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Citizens For Renewables/
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PO Box 1113
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September 9, 2019

Andrew Stamp, Hearings Officer
Coos County Planning Department
225 N. Adams St.
Coquille OR 97423

RE: Special Open Record comments concerning Coast Guard issues on Remand File No. REM-19-001/LUBA Case No. 2016-095

Dear Hearing Officer Stamp:

Please accept the following Special Open Record comments into the record in addition to comments that have been submitted previously on July 9, 2019, June 24, 2019, and June 10, 2019, including those submitted from Attorney Tonia Moro and also comments from Katy Eymann on behalf of Citizens for Renewables and Crag Law on behalf of Oregon Shores. An Index for the Exhibits that I submitted on July 9, 2019 has been included as ***Exhibit 1.***

1. Jordan Cove has not met Coast Guard requirements necessary for the transit of LNG tankerships in the Coos Bay.

On May 10, 2018, the U.S. Coast Guard issued a Letter of Recommendation (LOR) which stated that the Coos Bay was now suitable for LNG traffic. **But that LOR was contingent on the Applicant fulfilling a July 1, 2008 Water Suitability Analysis report** which clearly showed that the Coos Bay was NOT currently suitable for LNG traffic. On June 1, 2018 the May 10, 2018 Coast Guard LOR was uploaded for public preview into the FERC library.[1] (***See Exhibit 2***)

The Coast Guard May 10, 2019 LOR states among many other things the following: (*Emphasis has been added*)

> Jordan Cove LNG
> ANALYSIS SUPPORTING THE LETTER OF RECOMMENDATION ISSUED BY COTP SECTOR COLUMBIA RIVER ON MAY 10, 2018
>
> * * * *
>
> 2. *For the purposes of this analysis, the following assumptions were made:*

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[1] *Coast Guard Letter of Recommendation (LOR)* for the Jordan Cove LNG Project under CP17-495. http://elibrary.FERC.gov/idmws/file_list.asp?accession_num=20180601-3051

Exhibit: 63
Date: 9/9/19

a. ***<u>The applicant is fully capable of, and would fully implement, any and all risk management measures identified in their WSA</u>.***

b. The conditions of the port identified in the WSA fully and accurately describe the actual conditions of the port at the time of the WSA submission.

c. The conditions of the port have not changed substantially during the analysis process.

d. ***<u>The applicant will fully meet all regulatory requirements</u>*** *including* ***the development and submission of a Facility Security Plan, Emergency Manual, and Operations Manual.***

* * * *

Impact to Coast Guard Operations

1. The U.S. Coast Guard is responsible for screening LNG Carriers transiting *from foreign ports prior to arrival and will screen all vessels in accordance with existing policies and procedures.* ***<u>The vessels calling on the facility will be foreign flagged and the flag state is yet to be determined</u>****....*

* * * *

Decision Making Process

* * * *

11. ***<u>This recommendation is contingent upon the applicant completing all actions outlined in the Waterways Suitability Assessment as submitted, and actions associated with subsequent annual updates, and completing all actions outlined in the most current WSA and actions under the control of the applicant from the July 1, 2008, Waterway Suitability Report</u>.***

Waterway Conditions Adjacent to the Facility

1. ***Depth of Water****. The channel is currently maintained at a 37' depth.*

2. ***Tidal Range****. The tides of Coos Bay are of the mixed semi-diurnal type with paired highs and lows of unequal duration and amplitude. The tidal range increases upstream to the City of Coos Bay and the time difference between peak tides at the entrance and City of Coos Bay is about 40-90 minutes, depending on the location. The head of the tide is located at River Mile 27 on both the Millicoma and South Fork Coos Rivers.* ***The tidal range is 7.5 feet near the open sea channel and 6.7 feet at the entrance to Charleston Harbor.***

* * * *

7. ***Maximum Vessel Size by Dock****. The primary dock can accommodate a vessel with a maximum length of 300 meters, 52 meters in breadth, and a draft which can be accommodated by the existing channel. Although the facility dock is able to accommodate vessels drafting up to 12m (39ft), current channel draft is 11m (37ft) with future plans to dredge the channel to accommodate larger deep draft vessels.* ***<u>Jordan Cove Energy Project and the local pilots must ensure transiting LNG vessels are able to maintain 10% under keel clearance as required by JCEP's LNG Transit Management Plan</u>.***

The U.S. Coast Guard 2008 WSA for Jordan Cove states on pages 2 and 3 the following: (*Emphasis has been added*)

> *LNG Tanker Size Limitations: Based on the Ship Simulation Study conducted by Moffatt & Nichol on March 17-20, 2008, the maximum size LNG tanker permitted to transit through the Port of Coos Bay is a spherical containment LNG carrier with the physical dimensions of a 148,000 m1 class vessel. The ship dimensions used in the study reflect a length overall of 950 feet, beam of 150 feet* ***and a loaded draft of 40 feet*****.** ***The channel must demonstrate sufficient adequacy to receive LNG carriers for any single dimension listed****. Consequently, prior to approving the transit of an LNG ship larger than 148,000 m3, or any increase in the physical dimensions cited, additional simulator studies must be conducted in order to assure the sufficiency of the channel.*
>
> *• Safety/Security Zone:* ***A moving safety/security zone shall be established around the LNG vessel extending 500-yards around the vessel but ending at the shoreline. No vessel may enter the safety/security zone without first obtaining permission from the Coast Guard Captain of the Port (COTP)****. The expectation is that the COTP's Representative will work with the Pilots and patrol assets to control traffic, and will allow vessels to transit the Safety/Security zone based on a case-by-case assessment conducted on scene. Escort resources will be used to contact and control vessel movements such that the LNG Carrier is protected.*
>
> ***While the vessel is moored at the facility there shall be a 150 yard security zone around the vessel, to include the entire terminal slip****. In addition, while there is no LNG vessel moored, the security zone shall cover the entire terminal slip and extend 25-yards into the waterway.*
>
> *Resource Gap: Resources required to enforce the safety/security zone are discussed under Security Measures in the supplemental report.*
>
> *Vessel Traffic Management:* ***Due to a narrow shipping channel, navigational hazards, and the proximity to populated areas, LNG vessels will be required to meet the following additional traffic management measures****:*
>
> > *o A Transit Management Plan must be developed in coordination with the Coos Bay Pilot*
> > *Association, Escort Tug Operators, Security Assets and the Coast Guard prior to the first transit.*
> > *o This plan must be submitted to the COTP no less than 6 months to initial vessel arrival, and followed by an annual review to ensure that it reflects the most current conditions and procedures.*
> > *o* ***For at least the first six months, all transits will be daylight only, unless approved in advance by the COTP****.*
> > *o The LNG Vessel must board Pilots at least 5 miles outside the sea buoy.*
> >
> > > *•* ***Overtaking or crossing the LNG tanker within the security zone is prohibited for the entire transit from the Coos Bay Sea Buoy to mooring the vessel at the LNG terminal****.*

o Vessel transits and bar crossings will be coordinated so as to minimize conflicts with other deep draft vessels, recreational boaters, seasonal fisheries, and other Marine Events.
o 24 hours prior to arrival, the Coast Guard, FBI, Coos Bay Pilot Association, Escort Tug Masters, and other Escort assets will meet to coordinate inbound and outbound transit details.

Resource Gaps: The Vessel Transit Management Plan must be approved by the COTP at least 60 days prior to the first vessel arrival.

* * * *

The U.S. Coast Guard 2008 WSA for Jordan Cove states the following on pages 3 to 5:

Safety Measures:

Emergency Response Planning: ***Regional emergency response planning is limited in the region. Emergency response planning resources will need to be augmented to adequately develop emergency response procedures*** *and protocols as well as continuously update those plans as conditions change.*

Resource Gap: To be determined in conjunction with local and regional response agencies through the Emergency Response Planning process.

- *Vessel and Facility Inspections: LNG tankers and facilities are subject to (at a minimum) annual Coast Guard inspections to ensure compliance with federal and international safety, security and pollution regulations. In addition, LNG vessels and facilities are typically required to undergo a pre-arrival inspection, and transfer monitor.*

Resource Gap: Additional Coast Guard Facility and Vessel Inspectors.

- *Shore-Side Fire-Fighting:* ***Firefighting capability is limited in the area surrounding the proposed LNG terminal. Shore side firefighting resources and training will need to be augmented in order to provide basic protection services to the facility as well as the surrounding communities along the transit route.***

Resource Gap: To be determined in conjunction with local and regional response agencies through the Emergency Response Planning process.

- *In-Transit Fire-Fighting:* ***Firefighting capability is limited along the entire transit route for proposed LNG vessels.***

Resource Gap: A plan must be developed for managing underway firefighting, including provisions for command and control of tactical fire fighting decisions as well as financial arrangements for provision of mutual aid and identification of suitable locations for conducting fire fighting operations along the transit route. To be determined in

> *conjunction with local and regional response agencies through the Emergency Response Planning process.*
>
> *Public Notification System and Procedures: Adequate means to notify the public along the transit route, including ongoing public education campaigns, emergency notification systems, and adequate drills and training are required. Education programs must be tailored to meet the various needs of all waterway users, including commercial and recreational boaters, local businesses, local residents, and tourists.*
>
> *Resource Gap:* ***A comprehensive notification system, including the deployment of associate equipment and training, must be developed****. To be determined in conjunction with local and regional response agencies through the Emergency Response Planning process.*
>
> • *Gas Detection Capability: No gas detection capability exists at the Port of Coos Bay, along the transit route and at the site of the proposed facility. Emergency response personnel require appropriate gas detection equipment, maintenance, and training. Additionally, the use of fixed detection equipment will ensure accurate and expedited gas detection in the event of a large scale LNG release. The installation of these detectors at strategic points along the waterway must be developed.*
>
> ***Resource Gap: Gas Detectors, appropriate training, and maintenance infrastructure.*** *To be determined in conjunction with local and regional response agencies through the Emergency Response Planning process*

The U.S. Coast Guard 2008 WSA for Jordan Cove states on page 5 the following:

> ***In the absence of the measures described in this letter and the resources necessary to implement them or changes in Coast Guard policy upon which the resource decisions are based, Coos Bay would be considered unsuitable for the LNG marine traffic associated with the Jordan Cove LNG Terminal*****.....**
> (Emphasis added)

The above U.S. Coast Guard requirements have not been met and Jordan Cove has provided no mitigation plans that show the channel would be able to demonstrate sufficient adequacy to receive LNG carriers for any single dimension listed.

