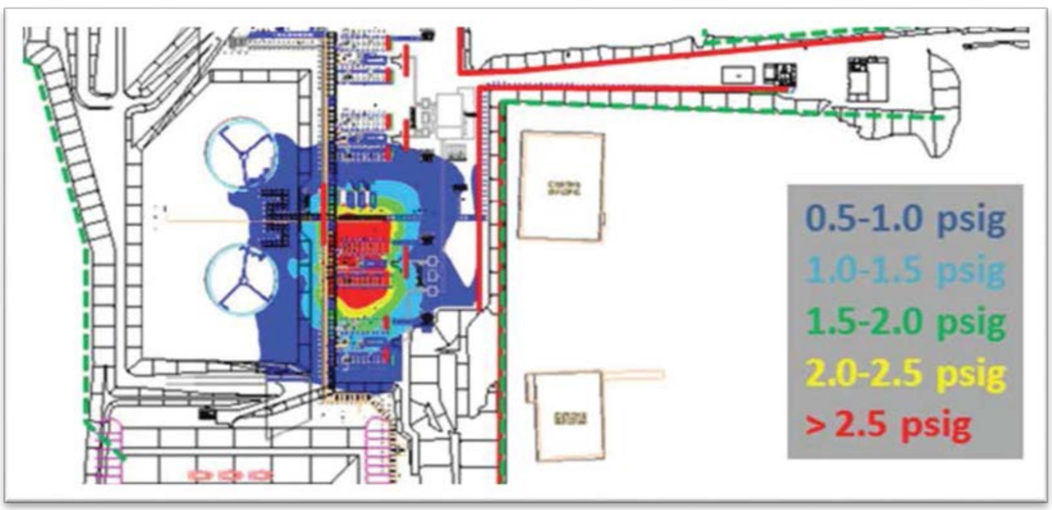
- The LNG spills are huge, and the vapor clouds formed have linear dimensions of hundreds of meters, with a corresponding potential for excessive flame acceleration.

- Secondary explosions that could boost the explosion processes cannot be discounted.

Nor do the overpressure calculations for the mixed refrigerant spills offer any consolation:

- The calculations of overpressure presented indicate very large areas of flammable gas envelopment of process equipment as well as the LNG tanks

- There are regions with linear dimensions of approximately 100 meters where the calculated pressures exceed 2.5 psig, but there is no specification of the maximum pressures reached. (See Figure 4.15-13 from the DEIS below.)



- If there exists evidence of agreement of the calculation methods used in the DEIS with large scale experiments and/or accidents that provide some confirmation of these predictions, including statements of the uncertainty which must be assumed in the overpressure predictions, such evidence should be made available for assessment, otherwise the calculations have little value, particularly in the face of recent accident experience we present below.

The DEIS acknowledges the potential for ethylene vapor clouds to detonate, but there are no overpressure calculations presented to accompany the ethylene dispersion calculations presented earlier. The mixed refrigerant spill overpressure calculations indicated approximately 2.3 psig overpressure at the LNG storage tanks. This statement is followed by "Jordan Cove stated that the LNG storage tanks would be designed to withstand an overpressure of 2.3 psig"… and that "We (presumably FERC) conclude that the siting of the proposed Project would not have a significant impact on public safety". In our opinion that statement does not indicate good engineering judgment, as it assumes a precision and accuracy of the model predictions that no scientist or engineer we know would endorse.

Potential for Catastrophic Unconfined Vapor Cloud Explosions (UVCEs)

Recent accident experience demonstrates that conditions are best for large vapor clouds to form if there is a mechanism for rapid evaporation of the spilled liquid and if there are near calm conditions which prevent rapid dispersion. The design spills considered for the Jordan Cove Export Terminal fit both criteria; the conditions considered are low-wind, near calm, and the materials are highly volatile; most volatile in the order of decreasing carbon content: methane, ethylene, propane, and pentane. The simple fact is that while the vapor clouds considered in this DEIS are prevented by physical barriers (vapor fences) from posing a vapor cloud hazard extending much beyond the property line, the holdup of very large quantities of flammable hydrocarbons by the vapor fences causes the gases to accumulate, with spreading largely driven by gravity spreading, so as to completely fill the affected areas to depths of a few meters, with large portions of those gas clouds having concentrations between the flammable limits. With these hazard-worsening conditions and the presence of densely packed processing equipment and the vapor fences which become enveloped in the cloud, one could hardly design the releases to better maximize the potential for catastrophic explosion hazard.

Catastrophic UVCEs are Becoming More Frequent

Confirmed scientific knowledge of the causes of UVCEs indicates that their frequency would increase with the potential for release of large quantities of hydrocarbons, especially highly volatile ones. As we have stated earlier, the sizes of flammable hydrocarbon vapor clouds described in the JCE DEIS have lateral dimensions of up to 720 meters (~2,400 feet). To our knowledge, there have been no UVCEs in the continental United States involving flammable clouds that large. The largest vapor cloud considered at JCE, which would follow a spill of ~3/4 million gallons of LNG, involves the most volatile of the hydrocarbons, methane (CH_4), which is lowest on the explosion sensitivity scale; but the mixed refrigerant liquid (MRL) spills are very large, and they approach the range of maximum sensitivity to explosion.

It appears that the relative rarity of large UVCEs (until recently) is very likely due to the fact that most of the very large spills that have occurred did not evaporate rapidly enough, and/or were dispersed readily by the action of wind, to allow formation of a large flammable cloud . But, now there have been at least four instances within the last ten years of devastating UVCEs following very large releases of gasoline class hydrocarbons where the evaporation of the fuels was rapid enough, and the wind speed essentially non-existent, to allow the formation of flammable vapor clouds with lateral dimensions of several hundred meters. In all four cases these clouds were ignited (presumably accidentally) and the explosions resulted in cascading events leading to catastrophic damages to the facilities (refineries/tank-farms) and injury/and/or deaths in the public sector. The first occurred in December, 2005, at Buncefield in the United Kingdom. There followed three more: Jaipur, India, 2009; San Juan, Puerto Rico, 2009; and Amuay, Venezuela, 2012. The following facts are a matter of record for all four:

- The events occurred in very low wind (near calm or calm) weather conditions.
- The maximum linear extents of the flammable clouds were at least 250 meters, ranging to at least 650 meters at Amuay.
- UCVEs occurred in every case that registered above 2.0 on the Richter Scale.
- The initiating explosions resulted in cascading events leading to total loss of the facilities.

We provide below photographs of these accidents (depicting the cascading fire and explosion effects) indicating the catastrophic damages that resulted. In our view, these four events, which have similar descriptions of the weather conditions and physical factors that could cause extremely large flammable vapor clouds to form, and with which the vapor cloud scenarios considered in the JCE DEIS are clearly similar, should be a clear warning to parties planning facilities with similar potential for catastrophe.

Buncefield, United Kingdom

Jaipur, India

Amuay, Venezuela

San Juan, Puerto Rico

Scientific Conclusions re the Buncefield Event are Directly Relevant to the JCE DEIS

To our knowledge, detailed reports of the explosions in India, Venezuela, and Puerto Rico have not been completed. However, during the decade 2005-2015 since the Buncefield explosion occurred there have been published extensive reports of analyses thereof. The Buncefield explosion, which has been definitely established to be a UVCE, is thought to be the largest explosion that has occurred in peacetime Europe; damages now exceed two billion dollars.

In 2012, there appeared a paper in the Philosophical Transactions of The Royal Society (Great Britain) by D. Bradley, G.A. Chamberlain and D.D. Drysdale[5] entitled “Large vapour cloud explosions, with particular reference to that at Buncefield”. As this paper appears to be the most

[5] Phil. Trans. R. Soc, A 2012 370, doi: 10 1098/rsta.2011.0419, published 2 January 2012

recent to summarize the present understanding of the increasing potential hazards of unconfined vapor cloud explosions (UVCE) of hydrocarbon-air mixtures, we quote directly from the Conclusions section thereof:

> **A number of mechanisms for the propagation of combustion have been discussed, without reaching any definite conclusions as to what precisely happened at Buncefield. Of particular importance was the acceleration of turbulent flames along the line of trees and hedgerows. There was no unequivocal evidence that a principal mode of reaction was a fully developed detonation sweeping across the site. There was, however, evidence that the observed damage and various camera records could be explained in terms of high-speed deflagrations and quasi-detonations. The former could generate localized flamefront over-pressures of 400 kPa and, with sufficient confinement, shock pressures of 1 MPa. Quasi-detonations, the details of which are complex, can create constant volume combustion over-pressures of about 0.7-0.8 MPa, while a detonation would give a pressure spike of 1.75 MPa.**
>
> **…**
>
> **Other areas for further study emerge, some of which are included in the Buncefield Explosion Mechanism Phase 2 programme. The most significant should include the following.**
>
> **i. Analysis of the complexities of multi-component gasoline spillage, involving droplet break-up, air entrainment and vapour production, followed by dispersion in still air over uneven terrain. Dispersion under almost still conditions provides significant modelling challenges.**
>
> **ii. The mathematical modelling of explosions through densely packed, small-scale, flexible obstacles and the question of whether reactant temperatures and pressures can become high enough for a DDT. The modelling of transitions to detonation and the conditions for their continuing propagation are particularly challenging, in terms of both the underlying science and the required computing power.**
>
> **iii. A related experimental investigation of flame acceleration, with and without "bang-box" initiation, along hedgerows and lines of trees to ascertain the probability of a DDT and its continuing propagation into an uncongested cloud. Further investigations are also needed of direct jet flame "bang-box" ignition of external vapour clouds, to define the conditions that can lead to detonation of the cloud.**
>
> **iv. The generation of necessary fundamental experimental and theoretical data on autoignition delay times, laminar burning velocities, and the effects of flame stretch on high turbulent burning velocities, including extinctions, all over the relevant ranges of temperature and pressure. The combinations of (ii), (iii), and (iv) could provide retrospective guidance on the relative contributions of high-speed deflagrations, quasi-detonations and detonations to the damage at Buncefield.**