Unfortunately, the Coast Guard is relying on local people who know nothing really about LNG or LNG hazards to help develop their Emergency Response Plan (including evacuation). Although I am not privy to the safety risk information JECP has shared with our local Emergency Responders and do not know the extent to which these Emergency Responders understand LNG –related hazards, **I believe there is ample reason for concern that the hazard potential of the proposed Jordan Cove LNG facility and the level of emergency response preparedness necessary to cope with such hazards have been significantly underestimated.** Jordan Cove's consultants may have some experience in petroleum vessel oil spills but they have not provided any evidence that they have experience with LNG spills or the safety requirements for handling LNG hazards. They are relying on people who do not have the knowledge or experience to be making these serious decisions and Jordan Cove's consultants continue to use hazard modeling that has NOT BEEN APPROVED in their LNG hazard analysis and assessments. (***See Exhibit 3***) This undermines their entire safety effort and greatly affects what protocols are being established by them.

As explained in detail in our June 24, 2019 comments, safety measures incorporated in the proposed Jordan Cove LNG terminal actually increase the chance of a catastrophic failure and present a far more serious public safety hazard than regulators have analyzed and deemed acceptable.[2] Jerry Havens, Distinguished Professor of Chemical Engineering at University of Arkansas, and James Venart, Professor Emeritus of Mechanical Engineering at University of New Brunswick, have asked specific questions to the FERC concerning these hazard issues.[3] Those questions need to be addressed properly. This would impact potential future industry and the Ports proposed Oregon Gateway cargo terminal to the East of the proposed LNG facility, which would not be allowed to operate in these hazard areas.

See the following Exhibits that we submitted on December 7, 2015 into the HBCU-15-05 record:

> **Exhibit D:** Jordan Cove LNG Hazard "Zones of Concern" from Jordan Cove 2009 FERC EIS (Page 4.7-3).
>
> **Exhibit E:** January 14, 2015 FERC submittal of Jerry Havens , Distinguished Professor of Chemical Engineering at University of Arkansas, and James Venart, Professor Emeritus of Mechanical Engineering at University of New Brunswick concerning Jordan Cove's underestimated LNG export hazards.
>
> **Exhibit F:** February 6, 2015 FERC submittal of Jerry Havens , Distinguished Professor of Chemical Engineering at University of Arkansas, and James Venart, Professor Emeritus of Mechanical Engineering at University of New Brunswick requesting FERC to answer questions regarding Jordan Cove's underestimated LNG export hazards.
>
> **Exhibit G:** "*Site Selection & Design for LNG Ports & Jetties – Information Paper No. 14*" - Published by *Society of International Gas Tanker and Terminal Operators Ltd* / 1997

See also the following Exhibits that we submitted on January 12, 2016 into the HBCU-15-05 Record:

> **Exhibit 23:** CRS Report for Congress / Order Code RL32073 / *Liquefied Natural Gas (LNG) Infrastructure Security: Background and Issues for Congress* / September 9, 2003

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[2] January 14, 2015 Report filed by Jerry Havens Ph.D and James Venart Ph.D. to FERC concerning *discrepancies and problems with Jordan Cove Energy Project hazard analysis* under CP13-483 et. al.
http://elibrary.FERC.gov/idmws/file_list.asp?accession_num=20150114-5038

[3] Feb 6, 2014 Follow-up Report/ *Questions concerning discrepancies and problems with Jordan Cove's hazard analysis* under CP13-483 et al.
http://elibrary.FERC.gov/idmws/file_list.asp?accession_num=20150206-5040

Paul W. Parfomak, Specialist in Science and Technology, Resources, Science, and Industry Division

Exhibit 24: Coast Guard Water Suitability Assessment – July 1, 2008

Exhibit 29: *LNG and Public Safety Issues -Summarizing current knowledge about potential worst-case consequences of LNG spills onto water. By* Jerry Havens Professor, Chemical Engineering, University of Arkansas. 2005 Coast Guard Journal Proceedings

Exhibit 51:

- 6-7-2005 Direct Testimony of Fall River Fire Chief David L Thiboutot under FERC Docket CP04-36-000.
- 6-7-2005 Direct Testimony of Fall River Police Chief John M. Souza under FERC Docket CP04-36-000.
- 6-7-2005 Direct Testimony of Town of Somerset Fire Chief Stephen J. Rivard under FERC Docket CP04-36-000.

Exhibit 66: Articles about the 2004 LNG Explosion in the Algeria Liquefaction Industrial Zone.

Exhibit 80: Oregon Dept of Energy - **Oct 4, 2007 Safety Advisory Report** for the Jordan Cove LNG Import Terminal.

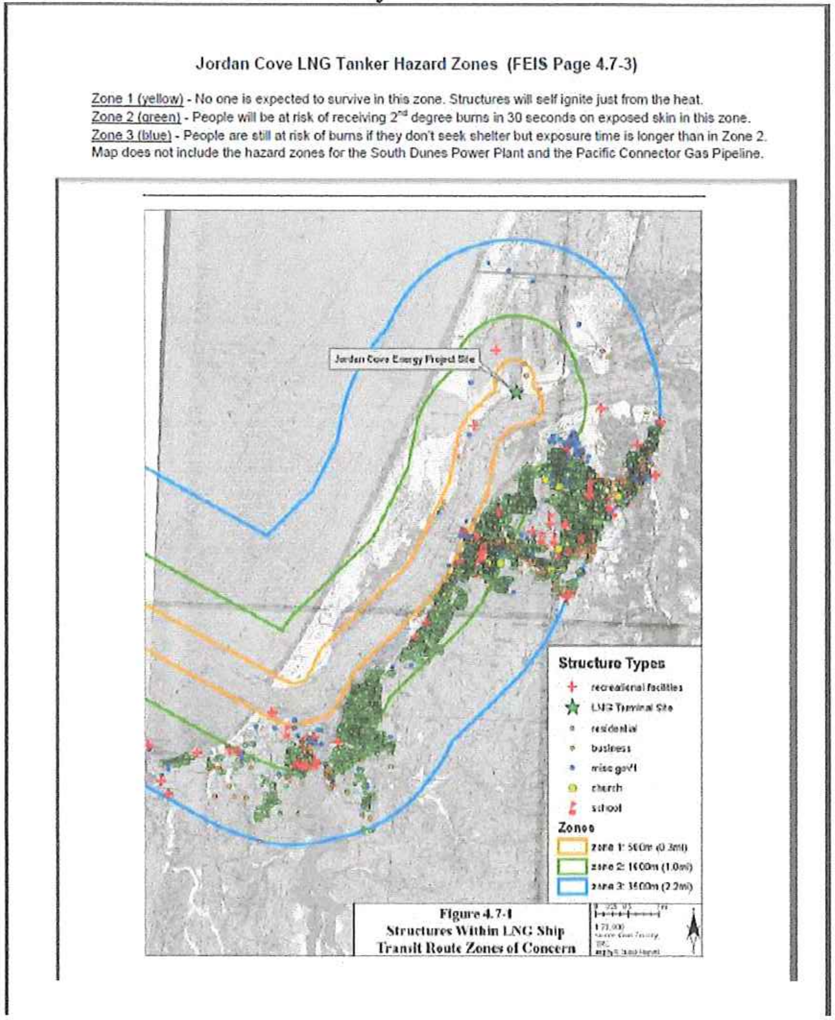
Exhibit 84: *Coast Guard preparing for port shutdowns;* By Hunter Sauls; The Facts Published April 14, 2008; http://thefacts.com/story.lasso?ewcd=f482d0ca682cb716

"*Once ignited, as is very likely when the spill is initiated by a chemical explosion, the floating LNG pool will burn vigorously...Like the attack on the World Trade Center in New York City, **there exists no relevant industrial experience with fires of this scale from which to project measures for securing public safety.***" – Statement by Professor James Fay, Massachusetts Institute of Technology
(Emphasis added.)

Sandia Laboratory's Dec 2004 Report; "*Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water*", states on page 83; "*... The distance from the fire to an object at which the radiant flux is 5 kW/m2 is 1.9 km*" (1.181 miles). **To clearly understand this one must understand that 5 kW/m2 is the heat flux level that can cause 2nd degree burns on exposed human skin in 30 seconds. (*See Exhibit 7*)**

As we have explained in detail in prior comments, LNG is natural gas that has been condensed down some 600 times the volume of its gaseous state. The hazardous burn zones can go out for several miles depending on the size of the spill and type of fire that develops. An estimated 16,922 people in the Coos Bay area would live in the hazardous burn zones of concern according to the former Jordan Cove Export Final EIS (page 4-1031) under Dockets CP13-483-000/CP13-492-000, and yet there is little concern given for their safety. No amount of resources can mitigate much of the death, damage and injury expected within these hazardous burn zones.

Trees and burnable scrub brush cover our area. Secondary fires will be paramount and **most of our emergency responders are located in the LNG hazardous zones of concern.** The Coos Bay area has only one hospital and that hospital does not have a "Burn Unit." We have yet to see an emergency response plan on how the medical response to even a minor LNG hazardous event could be handled in light of our area's obvious insufficiency of appropriate medical facilities and personnel. This was just one of many concerns that were raised in scoping comments to FERC that have yet to be addressed.



Jordan Cove LNG Tanker Hazard Zones (FEIS Page 4.7-3)

Zone 1 (yellow) - No one is expected to survive in this zone. Structures will self ignite just from the heat.
Zone 2 (green) - People will be at risk of receiving 2nd degree burns in 30 seconds on exposed skin in this zone.
Zone 3 (blue) - People are still at risk of burns if they don't seek shelter but exposure time is longer than in Zone 2.
Map does not include the hazard zones for the South Dunes Power Plant and the Pacific Connector Gas Pipeline.

Figure 4.7-1
Structures Within LNG Ship Transit Route Zones of Concern

Above Diagram from the Jordan Cove Import Final EIS page 4.7-3 under CP07-444-000/CP07-441-00.

On Friday, March 29, 2019 the Federal Energy Regulatory Commission (FERC) released the Draft Environmental Impact Statement (DEIS) on Pembina's proposed Jordan Cove LNG Export project under Docket Nos. CP17-494-000 and CP17-495-000. While the DEIS is not a FINAL Document yet as it **<u>is still under review</u>**, the DEIS for the Jordan Cove/Pacific Connector project shows the following diagram on page 4-709:

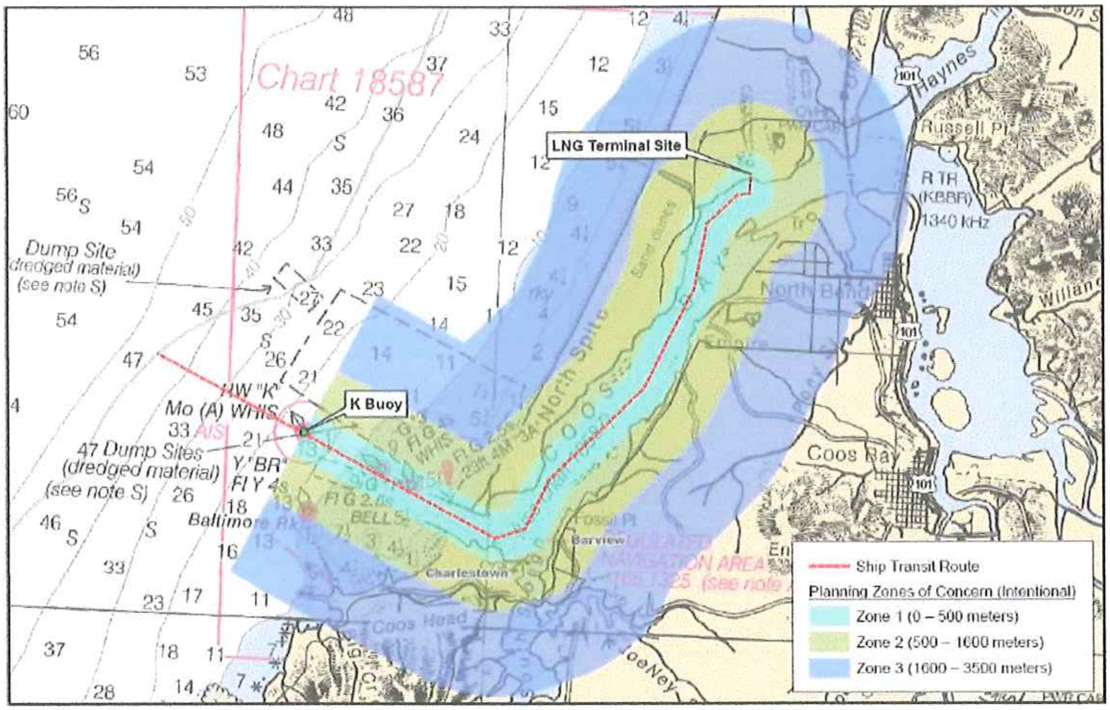


Figure 4.13-2. Intentional Hazard Zones along LNG Marine Vessel Route

On Monday, April 1, 2019, Jerry Havens, Distinguished Professor of Chemical Engineering at University of Arkansas, submitted detailed comments on the DEIS with respect to public safety hazards being underestimated at the proposed Jordan Cove LNG terminal. (***See Exhibit 3***)

See also the following Exhibits submitted into the Remand record on July 9, 2019:

> **Exhibit D:** April 1, 2019, Comment by Jerry Havens, Distinguished Professor of Chemical Engineering at University of Arkansas, on the FERC DEIS under CP-17-494 and CP-17-495. Concerns public safety hazards being underestimated at the proposed Jordan Cove LNG terminal
>
> **Exhibit E** *"Scientists say public safety hazards at Jordan Cove LNG terminal in Coos Bay are underestimated"* by Ted Sickinger; The Oregonian; January 16, 2015
>
> **Exhibit F:** June 7, 2016, article, *"Explosive LNG issues grab PHMSA's attention" by* E&E reporter, Jenny Mandel.

In order to better explain why the Coast Guard MUST maintain a strict enforcement policy concerning the 500 yard bubble that surrounds an LNG tankership, I am also submitting into the record the following documents:

SAFETY AND SECURITY EXHIBITS

Exhibit 4: Communication with the Coast Guard concerning LNG hazards and concerns.

Exhibit 5: Highlights of United States Government Accountability Office, Report to Congressional Requesters, Maritime Security; "*Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification*", February 2007; GAO-07-316: http://www.gao.gov/new.items/d07316.pdf

Exhibit 6: U.S. Department of Energy "*Liquefied Natural Gas Safety Research* "Report to Congress May 2012; http://energy.gov/sites/prod/files/2013/03/f0/DOE_LNG_Safety_Research_Report_To_Congre.pdf

Exhibit 7: SANDIA REPORT "*Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water*"; Mike Hightower, Louis Gritzo, Anay Luketa-Hanlin, John Covan, Sheldon Tieszen, Gerry Wellman, Mike Irwin, Mike Kaneshige, Brian Melof, Charles Morrow, Don Ragland; SAND2004-6258; Unlimited Release; Printed December 2004;

Exhibit 8: "*Understanding the Stoll Curve*"; Oberon 2005; http://csaz462.ca/data/1/rec_docs/102_Oberon_WP_Understanding_the_Stoll_Curve.pdf

Exhibit 9: "*An Assessment of the Potential Hazards to the Public Associated with Siting an LNG Import Terminal in the Port of Long Beach*" - Dr. Jerry Havens, September 14, 2005

Exhibit 10: "*LNG and Public Safety Issues – Summarizing Current Knowledge about Potential Worst Case Consequences of LNG spills onto water*". Jerry Havens, Coast Guard Journal Proceedings, Fall 2005

Exhibit 11: *WILLIAMS COMPANIES FAILED TO PROTECT EMPLOYEES IN PLYMOUTH LNG EXPLOSION* The natural gas company eyeing other Northwest projects has a history of unsafe work conditions. Author: Tarika Powell; June 3, 2016 https://www.sightline.org/2016/06/03/williams-companies-failed-to-protect-employees-in-plymouth-lng-explosion/

Exhibit 12: *Safe Harbor?* Ships bringing liquefied natural gas from the Middle East pass regularly through Boston Harbor. Experts say there's little chance of an LNG tanker going up in a fireball. Then why are city officials so worried? Should you be? ; By JASON SCHWARTZ. 6/28/2010

Exhibit 13: "*Liquefied Natural Gas Tankers Remain Giant Terror Targets*" Cindy Hurst, The Cutting Edge News, June 16th 2008: http://www.thecuttingedgenews.com:80/index.php?article=531

Exhibit 14: "*LNG demand growth risks fall in shipping standards*" By Paul Marriott, India Yahoo News - http://in.news.yahoo.com/060620/137/65814.html

Exhibit 15: "*The Terrorist Threat to Liquefied Natural Gas: Fact or Fiction?*" By LCDR Cindy Hurst; Feb 2008; Institute for the Analysis of Global Security (IAGS); http://www.iags.org/hurstlng0208.pdf

Exhibit 16: The Memory Hole: "*LNG Security at Distrigas Facility*": http://www.thememoryhole.org/energy/lng_security_distrigas.htm

2. Relying on the Coast Guard does NOT Guarantee the Safety of LNG Transits in the Coos Bay.

A recent news story entitled, *Fishing Vessel runs aground on the North Spit after losing power,*[4] (***See Exhibit 17***) proves current Coast Guard protocols have not changed much since the grounding of the New Carissa in 1999 which ended up being a total vessel disaster. The same thing could easily happen again but with much dire consequences involving LNG transits and hazards.