In closing with these selected conclusions of this scientific paper summarizing the research that experts consider necessary in order to develop a methodology applicable to the determination of the potential for unconfined vapor cloud explosions of hydrocarbon-air mixtures, we hope to send a clear message to the Federal Energy Regulatory Commission as well at the regulatory authority (DOT) that the methodologies depended on to ensure Public Safety in the Jordan Cove Export DEIS require careful, scientific, adjudication of the concerns we have raised – all of which we believe are supported by the extensive research regarding UVCE potential hazards post-Buncefield.

Appendix - A Brief History of LNG Regulation for Public Safety

LNG trans-ocean shipping, enabling import and export projects, has a relatively short history. The first cargo of LNG (27,400 m^3) shipped trans-ocean was delivered in 1964 from Lake Charles, Louisiana to Canvey Island (near London) in the United Kingdom[6]. The number of LNG carriers has now increased to more than 370, while ship capacities have increased by a factor of ten, with the largest ships today each carrying 266,000 cubic meters (70,264,000$^+$ gallons) of LNG. As the development of this industry has been decidedly fast-track, yet involves truly huge concentrations of energy-posing hazards in storage on land and in the ships, it is important to review the history of the development of methodology currently used by the United States Government to identify and regulate the hazards to the public that attend the operation of such facilities, onshore and off.

The Federal regulation 49 CFR 193: *Liquefied Natural Gas Facilities: Federal Safety Standards* was promulgated in 1980. 49 CFR 193, addressing the safety requirements regulated by DOT, is applicable on the land portion of the terminal(s) only. For our purposes in these comments, DOT's regulatory authority can be assumed to end at the point where the connections are made from the storage tanks on land to the loading lines on the ship. Beyond the shore-to-ship connection point, the principal authority granting approval for and regulating the operations is the Coast Guard. Both DOT and the Coast Guard have conducted extensive research, including field scale experiments, to define and quantify the hazards of fire radiation (heat damage) that could occur from vapor cloud and liquid pool fires, as well as the potential for explosion (generation of damaging overpressures) should a vapor cloud explode, to determine the appropriate measures which must be taken to provide for public safety.

Historically, the hazards of LNG are regulated based on the assumption that LNG is (primarily) liquefied methane (CH_4). In contrast, heavier-than-methane hydrocarbons, including the so-called Liquefied Petroleum Gases (LPG) which are necessarily present in large quantity in an LNG export terminal, are mixtures of hydrocarbon gases with molecular weights heavier than methane, such as ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and pentane (C_5H_{12}). According to the JCE DEIS the heaviest hydrocarbons handled in significant quantities at this terminal will be C_5H_{12}. This is a vitally important point for the present discussion, because while it may be reasonable to identify, even limit, LNG hazards at import terminals assuming the LNG properties are similar to those of pure methane, LNG export terminals are another matter. Export terminals thus must receive gas (normally by pipeline) for liquefaction and shipping that contain significant amounts of heavier (than methane) hydrocarbons. Because shipped LNG must be sufficiently pure methane in order to be burned efficiently in typical natural gas burning equipment, the heavier hydrocarbons present in the gas feed stream must be removed in a natural-gas-liquefaction facility before shipping. Significant amounts of heavier-than-methane hydrocarbons must be temporarily stored at the export terminal site and ultimately become part of the products that are shipped out of the

[6] http://www.eia.gov/todayinenergy/detail.cfm?id=16771

export terminal by various means. The result is that export terminals involve storage, handling, and usage of significant amounts of these heavy hydrocarbons which constitute hazards different from, and often more-severe-than, methane (the principal component of LNG).

The first author began research on LNG safety in 1976 (before the advent of 49 CFR 193) while on leave from the University of Arkansas serving as a technical advisor to the Office of Merchant Marine Safety of Coast Guard Headquarters in Washington, D.C. Havens' initial assignment was to review a collection of six mathematical (computer) model predictions of the maximum distance that could be reached by a flammable cloud of methane and air formed by spillage on water of the contents of a single tank of LNG from a typical LNG carrier of that day. The contents of a single tank on such a ship (typically containing five such tanks) was 25,000 cubic meters, or about 6 million gallons.

The problem the Coast Guard faced in 1976 was that the predictions of maximum flammable-gas-cloud extent from such a spill by six independent expert-preparers ranged from ¾ mile to 75 miles! In 1977 near the end of his off-campus-leave period Havens completed an analysis of the collection of predictions and prepared a report[7] for the Coast Guard which concluded that the lowest and highest estimates of distance were not credible and suggested that the range of distances would be much more likely to be between 3 and 10 miles. This was some progress, but the Coast Guard wanted a higher-confidence answer. Havens returned to the University of Arkansas with a contract to develop a personal-computer (PC) model capable of predicting hazardous vapor cloud dispersion distances for specified amounts of LNG spilled on water. The result was the DEGADIS model adopted by DOT and incorporated in 49 CFR 193 as the dispersion model used for LNG facility regulation to determine vapor dispersion exclusion zone (safe separation) distances.

Havens' 1977 report, in addition to enabling continuation of research on LNG vapor dispersion upon return to the University of Arkansas, had another very important effect on Havens, one which was brought back vividly while studying the Jordan Cove Export Project DEIS in preparation of these comments. Havens, at the suggestion of the Coast Guard, had sent his draft report to the authors of the predictions, requesting they provide reply-comments to the (Coast Guard) report. The authors of the predictions were informed that their replies would be published as part of the report. While all of the model-prediction-preparers provided written comments which were published in the report, and all were helpful, one preparer's reply still profoundly affects Havens' conclusions about the effectiveness of the United States regulatory program to provide for the public safety. Dr. James Fay, Professor of Mechanical Engineering at MIT, replied to Havens' request beginning with the paragraph quoted below.

> *"The discussion in the introduction (pp. 15-17) of the probability of various accident scenarios, which is clearly not an aspect of the scientific review of the various dispersion theories but more nearly a policy statement regarding risk, unfortunately tends to denigrate the value of this analysis. The reader may wonder whether the assessment is to be taken seriously, or has been carefully made, given the asserted unlikelyhood of the process being discussed. But if one ignores the casuistry of this portion of the introduction, the subsequent analysis is scientifically useful and more than worth the effort to have performed it."*

Fay's statement had focused on a very important failing of the report - the fact that Havens

[7] Havens, Jerry, "Predictability of LNG Vapor Dispersion From Catastrophic Spills Onto Water: AN ASSESSMENT", USCG-M-09-77, April 1977.
http://www.dtic.mil/dtic/tr/fulltext/u2/a040525.pdf

appeared to have felt a responsibility to give the report's readers an excuse to discount the hazards being discussed on the basis that they were very unlikely (low probability). But the report had provided absolutely no information supporting any estimate of such events' probability of occurrence; the inclusion of the statements about "likelihood" therefore had no valid purpose. Havens continues today to acknowledge that failure; Professor Fay was entirely correct. We leave it to the readers of the Jordan Cove Export Terminal DEIS to determine the validity/justification of the suggestions therein regarding the probability of the events under discussion. Of course, our concern is that any such analysis which includes discussion of the probability of occurrence of specific realizations of the hazards must be scientifically quantified to be useful. Without careful quantitative justification such assertions are likely to encourage wishful thinking that is dangerous given the potential severity of the consequences being considered.

There were five major SAFETY HAZARDS identified that determine the regulation of safe-siting (separation) distances from the terminal to protect the public. Those five hazards are still applicable to the Jordan Cove Export (JCE) Export Terminal (we are not addressing potential environmental hazards):

- Toxicity
- Cryogenic Exposure
- Liquid Pool Fires
- Vapor Cloud Fires
- Vapor Cloud Explosions

As this submission focuses on safety hazards to the public offsite, we agree that toxicity and cryogenic exposure hazards are not nearly as likely (compared to the remaining three) to pose serious threats to the public.

The United States Government has conducted major research programs to define and quantify the hazards that attend the siting on land of LNG import terminals and the marine operations associated with LNG ship carriage. We will not attempt to describe the research efforts conducted by industry; our discussion focuses on government sponsored research designed to quantify, for regulatory purposes to provide for public safety, the three hazards identified above; liquid pool fires, vapor cloud fires, and vapor cloud explosions.