(***See Exhibit 18***)
http://www.oregonlive.com/pacific-northwest-news/index.ssf/2015/12/coast_guard_closes_all_maritim.html
Coast Guard closes all maritime entrances in Oregon, Washington due to flood debris, high seas (video) By Stuart Tomlinson | The Oregonian/OregonLive ; on December 11, 2015

(***See Exhibit 19***)
https://theworldlink.com/lifestyles/food-and-cooking/dead-after-commercial-crabbing-vessel-capsizes-off-oregon/article_81b0bf8c-1e7c-51cb-a425-b25a96f39f45.html
3 dead after commercial crabbing vessel capsizes off Oregon
By GILLIAN FLACCUS Associated Press
Jan 10, 2019

* * *

> ***The men had called for an escort across the bar and a responding Coast Guard boat was nearby when the crabbing boat capsized "without warning,"*** *the Coast Guard said Wednesday evening in a news release....*

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[4] *Fishing Vessel runs aground on the North Spit after losing power;* Nicholas A. Johnson - The World Jun 21, 2018; https://theworldlink.com/news/local/fishing-vessel-runs-aground-on-the-north-spit-after-losing/article_e90717d9-613b-5201-9823-bcec642599fa.html

> *...But those in the industry said the loss hit particularly hard this year, when crabbers were rushing to sea to try to catch up after the annual Oregon Dungeness crab season was delayed more than a month. The season usually begins Dec. 1, but this year it only began last week because the crabs were too small and didn't have enough meat to harvest.*
>
> *Then, a series of bad storms in the first week of the season prevented many crabbers from recovering their pots on Jan. 4, the first day they could do so, said Tim Novotny, spokesman for Oregon Dungeness Crab Commission.*
>
> *"When they did get out, some of them had to stay out a little longer because of the weather. The difficulty is once you're out at sea, they can handle a lot of conditions. **But the trouble is trying to get back across those bars**," Novotny said.*
>
> *A bar is an area near the coast where a river — in this case the Yaquina River — meets the sea. The force of the river water colliding with the ocean can create hazardous currents and swells, particularly during a storm....*
>
> *...The 10-year average haul for Dungeness crab in Oregon is 16 million pounds, but last year crabbers brought in 23 million pounds. **That haul was worth more than $74 million at the docks and pumped $150 million into the state and local economy**, Novotny said.*

(*See McCaffree Exhibit 42 filed on June 24, 2019*)

https://kcby.com/news/local/after-a-year-of-planning-coos-bay-has-new-marine-patrol-boat-dock

After a year of planning, Coos Bay has new marine patrol boat dock

by KCBY

Wednesday, March 16th 2016

* * * *

> *"We're going to be upgrading the training for all our deputies in boat handling. If LNG comes, there's going to be requirements for us to be able to respond in the bay and it requires better than just being a boat operator, but operating amongst other boats and doing some routine inspections and those types of things."*
>
> ***Dybevik says the lower bay is always crowded with boats during the summer.***
>
> ***He says he's as counted as many as 100 boats in that area at one time.***

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https://www.oregonlive.com/business/2014/06/coos_bay_lng_terminal_designed.html

Jordan Cove LNG terminal at Coos Bay designed for Cascadia quake, tsunami though hazards remain; By Ted Sickinger – The Oregonian; Jan 10, 2019

* * * *

> *"__I'm very skeptical that anything can be done in a near-shore tsunami" to protect the tanker__," said __Randy Clark, a security specialist with the U.S. Coast Guard__. "__There simply isn't enough time__. ... There are no real regulations. There is no requirement to mitigate this risk."*[5]

If the Coast Guard does not follow the same protocols that they have established in other areas for LNG transits, such as the terminal at Everett in the Boston area, then thousands of people living in the Coos Bay area would be placed at extreme risk. **That would not be in the public interest**. The Coos Bay area does not have the experienced people here to handle even a small LNG incident. Attached ***Exhibits 16 and 12*** show the kinds of security that is done by the Coast Guard at the Everett LNG terminal. The United States Sandia Report and Government Accountability Office Report (***See Exhibits 5 and** 7*) determined that the hazardous burn zone for these LNG tankers can go out for more than a mile. This is the distance where people can receive 2nd degree burns in 30 seconds just from the heat flux should there be an incident with an LNG tankership and a pool fire was to develop.

Jordan Cove is proposing to build an LNG export terminal on dredging spoils located on a sand spit (an unstable sand dune area), directly across the bay from an airport runway, in the flight path of the runway, in an extreme tsunami inundation zone, in an earthquake subduction zone, in an area known for high winds and ship disasters, less than a mile from a highly populated city. Thousands of people in the Coos Bay/North Bend area would be put at risk due to living in Jordan Cove's LNG Hazardous Burn Zones. The Project is one of the worst sited LNG export proposals out there.

LNG tankerships would cross within feet from the end of the runway at the Southwest Oregon Regional Airport. Despite the Coast Guard's 500 yard Safety and Security zone also extending 500 yards up in the air, they have given NO CONSIDERATION for this extreme hazard. As we have previously shown in detailed comments and exhibits submitted into the record (*See McCaffree-CFR comments submitted on June 24, 2019 page 53*), on May 7, 2018 the FAA released 13 determinations of PRESUMED AIRPORT HAZARD with respect to the proposed Jordan Cove Project.[6] Jordan Cove has not resolved these issues and they would not be something that could really be mitigated. Nine of these FAA Presumed Airport Hazards involve transiting LNG tanker ships at various points within the Coos Bay Estuary. (*See Exhibit 1 filed on June 10, 2019*) This would be devastating to the Southwest Oregon Regional Airport operations, navigation and fishing and clearly violates OAR 141-122-0020(5)(a) and ORS 196.825(1)(a)(b);(3)(a)(e)

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[5] *Jordan Cove LNG terminal at Coos Bay designed for Cascadia quake, tsunami though hazards remain;* By Ted Sickinger – The Oregonian; Jan 10, 2019; https://www.oregonlive.com/business/2014/06/coos_bay_lng_terminal_designed.html

[6] See Part 8 of Jordan Cove response filing with the FERC that includes the 13 FAA documents: http://elibrary.FERC.gov/idmws/file_list.asp?accession_num=20180510-5165

The proposed Jordan Cove LNG project would not be in the public interest and has not proven the project would not ***unreasonably interfere with public trust rights***; For these reasons and all those stated previously, please deny the Jordan Cove LNG project terminal application.

Sincerely,

/s/ Jody McCaffree

Jody McCaffree

Index for Exhibits

September 9, 2019

McCaffree / Citizens For Renewables / CALNG

For Jordan Cove / Pacific Connector

REM-19-001

NOTE: The following Exhibit 11 was referenced as Exhibit H in comments submitted on July 9, 2019

Exhibit 1: Ref for Index for Exhibits submitted by McCaffree-CFR on July 9, 2019

Exhibit 2: May 10, 2018 Coast Guard Letter of Recommendation (LOR) for the Jordan Cove LNG Project under CP17-495.

Exhibit 3: Testimony and Exhibits submitted by Professor Jerry Havens to the PHMSA and FERC on

Exhibit 4: Communication with the Coast Guard concerning LNG hazards.

Exhibit 5: Highlights of United States Government Accountability Office, Report to Congressional Requesters, Maritime Security; "*Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification*", February 2007; GAO-07-316: http://www.gao.gov/new.items/d07316.pdf

Exhibit 6: U.S. Department of Energy "*Liquefied Natural Gas Safety Research* "Report to Congress May 2012; http://energy.gov/sites/prod/files/2013/03/f0/DOE_LNG_Safety_Research_Report_To_Congre.pdf

Exhibit 7: SANDIA REPORT "*Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water*"; Mike Hightower, Louis Gritzo, Anay Luketa-Hanlin, John Covan, Sheldon Tieszen, Gerry Wellman, Mike Irwin, Mike Kaneshige, Brian Melof, Charles Morrow, Don Ragland; SAND2004-6258; Unlimited Release; Printed December 2004;

Exhibit 8: "*Understanding the Stoll Curve*"; Oberon 2005; http://csaz462.ca/data/1/rec_docs/102_Oberon_WP_Understanding_the_Stoll_Curve.pdf

Exhibit 9: "*An Assessment of the Potential Hazards to the Public Associated with Siting an LNG Import Terminal in the Port of Long Beach*" - Dr. Jerry Havens, September 14, 2005

Exhibit 10: *"LNG and Public Safety Issues – Summarizing Current Knowledge about Potential Worst Case Consequences of LNG spills onto water"*. Jerry Havens, Coast Guard Journal Proceedings, Fall 2005

Exhibit 11: *WILLIAMS COMPANIES FAILED TO PROTECT EMPLOYEES IN PLYMOUTH LNG EXPLOSION* The natural gas company eyeing other Northwest projects has a history of unsafe work conditions. Author: Tarika Powell; June 3, 2016

https://www.sightline.org/2016/06/03/williams-companies-failed-to-protect-employees-in-plymouth-lng-explosion/

Exhibit 12: *Safe Harbor?* Ships bringing liquefied natural gas from the Middle East pass regularly through Boston Harbor. Experts say there's little chance of an LNG tanker going up in a fireball. Then why are city officials so worried? Should you be? ; By JASON SCHWARTZ. 6/28/2010

Exhibit 13: "*Liquefied Natural Gas Tankers Remain Giant Terror Targets*" Cindy Hurst, The Cutting Edge News, June 16th 2008: http://www.thecuttingedgenews.com:80/index.php?article=531

Exhibit 14: "*LNG demand growth risks fall in shipping standards*" By Paul Marriott, India Yahoo News - http://in.news.yahoo.com/060620/137/65814.html

Exhibit 15: "*The Terrorist Threat to Liquefied Natural Gas: Fact or Fiction?*" By LCDR Cindy Hurst; Feb 2008; Institute for the Analysis of Global Security (IAGS); http://www.iags.org/hurstlng0208.pdf

Exhibit 16: The Memory Hole: "*LNG Security at Distrigas Facility*": http://www.thememoryhole.org/energy/lng_security_distrigas.htm

Exhibit 17: *Fishing Vessel runs aground on the North Spit after losing power;* Nicholas A. Johnson - The World; Jun 21, 2018; https://theworldlink.com/news/local/fishing-vessel-runs-aground-on-the-north-spit-after-losing/article_e90717d9-613b-5201-9823-bcec642599fa.html

Exhibit 18: *Coast Guard closes all maritime entrances in Oregon, Washington due to flood debris, high seas (video);* By Stuart Tomlinson | The Oregonian/OregonLive; December 11, 2015; http://www.oregonlive.com/pacific-northwest-news/index.ssf/2015/12/coast_guard_closes_all_maritim.html

Exhibit 19: "*3 dead after commercial crabbing vessel capsizes off Oregon*" ; By GILLIAN FLACCUS Associated Press; Jan 10, 2019 https://theworldlink.com/lifestyles/food-and-cooking/dead-after-commercial-crabbing-vessel-capsizes-off-oregon/article_81b0bf8c-1e7c-51cb-a425-b25a96f39f45.html

Exhibit 20: *Coast Guard preparing for port shutdowns*; By Hunter Sauls; The Facts ; Published April 14, 2008

Exhibit 1

Index for Exhibits

July 9, 2019

McCaffree / Citizens For Renewables / CALNG

For Rebuttal Comments re Jordan Cove / Pacific Connector

REM-19-001

Exhibit A: Corrected Table of Contents submitted for Comments submitted on June 24, 2019 under REM-19-001

Exhibit B: ECONorthwest October 16, 2006 *Forecast of the Net Economic Benefits of a Proposed LNG* [Import] *Terminal in Coos County, Oregon*

Exhibit C: September 12,. 2012 Answer filed with the U.S. Department of Energy Concerning Jordan Cove's LNG Export Application under FE Docket No. 12–32–LNG concerning problems with ECONorthwest analysis.

Exhibit D: April 1, 2019, Comment by Jerry Havens, Distinguished Professor of Chemical Engineering at University of Arkansas, on the FERC DEIS under CP-17-494 and CP-17-495. Concerns public safety hazards being underestimated at the proposed Jordan Cove LNG terminal

Exhibit E *"Scientists say public safety hazards at Jordan Cove LNG terminal in Coos Bay are underestimated"* by Ted Sickinger; The Oregonian; January 16, 2015

Exhibit F: June 7, 2016, article, *"Explosive LNG issues grab PHMSA's attention" by* E&E reporter, Jenny Mandel.

Exhibit G: 5-2-2019 Department of Transportation Pipeline and Hazardous Materials Safety Administration [Docket No. PHMSA-2019-0087] Bulletin regarding *Pipeline Safety: Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards*

Exhibit H: Omitted due to computer glitch. (NOTE *See Sept 9, 2019 Exhibit 11*)

Exhibit I: The World – Coos Bay **UTVs to 'takeover' Box Car Hill this weekend**
NICHOLAS A. JOHNSON - The World, June 27, 2019
https://theworldlink.com/news/local/utvs-to-takeover-box-car-hill-this-weekend/article_c3258d6e-e77f-5073-b28c-8d2a657c7186.html

Exhibit J: Page 2435 from NB JCEP Rebuttal Comment filed on 6-10-2019 showing Jordan Cove plans for Boxcar Hill Campground.

Exhibit 2

MEMORANDUM TO:	Office of the Secretary
FROM:	U.S. Coast Guard [Posted by Ghanshyam Patel, FERC staff]
SUBJECT:	Letter of Recommendation (LOR) for the Jordan Cove LNG Project - Docket No. CP17-495-000
DATE:	June 1, 2018 [LOR dated May 10, 2018]

Please place the attachment in the public files for the Jordan Cove LNG Project under Docket No. CP17-495-000.

The attachment contains:

- U.S. Coast Guard's LOR
- LOR Analysis (Enclosure 1)
- April 24, 2009 LOR (Enclosure 2)
- Waterway Suitability Report (Enclosure 3)

U.S. Department of Homeland Security

United States Coast Guard

Captain of the Port
U. S. Coast Guard
Sector Columbia River

2185 SE 12th Place
Warrenton, Oregon 97146-9693
Staff Symbol: s
Phone: (503) 861-6211

16611
May 10, 2018

Director of Gas Environment and Engineering, PJ 11
Attn: Mr. Rich McGuire
Federal Energy Regulatory Commission
888 First Street NE
Washington, DC 20426

Dear Mr. McGuire:

This Letter of Recommendation (LOR) is issued pursuant to 33 Code of Federal Regulations (CFR) 127.009 in response to the Letter of Intent submitted by Jordan Cove Energy Project. L.P. (Jordan Cove) on January 9, 2017. Jordan Cove proposes to construct and operate the Jordan Cove LNG facility in Coos Bay, Oregon from which Liquefied Natural Gas (LNG) is proposed to be transferred in bulk to a vessel for export. This LOR conveys the Coast Guard's recommendation on the suitability of the Coos Bay Channel for LNG marine traffic as it relates to safety and security. In addition to meeting the requirements of 33 CFR 127.009, this LOR fulfills the Coast Guard's commitment for providing information to your agency under the Interagency Agreement signed in February 2004.

After reviewing the information in the applicant's Letter of Intent (LOI) and Waterway Suitability Assessment (WSA) with subsequent annual updates and completing an evaluation of the waterway in consultation with a variety of state and local port stakeholders, I recommend that the Coos Bay Channel be considered suitable for LNG marine traffic. My recommendation is based on review of the factors listed in 33 CFR 127.007 and 33 CFR 127.009. The reasons supporting my recommendation are outlined below.

On November 1, 2017, I completed a review of the WSA for the Jordan Cove Energy Project, submitted to the Coast Guard by KSEAS Consulting on behalf of Jordan Cove in February 2007. This review was conducted following the guidance provided in U.S. Coast Guard Navigation and Vessel Inspection Circular (NVIC) 01-2011, dated January 24, 2011. In conducting this review and analysis, I focused on the navigation safety and maritime security aspects of LNG vessel transits along the affected waterway. My analysis included an assessment of the risks posed by these transits and validation of the risk management measures proposed by the applicant in the WSA. During the review, I consulted a variety of stakeholders including the Area Maritime Security Committees, Harbor Safety Committees, State representatives, Pilot Organizations, and local emergency responders.

Based upon a comprehensive review of Jordan Cove's WSA, and after consultation with State and Local port stakeholders, I recommend that the Coos Bay Channel be considered suitable for accommodating the type and frequency of LNG marine traffic associated with this project.

The attached LOR Analysis contains a detailed summary of the WSA review process that has guided this recommendation. It documents the assumptions made during the analysis of Jordan Cove's WSA. It discusses details of potential vulnerabilities and operational safety and security measures that were analyzed during the review. The portion of the LOR Analysis which addresses matters that affect maritime security is marked as Sensitive Security Information and is withheld from distribution.[1] The LOR Analysis sets forth the navigational safety and maritime security resource gaps that currently exist in, on, and adjacent to the waterway, including the marine transfer area of the proposed facility, and which, to the extent allowable under FERC's existing legal authority, may be addressed in its Commission Order if one is issued. To the extent implementation of specific mitigation measures fall outside the scope of FERC's legal authority, the applicant is expected to examine the feasibility of implementing such mitigation measures, in consultation with the Coast Guard and State and Local agencies as applicable.

This recommendation is provided to assist in the Commission's determination of whether the proposed facility should be authorized. This Letter of Recommendation is not an enforceable order, permit, or authorization that allows any party, including the applicant, to operate a facility or a vessel on the affected waterway. Similarly, it does not impose any legally enforceable obligations on any party to undertake any future action be it on the waterway or at the proposed facility. It does not authorize, nor in any way restrict, the possible future transit of properly certificated vessels on the Coos Bay Channel. As with all issues related to waterway safety and security, I will assess each vessel transit on a case by case basis to identify what, if any, safety and security measures are necessary to safeguard the public health and welfare, critical marine infrastructure and key resources, the port, the marine environment, and vessels. In the event the facility begins operation and LNG vessel transits commence, if matters arise concerning the safety or security of any aspect of the proposed operation, a Captain of the Port Order could be issued pursuant to my authority under the Ports and Waterways Safety Act of 1972, as amended by the Port and Tanker Safety Act of 1978, 33 U.S.C. § 1221 – 1232, among other authorities, to address those matters.

Please note that Enclosures (4) is Sensitive Security Information (SSI) and shall be disseminated, handled and safeguarded in accordance with 49 CFR Part 1520, "Protection of Sensitive Security Information."

If you have any questions on this recommendation, my point of contact is Lieutenant Commander Laura Springer. She can be reached at the address listed above, by phone at (503) 209-2468, or by email at Laura.M.Springer@uscg.mil.

Sincerely,

W. R. TIMMONS,
Captain, U. S. Coast Guard
Captain of the Port, Sector Columbia River

Enclosure (1) LOR Analysis
(2) LOR issued by Sector Portland on April 24, 2009
(3) U.S.C.G.'s Waterway Suitability Report for the Jordan Cove Energy Project
(4) LOR Analysis (SSI Portion)

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[1] Documents containing SSI may be made available upon certification that the requestor has a need to know and appropriate document handling and non-disclosure protocols have been established.