The interest in LNG importation in the United States has been highly cyclic. During the period ~1970-1985, the first four import terminals were constructed in the continental U.S., all on the East and Gulf Coasts: Everett, MA; Cove Point, MD; Elba Island, GA; and Lake Charles, LA. There were several import terminals proposed onshore and offshore California, but none were ever constructed. Extensive LNG research was performed during this period to develop the Government's knowledge base supporting public safety-regulation. Then, after a decade or more lull in interest in LNG terminals, another rush to construct import terminals developed at the turn of the century with more than fifty import terminals proposed in short order. The attack on the World Trade Towers on 9-11-2001 heightened concerns about LNG safety, partly because of the presence of the import terminal in Boston Harbor (Everett, MA). The Government's responses to the multiple terrorist attacks on 911 included preventing a scheduled LNG ship from entering the Everett, MA, terminal, holding it offshore for several days before directing it to proceed to Elba Island, GA to unload. This was due to concerns that LNG facilities in highly populated areas might be considered attractive targets for terrorist attack; this concern is still with us. Research directed to LNG safety following 911 was primarily directed to hazards to the public of the shipping side of import projects then operating. There developed as a result another period of

LNG safety research, primarily directed at marine (shipping) operations, which has continued to the present.

The First Research Period: ~1970-1985

At about the same time that Havens was digesting Professor Fay's review of the Coast Guard Report, Congress appropriated substantial sums (~$40,000,000) for the Lawrence Livermore Laboratory (LLNL) and several other Contractors, including the China Lake Naval Weapons Center, to research outstanding questions about LNG liquid pool fires, vapor cloud dispersion, and vapor cloud explosion hazards. LLNL built a purpose-designed spill test facility at the Nevada Test Site on the old (Frenchman Flat) nuclear weapons test site to conduct LNG spill research. A principal product of this work was the complex mathematical model for LNG vapor dispersion called FEM3 (acronym for Finite Element Model – 3 dimensional). The model was designed to address the need for prediction of vapor dispersion in the presence of terrain effects and obstacles such as buildings and plant structures. Extensive reports of this work are available. The University of Arkansas was subsequently contracted by the then Gas Research Institute to develop a PC version of FEM3, and the University carried out some validation experiments using a purpose-built ultra-low-speed wind tunnel (the largest ultra-low-speed wind tunnel in the world at that time). That PC version became known as FEM3A, and it was adopted by DOT as an alternative (to DEGADIS) model that could be used by LNG facility applicants to consider the effects on dispersion distances that would result from the presence of obstacles or terrain features.

Meanwhile, the China Lake Naval Weapons Test Station conducted (for the Coast Guard) a series of liquid methane and propane spills to investigate the potential for fire radiation damage extending from fires of different sizes and also conducted an extensive series of tests of unconfined gas clouds of methane and propane mixtures of uniform concentration (contained in balloons) to determine the potential for such clouds to cause damaging overpressures (explosions). Extensive reports of this work are available.

The pool fire test data from China Lake was used to develop the LNGFIRE model series, which is still used to determine the regulation-required separation distances to prevent radiative (fire) fluxes that can cause serious burns to the public. The principal results of the unconfined gas cloud explosion work, here intentionally simplified for brevity, were:

- Pure methane (unconfined) did not burn with damaging overpressures (explode) unless a sufficiently energetic "starting" explosion ignited the cloud.
- The presence of sufficient amounts (say >10-15%) heavier components such as propane mixed with methane resulted in damaging overpressures.

Since that early work there have been numerous severely-damaging accidental explosions of <u>unconfined</u> mixtures of propane (and heavier hydrocarbon gases) with air.

The research conducted by the Government described above occurred in the same decade in which the Atomic Energy Commission was abolished in favor of the Energy Research and Development Agency, later succeeded by the present Department of Energy. At first there was a move to design the regulatory framework for LNG management (LNG had been promoted to the class of Major Hazards by the British Health and Safety Agency by that time) based on probabilistic risk assessment procedures, as was being suggested as the favored method to regulate the safety aspects of nuclear electric power plants. However, DOE and DOT (the latter by that time the agency responsible for natural gas pipeline safety) took on the responsibility of developing regulations governing the siting of LNG terminals. The responsibility for the shipping side went to the Coast Guard.

DOT incorporated a purely consequence-based approach (with no consideration of quantitative measures of risk, meaning the probability with which an event might occur) which is still in use. Initially, regulations required the terminal applicant to determine safe separation distances, separately, for (unignited) vapor cloud travel and pool-fire radiation hazards. The applicant was required to use regulatory approved mathematical (computer) models to determine the maximum hazard distance for "worst case" vapor cloud releases and liquid pool fires. Up to ~2000, such calculations were required to be completed using DEGADIS (and later FEM3A) for vapor dispersion, and LNGFIRE for pool fires). The starting assumption (the event required to be modeled) was typically complete failure, resulting in rapid release, of the largest contained volume of LNG at the site, with no regard to the probability (or in many minds, the impossibility) of such an occurrence.

But, just as had occurred during this time period in the Nuclear Industry, there was soon adopted a practice of selecting so-called "Design" accidents which set lower requirements for the amounts of LNG to be released. The LNG regulations adopted specification of "Design" Spills to place limits upon the amount of material released and the rate at which it could be released. That is where we are today, which leads the authors to believe that an "inevitable" result has occurred - when the calculated distances required to separate the public from the hazard became "unmanageable" the release magnitudes (the so called "SOURCE" terms) were decreased. While we realize that the realities of economy as well as other factors can sometimes indicate, if not require, such changes, and that this pattern is established more or less world-wide today by major hazards industries in siting practice to protect the public, we believe it is a classic example of a process involving a seriously slippery slope. We believe that we have already reached the condition in LNG safety regulation where the determination of the design spill is effectively inseparable from the determination of the amount of land that the facility operator can purchase to insure that the public cannot intrude on. And, most importantly, the methodology for determining the "maximum" design spills that must be planned for appear to have evolved based on far-less-than-scientific reasoning processes. Although this issue is far too big to "take on" here, we want to state clearly our belief that the "agreements" on the sufficiency of the materials submitted to FERC by the applicants for the Jordan Cove Export Project have resulted far too much from "helpful cooperation" with the regulatory authority, with the result that the design spills (read spill quantity and rate of release as well as usage of vapor cloud travel "mitigation" methods) now effectively limit the hazard distances to a level considered "manageable" by the applicant.

The Second Research Period (2000-present)

As of October of 2014 seven more import terminals (beyond the original four) are in operation: Offshore Boston, Massachusetts (Excelerate Energy); Freeport, Texas; Sabine, Louisiana; Hackberry, Louisiana; Offshore Boston, Massachusetts (GDF-SUEZ); Sabine Pass, Texas; and Pascagoula, Mississippi. Three more import terminals have been approved, but are not yet under construction: Gulf of Mexico (Main Pass McMoRan Exp.); Offshore Florida; and Gulf of Mexico (TORP Technology– Benville LNG). Finally, (as of October, 2014), one export terminal has been approved and is under construction: Sabine, Louisiana. Three other export terminals have been approved but are not yet under construction: Hackberry, Louisiana; Freeport, Texas; Cove Point, Maryland. All of these import and export terminals have been approved by FERC based (with respect to safety and reliability requirements) on meeting the requirements of DOT Regulation 49 CFR 193 and Coast Guard Letters of Recommendation.

Following 911 (2001), new concerns arose that LNG ships, already plying the waters in heavily populated areas such as Boston, could pose unacceptably severe hazards to the public, either resulting from accidents or terrorist attacks. In response, Congress appropriated substantial additional sums for research to better quantify the severity of hazards that could be realized, with emphasis on LNG ship movements to and from, and berthed at, operating LNG facilities. This research was conducted principally by the Sandia National Laboratory and focused principally on two questions about the hazard distances that could extend from LNG ships which suffered accidental (or intentional) releases of LNG onto water; by vapor cloud travel (if the spill was not immediately ignited upon release), or by fire radiation (heat damage) from the liquid pool-on-water fires that would result if the release was ignited at the spill site. By this time, the "maximum credible" release (from a ship onto water) had been pared down by a factor of two, from 25,000 m^3, still considered the typical single-tank volume, to half that size, 12,500 m^3. This reduction was considered reasonable based on the fact that the principles of physics dictated that since about half of the LNG in a tank was below the water level exterior to the ship it was extremely unlikely that the entire tank could be spilled rapidly (which was the condition originally assumed).

For our purposes (in these comments), it is possible to briefly summarize the Sandia Research Results (published in 2004[8]) of the pool fire and vapor cloud hazard distances (to a concentration of ½ the lower flammable limit of methane, or 2.5%) as follows:

- Pool fire radiation distances - assuming rapid release onto water of ½ tank with immediate ignition, the maximum distance to heat flux levels that could cause second degree burns to unprotected human skin was estimated to be about one mile.
- Vapor cloud dispersion - maximum distances, assuming the cloud is not ignited, extending beyond 1600 meters. For the JCE facility, this suggests that an unignited cloud from a large ship spill could reach well beyond the property boundaries.