Copy: Commander, Coast Guard District Thirteen (dp)
Commander, Pacific Area (PAC-54)
Commandant (CG-OES), (CG-ODO), (CG-FAC), (CG-741), (CG-CVC), (CG-ENG), (LNGNCOE)
Marine Safety Center (CG MSC)
Jordan Cove

UNITED STATES COAST GUARD

Jordan Cove LNG

ANALYSIS SUPPORTING THE LETTER OF RECOMMENDATION ISSUED BY COTP SECTOR COLUMBIA RIVER ON MAY 10, 2018

Enclosure (1)

Introduction

1. This analysis is a supplement to my Letter of Recommendation (LOR) dated May 10, 2018, that conveys my recommendation on the suitability of the Coos Bay Ship Channel for liquefied natural gas (LNG) marine traffic associated with the Jordan Cove LNG (JCLNG) export terminal project Coos Bay, Oregon. It documents the processes followed in analyzing JCLNG's Waterway Suitability Assessment (WSA) and the suitability of the waterway for LNG marine traffic.

2. For the purposes of this analysis, the following assumptions were made:

   a. The applicant is fully capable of, and would fully implement, any and all risk management measures identified in their WSA.
   b. The conditions of the port identified in the WSA fully and accurately describe the actual conditions of the port at the time of the WSA submission.
   c. The conditions of the port have not changed substantially during the analysis process.
   d. The applicant will fully meet all regulatory requirements including the development and submission of a Facility Security Plan, Emergency Manual, and Operations Manual.

3. The Port of Coos Bay is a deepwater port located in Coos Bay, Oregon on the Pacific Coast of the United States. The Port of Coos Bay offers easy access to Asian markets and facilitates the international movement of goods between the United States and Asia. The Port of Coos Bay is managed under the jurisdiction of the Portland Navigation District and has an authorized channel depth of 37 feet. The channel width is 300 nominal feet. The principal exports are logs, wood chips, lumber, and plywood. The Port of Coos Bay is currently conducting a feasibility study to examine widening and deepening its ship channel.

4. The Port of Coos Bay is approximately 173 nautical miles south of the Columbia River and 367 miles north of the entrance to San Francisco Bay. The Port has seen declining arrivals and is not currently heavily trafficked.

5. Inbound and outbound traffic density in the Port of Coos Bay is currently minimal. In the summer months and during fishing season there are a number of commercial fishing vessels working in the region. The maximum anticipated LNG Carrier port calls per year is expected to be around 120. These projections are based on a maximum nominal LNG output of 7.8 MTPA. Other traffic transiting through the Port of Coos Bay include fishing vessels, recreational vessels, and towing vessels.

6. The Terminal will be sited at the north end of the Coos Bay Channel near Jordan Cove. All Terminal facilities will be located within an approximately 200-acre parcel of land. The approximate locations of the coordinates of the facility are: 43 degrees-25.5' North and 124 degrees 15.7' West.

7. The U.S. Coast Guard regulates the port under the Maritime Transportation Security Act (MTSA), Security and Accountability for Every Port Act (SAFE Port Act), Ports and Waterways Safety Act (PWSA) and other laws applicable to maritime safety and security. U.S. Coast Guard regulated facilities in the area include chip terminals and fuel transfer facilities.

8. Ships entering or departing Coos Bay require a pilot. The Coos Bay Pilots are state licensed Oregon pilots responsible for ensuring the safe transit of vessels transiting through the Port of Coos Bay. They handle approximately 50 vessel transits through the Port of Coos Bay each year.

9. In order to support operations associated with the facility, the applicant will provide additional towing vessels as outlined in their WSA. All tractor tugs must be at least 80 Ton Astern Bollard or larger and equipped with Class 1 Fire Fighting equipment.

10. The applicant established an emergency response planning group in preparation for facility construction and operation in 2006. This group is tasked with education and preparedness concerning this facility. It must be noted that there are schools located in the zones of concern.

Impact to Coast Guard Operations

1. The U.S. Coast Guard is responsible for screening LNG Carriers transiting from foreign ports prior to arrival and will screen all vessels in accordance with existing policies and procedures. The vessels calling on the facility will be foreign flagged and the flag state is yet to be determined. I do not intend to require additional government conducted safety inspections beyond those which already apply to deep draft LNG vessels.

2. Facility and vessel inspection activities will be supported by Marine Safety Unit Portland personnel.

3. Limited access areas (LAA) associated with the project have yet to be established. Sector Columbia River will use risk based decision making and work with existing policy to determine the appropriate LAAs. The proposed LAA in enclosure (3) was not put out for regulatory review and is not in effect.

4. LNG is not considered oil and all vessels calling on the facility will be required to comply with non-tank vessel response plan requirements. The applicant is highly encouraged to work with the Area Committees established under the National Contingency Plan to address issues associated with response in Coos Bay.

5. The Facility will be in the Sector Columbia River Captain of the Port Zone and falls under the purview of the Federal Maritime Security Coordinator who is also the Sector Columbia River Captain of the Port. Specific issues related to this are outlined in Enclosure (4).

Figure 1. Jordan Cove Conceptual rendering of facility

Decision Making Process

1. The following factors regarding the condition of the waterway, vessel traffic, and facilities upon the waterway, were taken into consideration during the LOR process. The processes used are detailed in this section.

2. To ensure all regulatory processes were met, Sector Columbia River took a systematic approach in the WSA validation process. To streamline and ensure transparency, Sector Columbia River worked with Jordan Cove, the Consulting Group KSEAS, and port partners though a series of ad hoc meetings and a one day workshop.

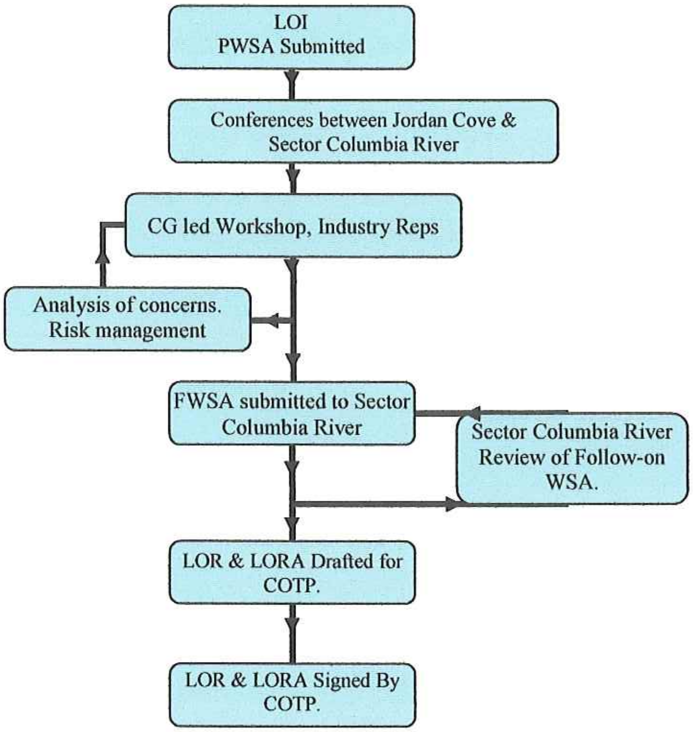

Figure 2 - LNG LOR Process
(Sector Columbia River)

3. NVIC 01-2011 provides guidance on the review and validation of a WSA. Applying NVIC 01-2011's procedural framework, my staff held several in-house reviews of the WSA, and facilitated discussions during a workshop held in Coos Bay, OR on October 16, 2017. The workshop included a wide range of participants, including representatives from; the USCG; Coos Bay Pilots Association; Port Authorities, the State of Oregon and law enforcement agencies.

Members	Position/Role
LCDR Laura Springer	Waterways Management Division Chief, MSU Portland
LCDR Ben Crowell	Surface Operations, Sector North Bend
LCDR Andrew Madjeska	Incident Management Division Chief, Sector Columbia River
LCDR Xochitl Castaneda	District Thirteen Prevention
Ms. Deanna Henry	Oregon Department of Energy
George Wales	Coos Bay Pilots
Richard Dybevik	Roseburg Forest Products
Doug Strain	Coos Bay Sheriff
Jim Brown	North Bend Fire Department
Doug Eberlein	Coos Bay Response Co-op (CBRC)
LT Ethan Lewallen	USCG LNG NCOE

Table 1 – Jordan Cove WSA Team 1 Nov 2017
(Port of Coos Bay)

4. The participants of this "ad-hoc" workshop, recommended by NVIC 01-2011, utilized their expertise on the physical characteristics and traffic patterns of the waterway, as well as their respective specialty knowledge of the marine environment, LNG, safety, security, and facility operations, to analyze the suitability of the waterway to support LNG marine traffic associated with JCLNG.

5. Participants considered the changes in the area's safety and security dynamics which may result from the introduction of LNG ship traffic associated with the JCLNG Project. Jordan Cove used the American National Standards Institute (ANSI)/American Petroleum Institute (API) Standard 780 Security Risk Assessment (SRA) Methodology, as the basic approach for assessing risk. The standard was published in June of 2013 as a U. S. standard for security risk assessments on petroleum and petrochemical facilities. The standard is a tool used to evaluate all security risks associated with petroleum and petrochemical infrastructure and operations, and assists owners and operators through the process of conducting thorough and consistent SRAs. For security purposes, participants considered potential threats and consequences of intentional act of aggression to the facility and developed security measures to mitigate the risks.

    a. Please see Enclosure (4) if you have a need to know concerning the results of this

6. During the above mentioned workshop held in Coos Bay, OR on October 16, 2017, the ad-hoc working group also evaluated safety factors including the potential impacts of groundings, collisions, and allisions and thoroughly examined the simulator data presented in the WSA.

7. Each of the recommended risk management measures from enclosure (7) of NVIC 01-2011 were considered. In the WSA workshop, additional risks and recommendations were discussed related to a Cascadia Subduction Zone Earthquake and associated implications for the facility and region if a laden vessel was tied up at the layberth.

8. The ad-hoc working group considered each scenario along each transit segment and evaluated the causes of accidental or intentional events. The workshop analyzed the contributing factors for each scenario and their likelihood of occurrence given the adequacy of safety and security layers.

9. Sector Columbia River followed the checklist found in NVIC 01-2011 during the review. Through this review, Sector Columbia River clarified certain points in the WSA to ensure that the document contained accurate information and that references were applicable. With the 2017 update to the WSA, Jordan Cove has satisfied the requirements of the LOR process.

10. Based on my review of the WSA completed on November 1, 2017, and input from state and local port stakeholders, and taking into account previously reviewed expansion projects, I recommend to the Federal Energy Regulatory Commission

that the waterway in its current state be considered suitable for the LNG marine traffic associated with the proposed project.

11. This recommendation is contingent upon the applicant completing all actions outlined in the Waterways Suitability Assessment as submitted, and actions associated with subsequent annual updates, and completing all actions outlined in the most current WSA and actions under the control of the applicant from the July 1, 2008, Waterway Suitability Report.

Waterway Conditions Adjacent to the Facility

1. **Depth of Water.** The channel is currently maintained at a 37' depth.
2. **Tidal Range.** The tides of Coos Bay are of the mixed semi-diurnal type with paired highs and lows of unequal duration and amplitude. The tidal range increases upstream to the City of Coos Bay and the time difference between peak tides at the entrance and City of Coos Bay is about 40-90 minutes, depending on the location. The head of the tide is located at River Mile 27 on both the Millicoma and South Fork Coos Rivers. The tidal range is 7.5 feet near the open sea channel and 6.7 feet at the entrance to Charleston Harbor.

Table 2 Tidal Datums, Coos Bay, OR NOAA Tide Stations 9432895, 9432879, and 9432780

Tide Level	Abbreviation	Tide Level (ft) North Bend	Tide Level (ft) Empire	Tide Level (ft) Charleston
Tide Station ID #		9432895	9432879	9432780
Latitude		43° 24.6'N	43° 22.6'N	43° 20.7'N
Longitude		124° 13.1'W	124° 17.8'W	124° 19.3'W
Extreme High Water	EHW	-	-	+10.5
Mean Higher High Water	MHHW	+8.4	+7.7	+7.6
Mean High Water	MHW	+7.8	+7.1	+7.0
Mean Sea Level	MSL	+4.7	+4.2	+4.1
Mean Low Water	MLW	+1.3	+1.3	+1.3
Mean Lower Low Water	MLLW	+0.0	+0.0	+0.0
Extreme Low Water	ELW	-	-	-3.0

3. **Protection from High Seas.** The entrance to Coos Bay is similar to most harbors along the Pacific Coastline of Northern California, Oregon, and Washington. Strong winds are often experienced at North Bend on Coos Bay during the months of June, July, and August. These winds blow at 17 knots or greater 15-20 percent of the time and at 28 knots or greater 1 to 2 percent of the time. The harbor consists of a river estuary at the mouth of the Coos River. Sand and silt

from the river are carried out to the sea from this entrance. As a result of this material meeting the predominantly westerly seas and swells of the Pacific, a sandy ridge bar is formed at the mouth. This sand ridge causes the channel to be known as "a Bar Channel". As such, a breaking bar does occur in this port.

4. **Natural Hazards**. The navigational hazards in the vicinity of the project site are rock jetties on either side of the channel entrance extending into the Pacific Ocean, and a submerged jetty which extends 50 yards off the east shore of Coos Bay. Discussions and simulations with the Coos Bay Pilots Association have shown that these hazards will not interfere with normal navigation and mooring operations and the applicant has developed transit mitigations to address this issue such as not bringing vessels in or leaving them at the lay berth during conditions that are not conducive to safe navigation i.e. restricted visibility, severe weather and and/or low tides.

5. **Fishing Vessels**. Heavy concentrations of fishing gear may be expected between December 1 and August 15, from shore to about 30 fathoms.

6. **Underwater Pipelines and Cables**. Based on current pipeline charts that are available, there are three cables which are submerged approximately 20 feet running across/underneath the channel in the vicinity of the town of Empire which is on the LNG Carrier transit route.

7. **Maximum Vessel Size by Dock**. The primary dock can accommodate a vessel with a maximum length of 300 meters, 52 meters in breadth, and a draft which can be accommodated by the existing channel. Although the facility dock is able to accommodate vessels drafting up to 12m (39ft), current channel draft is 11m (37ft) with future plans to dredge the channel to accommodate larger deep draft vessels. Jordan Cove Energy Project and the local pilots must ensure transiting LNG vessels are able to maintain 10% under keel clearance as required by JCEP's LNG Transit Management Plan.

    a. The dock must be able to accommodate all vessels calling on the facility.
    b. It must be equipped with adequate numbers of mooring hooks, fendering, and mooring dolphins.
    c. The mooring arrangement must also be able to accommodate safe working loads.
    d. In coordination with appropriate stakeholders, JCLNG must develop and implement vessel mooring/unmooring procedures to ensure safe and environmentally protective operations for LNG Carriers arriving and departing the JCLNG facility.

8. **Vessel Routing**. Included in the WSA, was a plan to divide the LNG Carrier transit route into five (5) inbound, one (1) loading at berth, and five (5) outbound segments. The total inbound transit from the Sea Buoy (pilot boarding area) to the terminal berth is approximately eight (8) miles and will take between 1.5 and 2.0

hours to berth, pilots will be transiting at around 4.5 knots. The route has been divided into segments in order to manage vessel traffic and increase the safety of LNG carrier transits. This was done in conjunction with the Coos Bay Pilots Association.

The route is reversed for outbound LNG Carrier transits with the exception of the turning/maneuvering basin which is bypassed on the outbound transit where the LNG Carrier is moved directly into the Coos Bay Ship Channel. The route and segments are shown in Figure 3.

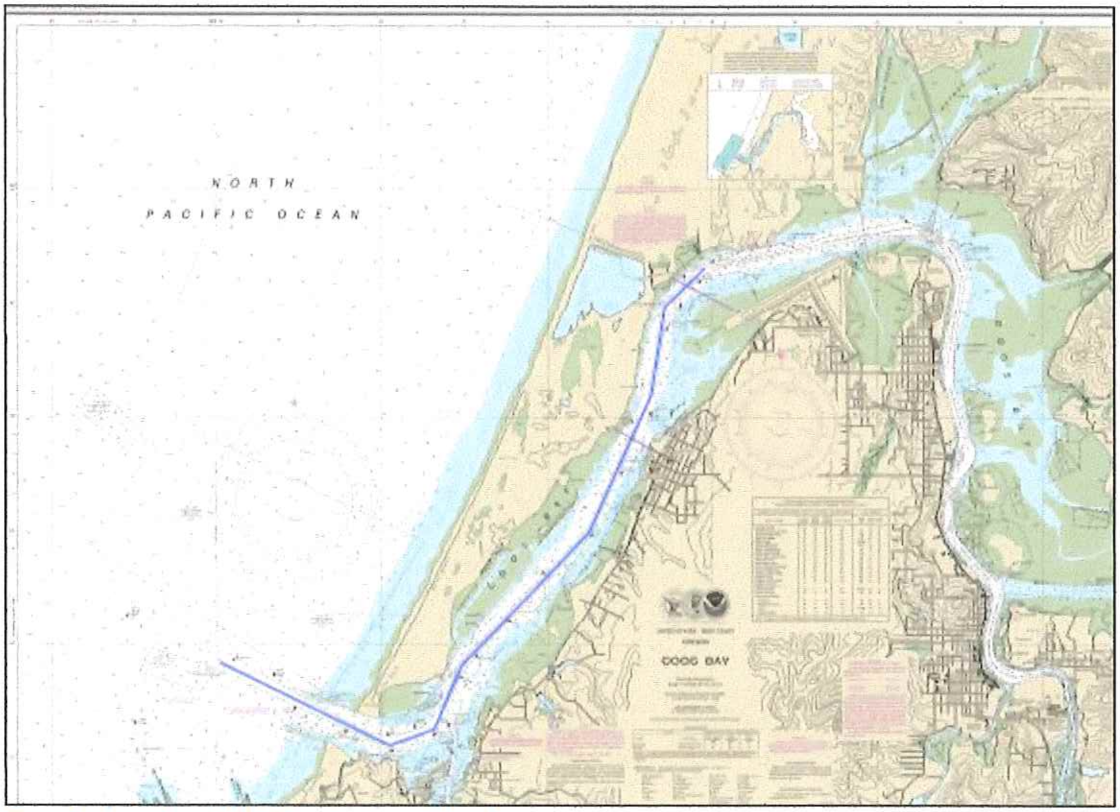

Figure 3. Overview of LNG Carrier Transit Route

9. **Vessel Operations** –LNG vessels will load cargo at the facility. 110-120 arrivals are expected at the facility annually with a dedicated fleet of LNG Carriers conducting cargo operations at the facility. A lay berth will be constructed to accommodate delays, repairs, and maintenance issues associated with Trans-Pacific Trade. Cargo operations will not be permitted at the lay berth and the applicant will outline procedures for the lay berth after the permitting process is complete.