Then, in 2007, the Government Accountability Office, as requested by Congress, delivered their report entitled "MARITIME SECURITY: Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification." This report detailed the findings of an expert panel (seventeen members, one of whom was the first author of these comments) who were individually questioned to provide their opinions on major LNG safety issues that remained controversial. The section of the report entitled "Results in Brief" is repeated verbatim below[9]:

> *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 three quarters of a mile to 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*

[8] Hightower, Mike, et. al., Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water, Sandia Report SAND2004-6258, December 2004.

[9] Maritime Security: Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification, GAO-07-316, February 2007.

of LNG spilled, key LNG fire properties, and environmental conditions, such as wind and waves. Three of the studies also examined other potential hazard 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 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 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).

As a result of the GAO report, Congress directed further research to be conducted by the Sandia National Laboratory. That research (thus far) concludes that the radiant heat fluxes from large LNG fires on water, which burn without much smoke, can exceed 300 kW/m^2, and that there are potential failure modes regarding LNG carriers that could lead to a ship being at risk of sinking. The ship-safety-research continues.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Risk analysis based LNG facility siting standard in NFPA 59A

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ABSTRACT

In the United States, liquefied natural gas (LNG) has the unique distinction of being the only flammable or hazardous material whose storage terminal (siting), handling and terminal operations are regulated by the federal government. Regulations are promulgated by the Pipeline and Hazardous Materials Administration (PHMSA) of the U.S. Department of Transportation (DOT). Storage and handling of all other flammable and hazardous materials are regulated by state laws. Current DOT regulations on LNG (49 CFR, part 193) are based on NFPA 59A, "Standard for the Production, Storage, and Handling of Liquefied Natural Gas," 2001 edition. These regulations are very prescriptive and inflexible in that they do not allow alternative safety mitigation considerations for LNG facility siting without applying for a special permit. The types and sizes of accidental releases to be evaluated are prescribed and no deviation is allowed. Without considering a spectrum of events, their likelihood of occurrence and the resultant consequences it is impossible to design proper mitigation actions or emergency response procedures. The benefit of knowing and preparing for a properly evaluated "most likely event" scenario is the resultant correct application of economics, and personnel resources of emergency responders.

The 2009 edition of NFPA 59A includes, in a mandatory annex, an alternative, risk-based requirements to evaluate the safety of land-based LNG facilities. DOT, in its regulations on the transportation of natural gas in interstate pipelines, requires the conduct of a "Pipeline Integrity Management" procedure to ensure public safety from accidental gas releases from interstate pipelines. The regulations refer to this procedure as "risk-based" even though frequencies of accidents or equipment failures are not considered. The National Association of Regulatory Utility Commissioners (NARUC) and the National Association of States Fire Marshals (NASFM) have recently passed resolutions calling on DOT (PHMSA) to initiate steps towards the development of risk-based LNG facility siting regulations.

This paper discusses the risk evaluation approach incorporated into a mandatory annex in the 2009 edition of NFPA 59A and possible other methods of performing a LNG facility risk assessment. Also discussed are the parameters that society has to agree to establish an 'acceptable' level of risk. The paper indicates the risk process used in other countries, particularly in Europe. The results from the application of a risk analysis procedure to a specific case are presented. A comparison of the risk-based results with those obtained from the application of the current prescriptive requirements in NFPA 59A (or 49 CFR, part 193) is indicated. Recommendations are provided for future actions.

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1. Introduction

Liquefied Natural Gas (LNG) has the unique distinction of being the only fuel for which specific and detailed requirements exist for storage facility siting and construction in the federal regulations (49 CFR, part 193) of the U.S. Department of Transportation (US DOT). These regulations applicable to LNG facilities have been in existence since 1979. In addition, the National Fire Protection Association (NFPA) publishes NFPA 59A, "Standard for the Production, Storage and Handling of Liquefied Natural Gas". This Standard contains the criteria that should be complied with for plant siting and layout, locations of process equipment, storage container design, safety assessment and calculation of the extent of exclusion zones, fire protection, safety and security, maintenance, personnel training etc. These requirements relate to both construction and operation of LNG plants. The NFPA Standard was originally published in 1971 and included requirements based on lessons learned from the LNG release accident in Cleveland in 1944

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Table 1
Definitions of Design spill (NFPA 59A-2009).

Container penetration	Design spill	Spill duration
Containers with penetrations below the liquid level without internal shutoff valves	A spill through an assumed opening at, and equal in area to, that penetration below the liquid level resulting in the largest flow from an initially full container	Until all of the liquid above the level of the hole is released
Containers with penetrations below the liquid level with shutoff valves	The flow through an assumed opening at, and equal in area to, that penetration below the liquid level that could result in the largest flow from an initially full container	Until all of the liquid above the level of the hole is released
Containers with over-the-top fill, with no penetrations below the liquid level	No design spill	Not applicable
Impounding areas serving only vaporization, process, or LNG transfer areas	The flow from any single accidental leakage source	For 10 min or for a shorter time based on demonstrable surveillance and shutdown provisions acceptable to the authority having jurisdiction
Full or double containment containers with concrete secondary containers	No design spill	Not applicable

Sources of information in table: NFPA 59A-2009.

(Lemoff, 2008). The 2001 edition of the NFPA 59A Standard has been adopted to form (with minor changes) the current 49 CFR, part 193, DOT regulations. The 59A Standard is revised in approximately 3 year cycles (latest being the 2009 edition)[1].

The important feature of both the NFPA 59A Standard and the US DOT regulations is that they are prescriptive. That is, they specify details of the types of accidents to be considered, the locations, durations and rates of potential LNG releases, quantitative engineering design requirements, types of harm to the public to be taken into account, etc. In addition, the requirements are "geography independent," in that the requirements are applicable irrespective of whether the proposed facility is in a densely populated area or a sparsely populated suburban/rural area. Also, the Standard and the Regulations do not allow considerations of alternative safety mitigation procedures or technologies in LNG facility siting without obtaining, *a priori*, a special permit for specific items from the authority having jurisdiction (AHJ).

The requirements in the U.S. are in stark contrast to regulations in other countries where performance standards are specified in terms of potential risk to the population. The acceptable risk criteria are specified. When the risk posed by a proposed LNG plant is below the acceptability threshold risk the siting of the plant is permitted. However, if the risk is in a "grey area," in between the upper and lower threshold of acceptable risk, then additional mitigation measures may be enforced to reduce the risk to the population. Of course, if the calculated risk is above the maximum allowable risk, the plant is not permitted.

Recently, the NFPA 59A Committee adopted a risk-based LNG sting requirements for inclusion in the 2009 edition of the Standard. However, due to the fact that this was the very first time that NFPA 59A had ventured into a risk-based Standard, the Committee adopted to include the risk requirements in a "Mandatory Annex" rather than in the main body of the document. The intent was to provide an option to an authority having jurisdiction (AHJ) to adopt the risk-based assessment, in lieu of the prescriptive Standard.

The objectives of this paper are to (i) compare the siting requirements in the "prescriptive" and "risk-based" Standards, and (ii) to discuss the details of the recent action by the NFPA 59A Committee to include, in the Annex of the 2009 edition of the Standard, a risk-based alternative Standard. Other risk-based regulatory procedures are indicated only for purposes of discussion and to highlight their features and differences with that included in the 2009 edition of NFPA 59A.

[1] All references to NFPA 59A Standard should be construed as being to the 2009 edition. Other editions, if mentioned, are cited with the publication year.

1.1. LNG siting requirements in the U.S.; NFPA 59A & 49 CFR, part 193

The requirements for safety assessment, in both the NFPA 59A Standard (2001 edition) and the US DOT Regulations are virtually identical. The safety assessment for a LNG plant consists of ensuring that for the "design spill" from a storage tank and under specified atmospheric conditions, (1) the radiant heat flux at the plant "property line that can be built upon" or at the nearest occupancies do not exceed the specified levels, and (2) the average concentration of LNG vapor in air does not exceed 50% of the lower flammability limit (LFL), in the case the vapor cloud generated by LNG release is not ignited but disperses in the atmosphere. For methane the LFL is 5% in air. Only in the case of dispersion of vapors the effects of certain passive migration measures (such as a provision to detain vapor, employing impounding surface insulation, providing water curtains and other methods) can be considered in the calculations, if provided in the design, and when acceptable to the AHJ. Table 1 shows the "design spill" specifications. Table 2 shows the radiant heat flux hazard criteria in NFPA 59A.

It is noted that the only types of "spills" considered are the releases from the storage tank with a hole size equal to size of penetration of the tank, and the release from a transfer piping (liquid withdrawal pipe) at the full flow rate. NFPA Standard assumes that there is no potential for release from a double containment tank with a concrete secondary container; however, the US Federal Energy Regulatory Agency (FERC) requires the

Table 2
Radiant heat flux limits to property lines and occupancies.

Radiant heat flux		Exposure
$Btu/hr/ft^2$	W/m^2	
1600	5000	A property line that can be built upon for ignition of a design spill
1600	5000	The nearest point located outside the owner's property line that, at the time of plant siting, is used for outdoor assembly by groups of 50 or more persons for a fire in an impounding area
3000	9000	The nearest point of the building or structure outside the owner's property line that is in existence at the time of plant siting and used for assembly, educational, health care, detention and correction, or residential occupancies for a fire in an impounding area
10,000	30,000	A property line that can be built upon for a fire over an impounding area

Sources of information in table: NFPA 59A-2009.

evaluation of the radiant heat effects due to roof collapse and a liquid pool fire on top of the tank. Clearly, the scenarios, types, locations, sizes and durations of potential releases to be considered are limited and very specific, irrespective of the any safety features and systems that may be included in the plant design. Also, no credence is given to how often (or the annual probability of) any type of release and the subsequently resulting LNG behavior scenarios will occur. All possibilities are weighted equally. Finally, no assessment of the possibility of ignition of a dispersing vapor, between the release location and the point at which the vapor concentration falls below ½ LFL, is allowed.

1.2. Elements of a risk-based assessment

There are many excellent books and monographs on risk analysis, its elements, procedure for calculating the risks to a given population from specified activities, risk communication and differences between voluntary and involuntary risk in the context of exposing a population to hazards (Glickman & Gough, 1990; Morgan (1993); Breyer (1993); CCPS (1999)).It is not, therefore, the intent in this paper to discuss these subjects in detail but to touch upon the salient concepts so that the application of the risk analysis principles to siting a LNG facility can be understood.

Risk analysis as applied to a LNG facility siting has five components. The first step is the assessment of the types of potential accidents/incidents that can lead to the release of LNG. The second step is the estimation of the location, size, rate and duration of releases. The third step is the determination of the probability of the different types of releases identified earlier and the conditional probability of each type of possible LNG behavior (or hazard) associated with each type of release. The fourth step is the determination of the consequences of each type of release in terms of specific hazard criteria or exposure of people and property. The last and final step is the comparison of the calculated risk with risk acceptability criteria. This process is schematically illustrated in Fig. 1.

Risk is often defined as the product of probability of occurrence of a detrimental event and its consequences (measured in accepted units). The overall risk is the sum of all risks from different elements and potential release modes. Equation (1) and equation (2) below represent the above concepts in mathematical form.

$$\text{Risk} = [\text{Frequency of occurrence of event, i.e. }\#/\text{year}] \times [\text{Consequence of the event}] \quad (1)$$

$$\text{Total Risk} = \sum_{\text{All events}} \text{Individual Event Risk} \quad (2)$$

Of the two elements on the right hand side of the above risk equation (1) the evaluation of the consequences of releases of hazardous materials has received much attention. The values for the frequency of occurrence of failures (mechanical or human caused) are much harder to estimate, especially where historical failure data are sparse or non-existent (as in the case of LNG industry and LNG plants). Generally, data for failures are obtained from experience base in other industries with similar plant constructions, equipment and operational features. One source for component failure rates for LNG risk assessment is the publication by the British Government agency, Health and Safety Executive (HSE, 2003, chapter 6k).

1.3. Risk acceptability criteria

Risk analysis can be conducted to evaluate both the individual risk and the societal risk to people living around a proposed facility. The following definitions of the two types of risks are generally used in the literature (Bottelberghs, 2000).

The **individual risk** for a point-location around a facility or a hazardous activity is defined as the (annual) probability that an average, unprotected, person permanently present at that point-location would get exposed to a hazardous level of harm (or suffer fatality) due to all types of accidents at the facility or, the hazardous activity.

The **societal risk** from a facility or a hazardous activity is the (annual) probability that a group of more than N persons would be exposed to hazardous level of harm (or suffer fatality) due to all types of accidents at the facility or, the hazardous activity.

The "individual risk" is dependent on only the location with respect to the facility and not on the characteristics of any individual or the density of population surrounding a facility. The "societal risk," on the other hand, is dependent on both the density of people surrounding a facility and the location of population with respect to the facility. The societal risk is generally presented in the form of a curve, on a log–log plot, expressing the relationship between the annual probability (F) of exceeding a given number of fatalities or other harm (N) and the number N.

In most countries the risk assessment is performed on the basis of potential fatalities to the exposed population. Different countries use slightly different criteria for risk acceptability. In the UK, the Health and Safety Executive (HSE) guidelines are to use the individual risk as the principal measure of risk and also use the societal risk criteria (for land use planning). The acceptability criteria levels for risks for facilities in the UK are specified by HSE (1989). Facilities are permitted only when these (published) criteria are met. In the Netherlands, however, both the individual risk criteria and the societal risk criteria have to be met when considering (in risk assessment) those events whose hazardous effects extend to such distances at which the conditional probability for lethality is higher than 1% (Bottelberghs, 2000). The risk tolerability criteria for fatalities established in various countries for both individual risks and societal risks are summarized in Table 3 below.

1.4. Why risk-based assessment may be preferable

The current criteria in the U.S. Standards for potential hazardous exposure from LNG facilities are defined only with a single exposure measure (such as the radiant heat flux in the case of fire exposure) where multiple measures (such as the time of exposure or dose) are needed to specify, correctly, the effect of the hazard. In addition, the hazard criteria are based on threshold injury only. The calculation of the threshold injury distances do not consider natural mitigating circumstances (such as, shadows of buildings and other objects that reduce/eliminate radiant heat effects in the case of fires and enhance the mixing of vapor with air in the case of dispersion of vapors, and naturally occurring ignition sources in an industrial/urban neighborhood which will ensure the quick ignition of a vapor cloud thus limiting its penetration distance). Last, but not the least, several other types of behaviors of LNG releases are not required to be considered. These types of LNG behavior include (i) Ignition of a dispersing vapor cloud in the presence of obstructions which enhance turbulence effects and lead to a deflagration type vapor cloud fire, (ii) Ignition of a dispersing vapor cloud in the presence of obstructions which enhance turbulence effects and lead to a possible vapor cloud explosion, (iii) Spill of LNG during transfers (say, at the dock) onto or into water and the consequences there from, (iv) LNG release in the form of a jet from a defect or leak in a pipeline and formation of a jet fire, etc. When these limitations are compared with the assessment process included in a risk analysis, it is seen that the latter approach will provide a better representation of the realistic hazard potential to the public from a LNG facility. It is, of course, necessary that risk

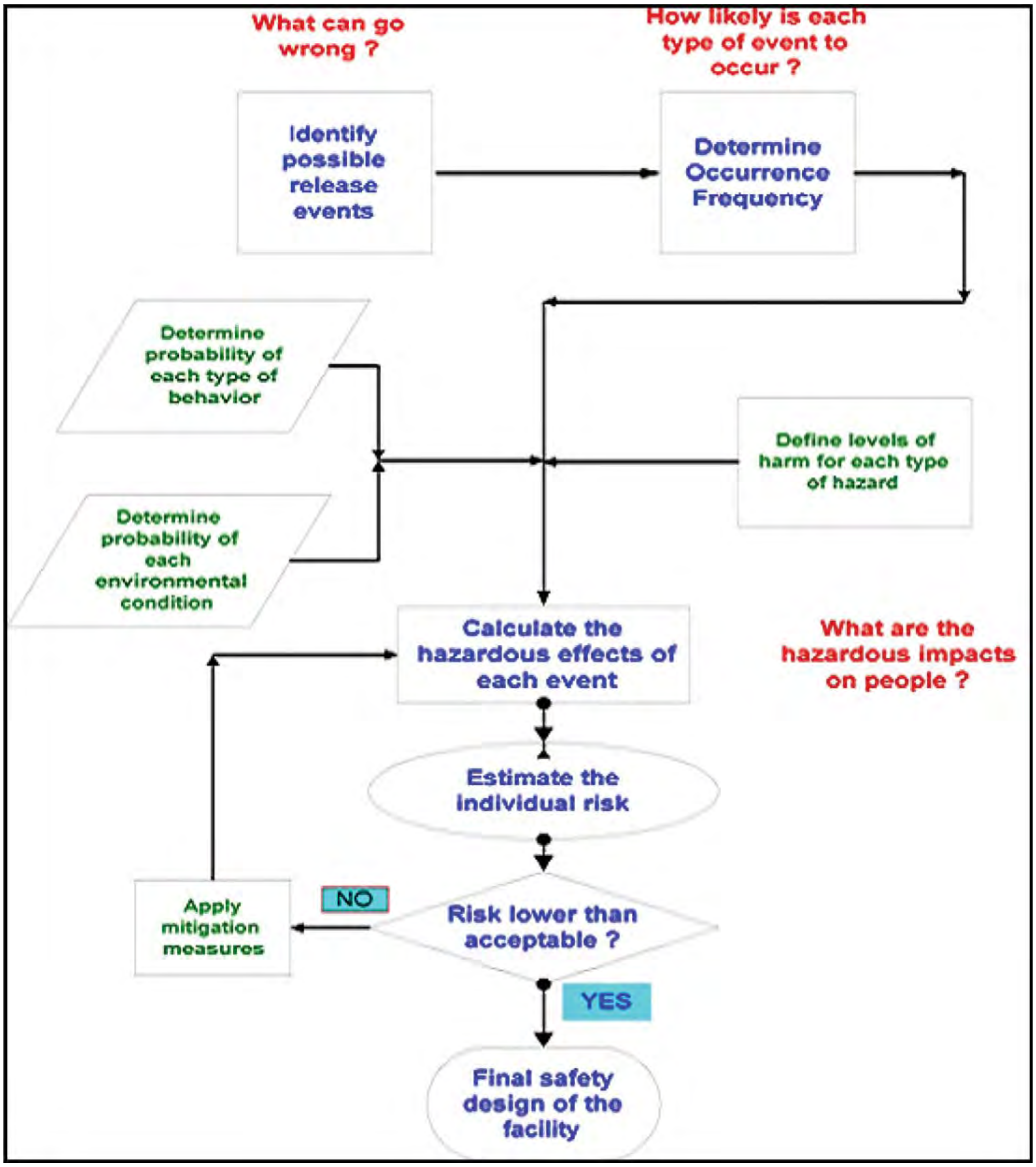

Fig. 1. Schematic illustration of Risk Assessment Procedure.

assessment should be conducted on a site-specific basis, which will take into account the specific nature of the topography, population distribution in the proposed plant vicinity, existence of physical structures immediately beyond the plant property line (that may mitigate some of the potential hazards), types of industrial or commercial activity in the neighborhood that may mitigate or amplify the potential for hazard, etc. Such specificity to a particular location of a proposed plant is, generally, absent in prescriptive standards.

In a risk-based approach, all types of failures and accidental conditions are considered. More importantly the release scenarios are weighted by the likelihood of occurrence, which provides a proper estimate of the potential (and realistic) sizes of accidents that need to be considered and, perhaps, responded to. Also, local conditions and distribution of occupancies, including densities of population in the surrounding areas, are taken into account. Risk analysis also provides a means of testing, *a priori*, the effect of any type of mitigation approaches in the extent of reduction of the risk. The process also lends itself to input from local authorities which can lead to optimal decision-making. The risk-based assessment and review of granting permits for new LNG and other facilities has been successfully employed in most other countries where there is a boom in LNG facilities construction.

It is because of these advantages with the risk-based sting of LNG facilities that the NFPA 59A-2009 Standard incorporated an alternative risk-based assessment (more details on this in section 3). Also, recently, both the National Association of Regulatory Utility Commissioners (NARUC) and the National Association of State Fire Marshals (NASFM) have adopted resolutions supporting the concept of Risk-based LNG facility siting (NARUC, 2008; NASFM 2009). This resolution recommends that the US DOT:

1 Evaluate and develop alternatives and risk-based regulations as a supplement to its existing LNG facility siting regulations, and
2 Perform the appropriate research and other activities as may be needed, including but not limited to, comparative analyses of alternative (including the Risk-Based Alternative Standards approach approved by NFPA's LNG Standards (59A) Committee), public workshops, and other studies.

Table 3
Summary of fatality risk tolerability criteria.

Country/Agency	Criterion Annual probability	Remarks	Reference
Individual Fatality Risks (IFR)			
UK/HSE	IFR $\leq 10^{-6}$	Tolerable "fatality" criterion for the public & workers	HSE (2001)
	IFR $\geq 10^{-4}$	Unacceptable "fatality" criterion for the public	
	IFR $\geq 10^{-3}$	Unacceptable "fatality" criterion for the worker	
Netherlands	IFR $\geq 10^{-6}$	Not acceptable for new housing	Bottelberghs (2000)
	IFR $\geq 10^{-5}$	Not acceptable for office buildings, restaurants, etc.	
Ireland/HSA	IFR $\leq 5 \times 10^{-6}$	Acceptable for non-residential structures	**New Facilities**: HSA (2006)
	IFR $\leq 10^{-6}$	Acceptable for nearest residential property	
	Zone 1: IFR $\leq 10^{-5}$	*Not permitted* – Residential, office and retail	**Existing Land use:** HSA (2006)
		Permitted: Occasionally occupied developments (ex., pump houses, transformer stations, etc).	
	Zone 2 $10^{-6} \leq$ IFR $\leq 10^{-5}$	*Not permitted*: Shopping centers, large scale retail outlets, restaurants, etc	
		Permitted: Work places, retail and ancillary services, residences in areas of 28–90 persons/ha density.	
	Zone 3: $3 \times 10^{-7} \leq$ IFR $\leq 10^{-6}$	*Not permitted*: Churches, schools, hospitals, other major public assembly areas and other sensitive establishments.	
		Permitted: All other structures and activities	
Societal Fatality Risks			
UK/HSE	$F = 2 \times 10^{-4}$, $N = 50$ Slope $= -1$	Unacceptable above the line in the previous column	HSE (2001)
	$F = 2 \times 10^{-6}$, $N = 50$ Slope $= -1$	Broadly acceptable below the line in the previous column	
	ALARP	Acceptable with review in the region between the two lines above	
Netherlands	$F = 10^{-5}$, $N = 10$ Slope $= -2$	Unacceptable above the line in the previous column	Ball and Floyd (1998)
Hong Kong	$F = 10^{-4}$, $N = 10$ Slope $= -1$	Unacceptable above the line in the previous column	
	$F = 10^{-6}$, $N = 10$ Slope $= -1$	Broadly acceptable below the line in the previous column	

2. Current risk-based assessments related to natural gas systems

The US DOT, in its regulations (49 CFR, part 192, Sub part O) concerning safety in gas transmission pipelines, requires an assessment of the pipeline integrity by a methodology, which it terms as 'risk-based." Unfortunately, the term "risk-based" used in this regulation is a misnomer since neither the probability of pipeline accident occurrence nor the consequences of each size accident is used in the assessment. To highlight what this regulation requires and why it is not a true risk assessment, a brief review of the requirements in this regulation is indicated below. The European Standard for the siting of LNG facilities requires, primarily, a risk-based approach to evaluating the site safety (al though a prescriptive, hazard based approach can also be used). These two approaches are described below in brief.

2.1. DOT pipeline integrity management

The pipeline integrity management system (PIMS) is intended to ensure the safe operation of a gas transmission pipeline without causing potential danger to the surrounding population or structures. The principal element of PIMS (49 CFR §192.911) includes the development of a baseline plan consisting of (i) identification of all high consequence areas along the pipeline route, and (ii) identification of threats to each covered pipeline segment using available data and risk assessment. The high consequence areas are defined by different classes of assets in §192.5 and the requirements for their consideration in the PIMS are indicated in §192.903. Table 4 shows the various classes of asset locations defined in 49 CFR, part 192.

The assessment procedure in US DOT's PIMS, even though it is called as a risk-based analysis, does not include the estimation of the threat occurrence probabilities or pipeline failure frequencies. The only hazard area calculated is the "***potential impact radius (R),"***where $R = 0.69\sqrt{pd^2}$, with 'R' is the radius of a circular area in feet surrounding the point of failure, 'p' is the maximum allowable operating pressure (MAOP) in psi in the pipeline segment, and 'd' is the nominal diameter of the pipeline in inches. The procedure, instead, involves the identification of the presence of any high consequence value assets and taking such preventive, mitigative or remedial actions as are necessary (including relocation of the pipeline path). Table 4 shows the definitions used in the regulations for different classes of pipeline locations and high consequence areas.

2.2. European National Standard – EN 1473

The European Standard (EN 1473, 2006) requires that LNG installations be designed to have risk levels at or below the generally accepted levels specified in the Standard (in Annex L, EN 1473). These risks refer to life and property outside and inside the plant boundaries. In order to ensure a high level of safety in the LNG facilities and its surroundings, EN 1473 requires that safety shall be considered throughout all the project development phases: - engineering, construction, start-up, operation and decommissioning. In particular, hazard assessments are required to be carried out to evaluate the dispersion of vapors produced by a LNG release as well as the radiant heat hazard from LNG fires. EN 1473's criteria for hazards are similar to (but not the same as) those in NFPA 59A; both use % of LFL as the criterion for vapor hazard extent and thermal heat flux levels for fire hazard. However, several countries (UK and Ireland) while adopting the EN 1473 procedure in risk analysis use different (dosage) criteria for heat hazards from fires. The risk acceptability criteria used in England are indicated in a HSE publication (HSE, 1989).

The risk analysis procedure required under EN 1473 includes the following steps[2]:

[2] Detailed values of the various criteria in EN 1473 annexes are not provided. This is because, these are similar to the ones incorporated into the Alternative Risk-based Standard NFPA 59A-2009 edition.

Table 4
Pipeline class locations.

Location Class #	Definitions	Remarks
1	(i) An offshore area; or (ii) A class location unit that has 10 or fewer buildings intended for human occupancy.	(1) A "class location unit" is an onshore area that extends 200 m on either side of the centerline of any continuous 1.6 km length of pipeline.
2	More than 10 but fewer than 46 buildings intended for human occupancy.	(2) Each separate dwelling unit in a multiple dwelling unit building is counted as a separate building intended for human occupancy.
3	(i) A class location unit that has 46 or more buildings intended for human occupancy; or (ii) An area where the pipeline lies within 91 m of either a building or a small, well-defined outside area (such as a playground, recreation area, outdoor theater, or other place of public assembly) that is occupied by 20 or more persons on at least 5 days a week for 10 weeks in any 12-month period. (The days and weeks need not be consecutive.)	The length of Class locations 2, 3, and 4 may be adjusted as follows: (1) A Class 4 location ends 200 m from the nearest building with four or more stories above ground. (2) When a cluster of buildings intended for human occupancy requires a Class 2 or 3 location, the class location ends 200 m from the nearest building in the cluster.
4	Any class location unit where buildings with four or more stories above ground are prevalent	

A high consequence area is defined as:	
(i)	A Class 3 location or
(ii)	A Class 4 location or
(iii)	Any area in a Class 1 or Class 2 location where the potential impact radius is greater than 200 m, and the area within a potential impact circle contains 20 or more buildings intended for human occupancy; or
(iv)	Any area in a Class 1 or Class 2 location where the potential impact circle contains an identified site.
	OR
	The area within a potential impact circle containing—
(i)	20 or more buildings intended for human occupancy, or
(ii)	An identified site.

Source: 49 CFR, part 192, §192.5 & §192.903.

1 Listing of potential hazards of external and internal origin;
2 Determination of the consequences of each hazard and their allocation into the Standard specified classes of consequence (Annex K);
3 Collection/input of failure rate data;
4 Determination of the probability or frequency of each hazard;
5 Summation of frequency for all hazards within any one allotted consequence class and classification by the frequency range for that consequence class (Annex J);
6 Classification of hazards in accordance with their consequences class and frequency range, in order to determine the level of risk (Annex L).

In this Standard, detailed assessments of individual or societal risks and the plotting of their contours (or the F vs. N curve) are required directly, as in the case of UK and Irish regulations.

A comparison of the important current requirements related to safety in NFPA 59A (prescriptive part of the standard) and EN 1473 is indicated in Table 5.

3. Details of alternative risk-based standard in NFPA 59A (2009)

The NFPA 59A Committee voted to include an alternative risk assessment-based standard in a mandatory annex in the 2009 edition of the LNG facility siting standard. The preamble to this risk-based standard states that "LNG plants shall be designed and located in such areas as to not pose unacceptable risks to the surrounding populations, installations or property." In addition, it states that reassessment of the risk to the surrounding population is required to be performed once in three years, or as required by the AJH or if the plant is modified or other conditions change, to ensure that the risk to the people does not exceed an acceptable level.

In the NFPA 59A (2009), the risk assessment procedure and criteria for acceptability for siting a LNG plant are based on "Societal Risk" considerations. That is, the annual frequency with which a certain level of hazard (in this case injury from exposure to radiant heat and vapor concentrations higher than LFL) may occur to a specified number (or less) of persons. Obviously, the risk result (based on such criteria) depends upon the local population density, among other variables. It is entirely possible that in future editions, other criteria based on "risk to a typical individual" would be included.

The principal requirements and features of the "Societal Risk-based" Risk Assessment protocol included in NFPA 59A, 2009 edition Annex are:

1 Consideration of a spectrum of LNG release scenarios obtained from systematic (ex, HAZOP type) analyses and including the release scenarios currently in prescriptive section.
2 Evaluation of the annual probabilities of occurrence of release scenarios, including the conditional probabilities of different types of LNG behavior, in different weather conditions.
3 Characterization of an event (taking into consideration the occurrence of conditional probability sub-events) into a probability class based on published class listings (Table 6)
4 Determination of the consequence categories according to the number of injuries (see Table 7). The criteria for injury, whether exposed to a fire or to a flammable vapor cloud concentration are the same as in the current Standard.
5 Mapping the frequency-consequence pair for each release scenario event into an acceptability matrix, indicated as Table 8.

If the risk (denoted by the annual probability of occurrence and the corresponding magnitude of consequence) is in the region denoted by "***A***" in Table 8, then the risk is deemed to be acceptable and no further review is needed of the facility design. In the case that the risk falls in the "**AR**" region then appropriate design changes (including provision of mitigating technologies and operational changes) need to be made, in consultation with and approval of the AHJ, to minimize the calculated risk. Should the risk fall in the "*NA*" region the design would not be acceptable.

The NFPA 59A risk approach is "Societal" in nature. It does not require the evaluation of individual risks. This is because, the Standard is more focused on the society and the location where the plant will be built (and hence the geographical and the demographical details are important).

Table 5
Comparison of prescriptive requirements for siting and operating LNG facilities In NFPA 59A and risk-based requirements in EN 1473- the European Standard.

Item #	Topic	NFPA 59A (prescriptive requirements)	EN 1473:2006
1	General philosophy	Siting criteria are based only on consequences from deterministic events. Specified types and magnitude of releases are required to be evaluated. No consideration is given to how often the specified releases may occur. No flexibility is allowed in considering any other types, sizes or frequency of releases.	Provides the option to consider the siting hazard assessment based on the hazardous effects of "credible" releases, or using risk analysis which considers an entire spectrum of events, their frequency of occurrence and their consequences.
2	Siting acceptability criteria	Based only on specific consequence metrics (for fire radiant heat hazard and vapor cloud concentration, see items 6 and 7 below). These consequence criteria shall not be exceeded for specified target classes within the exclusion zone.	Acceptability of a site is based on the calculated 'societal risk' from the plant being within acceptable range. This range is expressed in a matrix of class of event frequencies and magnitude class of events. EN 1473 defines a set of seven ranges of cumulative plant accident (all) frequencies and five classes of consequences (with three sub classes, namely fatalities, injuries and hydrocarbon quantity released). In the matrix certain regions are termed Risk Magnitude 1 region (low frequency –low consequence "cells"), Risk Magnitude 3 (high frequency- high consequence "cells") which is unacceptable and a Risk Magnitude 2 which is acceptable only with additional safety systems and procedures.
3	Types of LNG tanks allowed	Single containment, full or double containment types allowed. Bottom penetration tanks allowed.	Single containment cylindrical metal tank; double containment cylindrical metal inner tank and metal or concrete outer tank; full containment cylindrical metal inner tank and metal or concrete outer tank; pre-stressed cylindrical concrete tank with an internal metal membrane are acceptable. In addition, other types, such as cryogenic cylindrical concrete tank: internal concrete tank and pre-stressed concrete outer tank; spherical tank, is also acceptable if the tank meets the functional requirements specified in EN 1473. No penetrations of the primary and secondary container base or walls of tanks are allowed.
4	Impoundment sizing	For leaks from tanks the impoundment volume should be at least 110% of the largest tank's maximum capacity. For spills from transfer piping and in process areas, the impoundment volume is 100% of the volume spilled at the highest flow rate from the largest size equipment/ piping for 10 min or shorter time if the surveillance and shut off system is approved.	The spill collection system or impounding basin capacity for process areas are required to be at least 110% of the total liquid inventory of the largest equipment item and related piping and other equipment that can drain through this item. For transfer areas and in the interconnecting pipe-work the impounding basin capacity can be determined by risk analysis considering potential leak sources, flow rates, detection systems, manning levels and response times.
5	Spacing of containers and other exposures	Spacing requirements for containers and exposures are specified based on the size of the containers.. Inter-tank distance can also be calculated on the basis of specified allowable heat flux values on adjacent tank roofs from a fire on a tank. Consideration of the mitigative effects of active water spray or deluge systems are allowed.	The spacing between two adjacent tanks is to be obtained by a detailed hazard assessment. The minimum separation distance cannot be less than half the diameter of the secondary container of the larger tank.
		For large tanks the spacing between tanks is not less than 1/4th of the sum of the diameters of the tanks.	Other hazard area separation distances are to be based on an assessment of the vulnerability of equipment to fire or blast effects due to release from a neighboring equipment. Specific thermal flux levels are specified. It is the responsibility of the designer to justify the maximum thermal radiation flux level used by calculating the surface temperature consistent with the expected duration of the fire and show that it is sufficiently low to maintain the integrity of the structure. The heat flux level can be reduced to the required limit by means of separation distance, water sprays, fire proofing, radiation screens or similar systems.
6	Design spills	Design spill volumes are based on 10 min (or less time if the surveillance and shutoff systems are approved) spill at full flow rate from the largest size line from tanks with top penetration only. For bottom penetration tanks no time limit for spill indicated.	A spectrum of LNG release scenarios developed from HAZOP or other techniques are to be considered in performing a risk assessment. For the analysis based only on hazard considerations, "credible" spills are to be considered.
7	Hazard limit for exposure to fire radiant heat effects	Two radiant heat flux values are specified for the radiant heat (limit) fluxes for exposure at the property line or at a point used by assembly of 50 or more people. (See Table 2)	Allowed radiant heat levels (in kW/m^2) are Concrete outer surface of adjacent storage tanks = 32 Metal outer surface of adjacent storage tanks, = 15 outer surfaces of adjacent pressure storage vessels, etc. Control rooms, workshops, laboratories, warehouses, etc. = 8 Administrative buildings = 5 Area only infrequently occupied by few persons = 8 (ex, farmland, desert, etc.) Critical areas (occupied by persons with no protective = 1.5 Clothing, or population density $>$ 20/km^2 Other areas (industrial, LNG operator facilities, etc) = 5
8	Vapor concentration limit for hazard from the dispersion of vapor cloud	Hazard distance arising from the dispersion of vapor is to be determined by using the criterion that a this distance the average vapor concentration is equal to 50% of the lower flammability limit (LFL)	Hazard distance arising from the dispersion of vapor is to be determined by using the criterion that a this distance the average vapor concentration is equal to 100% of the lower flammability limit (LFL)
9	Consideration of the effects of passive mitigation systems	Passive mitigation allowed only for minimizing vapor dispersion hazards, when approved by the AHJ	Passive systems and other systems can be considered in the risk assessment, especially if the overall risk falls in the ALARP region

Table 9
Calculation of individual risk for a person at distance "S" from plant center.

Release scenario	Annual probability of release	Compass direction (10° sector)	Probability of wind in the compass direction	Total annual probability of hazard extending to hazard distance	Hazard distance in the specified direction ("X")	Individual risk from accidents for which X>=S
Impoundment fire	P1	E	Pd1	P1 × Pd1	X1	P1 × Pd1
Impoundment vapor source	P2	E	Pd1	P2 × Pd1	X2	P2 × Pd1
Transfer pipe break	P3	E	Pd1	P3 × Pd1	X3	0
				Total annual risk to an individual at "S"		Sum numbers in this column

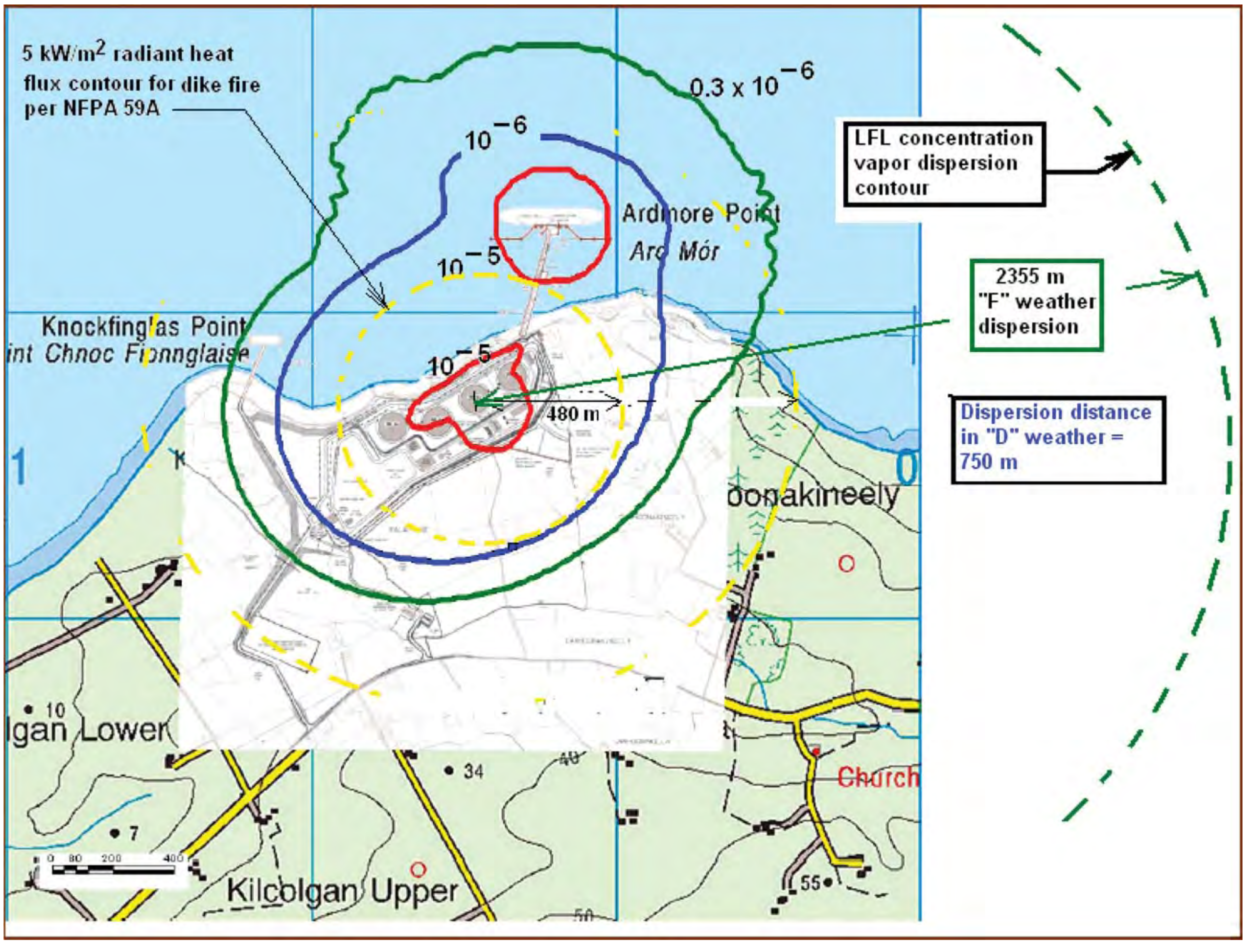

Fig. 3. Comparison of the results for an outdoor person's individual risk and NFPA 59A calculations for a LNG import terminal (Ireland) Source : Franks (2007).

4.2. Comparison of the risk results with application of NFPA requirements

NFPA 59A requires the calculation of pool fire radiant heat hazard distance as well as the dispersion distance of vapor generated by the "credible" spill to a mean concentration of 50% LFL. It is difficult to compare, on a par basis, risk results and definitive hazard distances. However, also shown in Fig. 3 are the exclusion zone distances from (the prescriptive requirements in) the NFPA 59A Standard with (1) the largest credible pool fire radiant heat hazard, and (2) the dispersion of vapor to 100% LFL concentration arising from the release of LNG from a 1000 mm diameter ship-to-shore tank transfer pipeline[3] It is seen that these distances, respectively, are 480 m (pool fire radiant heat effect) and about 2355 m (vapor dispersion in stable atmosphere). The maximum distance for the acceptable individual risk contour on land is about 800 m from the center of the storage tank. It is clearly seen that the above facility would not meet the vapor dispersion or the radiant thermal hazard distance requirements of NFPA 59A since the property line that can be built upon is within the respective contours for heat and vapor concentration.

5. Discussions & conclusions

In this paper the risk analysis process as practiced in other countries and those recently included in the NFPA 59A (2009) edition have been discussed. An example risk calculation, based on a consideration of the individual risk, has been presented for a real LNG import facility. This result has been compared with the exclusion zone result from the application of the currently applicable NFPA 59A (prescriptive) Standard's requirements. The results are significantly different simply because the parameters included in the Individual Risk (IR) calculations are different from those that are in the NFPA 59A requirements.

[3] It is noted that NFPA 59A requires the calculation of vapor dispersion hazard distance to 50% of LFL vapor concentration.

No attempt was made to compare the IFR result with that from the newly approved "societal risk-based requirements" included in the NFPA 59A, 2009 edition. This is because there are significant difficulties in comparing the IFR results with the societal risk results.

Acceptability of risk as the basis of permitting LNG facility siting depends very importantly on the criteria for acceptability. A first step has been made in the 2009 edition of NFPA 59A to include certain injury based risk criteria and risk acceptability in terms of the location of the calculated results on a risk acceptability matrix. The criteria in the NFPA 59A should be evaluated very carefully to ensure that these are acceptable to Authorities Having Jurisdiction (AHJs). If not other risk acceptability criteria should be developed. Also, consideration should be given to developing thermal dosage criteria for hazard from radiant heat and their dependence on classes of people exposed. In addition, the criteria should be developed based on potential fatalities and specified relationships between fatalities and levels of injury. Further research is also needed to incorporate the effects of emergency preparedness (on risk reduction), effects of at-event emergency action. Also, procedures should be developed to quantify them for consideration in a risk analysis based decision-making for siting LNG facilities.

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Glossary

AHJ: Authority having jurisdiction
CFR: Code of Federal Regulations (of the US)
DOT: Department of Transportation (of the US)
FERC: Federal Energy Regulatory Commission (of the US)
HSE: Health and Safety Executive (of the UK Government)
IFR: Individual Fatality Risk
LFL: Lower flammability limit (concentration)
LNG: Liquefied natural gas
NFPA: National Fire Protection Association
PHMSA: Pipeline and Hazardous Materials Safety Administration (of US DOT)
PIMS: Pipeline Integrity Management System
UK: The United Kingdom
US: The United States (of America)