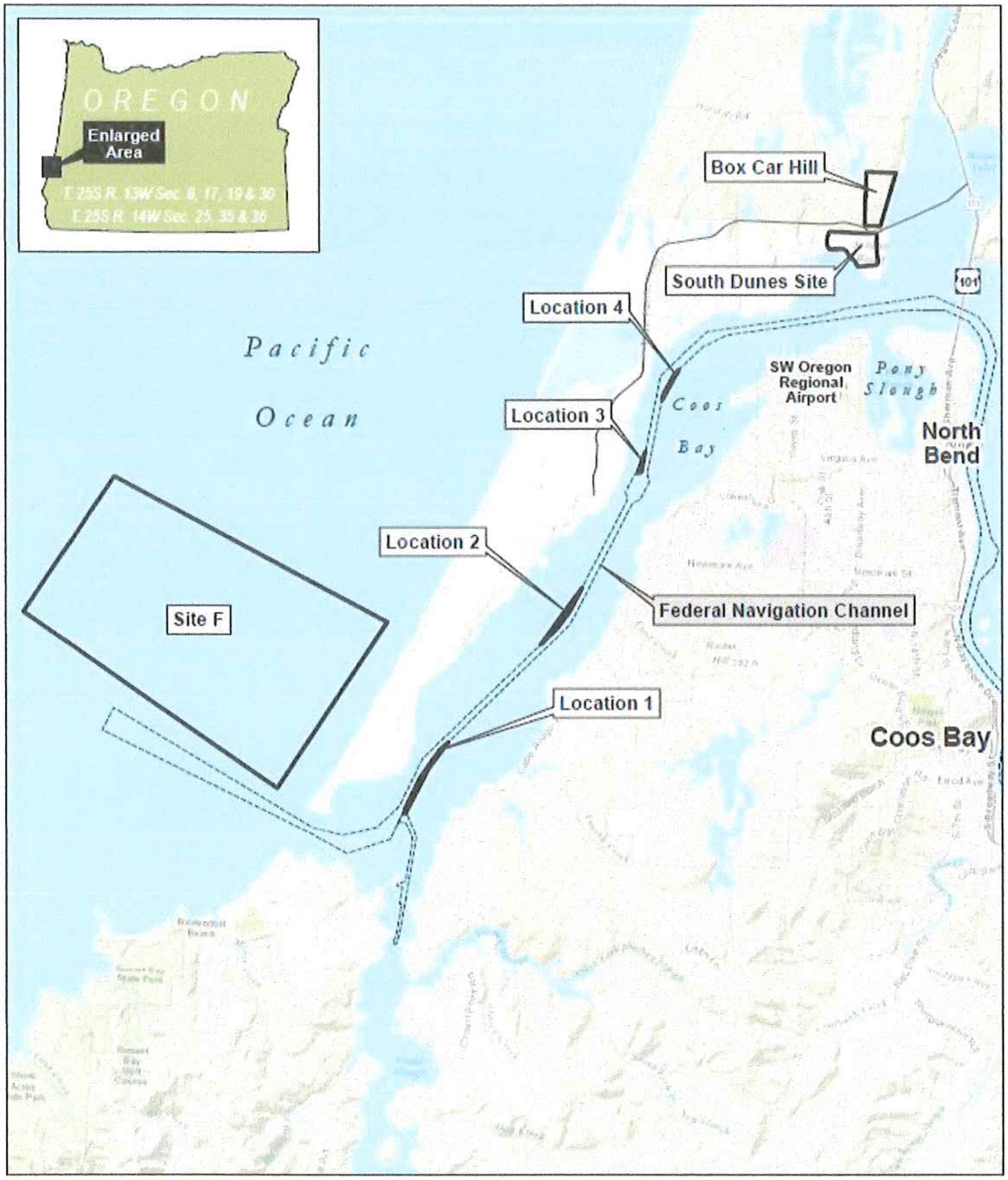

Figure 4. Channel Improvements

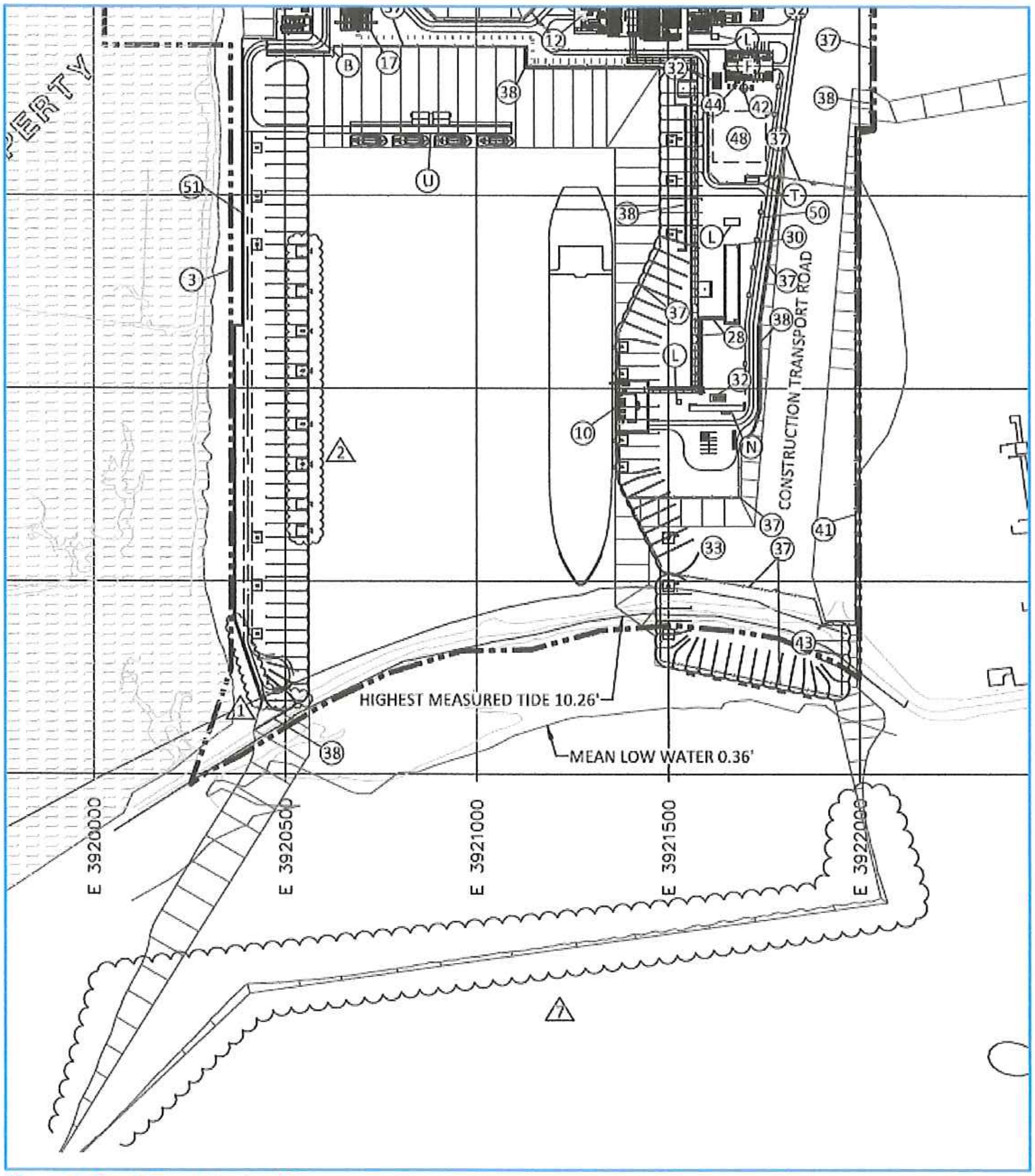

Figure 5. Dredging at the berth

U.S. Department of Homeland Security

United States Coast Guard

Commander
United States Coast Guard
Sector Portland

6767 N. Basin Avenue
Portland, Oregon 97217-3992
Phone: (503) 240-9374
Fax: (503) 240-9369
Russell.A.Berg@uscg.mil

16611/JORDAN COVE
April 24, 2009

Kimberly D. Bose, Secretary
Federal Energy Regulatory Commission
888 First Street, N.E.
Washington, D.C. 20426

LETTER OF RECOMMENDATION FOR JORDAN COVE LNG TERMINAL

Dear Ms. Bose:

This Letter of Recommendation (LOR) is issued pursuant to 33 C.F.R. § 127.009 in response to the Letter of Intent (LOI) submitted by Jordan Cove Energy Project, L.P. (Applicant) dated April 10, 2006 proposing to transport Liquefied Natural Gas (LNG) by ship to a proposed receiving terminal at Jordan Cove in Coos Bay, Oregon. It conveys the Coast Guard's determination on the suitability of Coos Bay for LNG marine traffic as it relates to safety and maritime security. In addition to meeting the requirements of 33 C.F.R. § 127.009, this letter also fulfills the Coast Guard's commitment for providing information to your agency under the Interagency Agreement signed in February 2004.

After reviewing the information in the applicant's LOI and completing an evaluation of the waterway in consultation with a variety of local port stakeholders, I have determined that the applicable portions of Coos Bay and its approaches are not currently suitable, but could be made suitable for the type and frequency of marine traffic associated with this project. My determination is based on review of the information provided in accordance with 33 C.F.R. § 127.007(d)(3) through (d)(6) and in consideration of the items listed in 33 C.F.R. § 127.009(b) through (d)(6). The reasons leading to my determination are outlined below.

On July, 1, 2008, I completed a review of the Applicant's Waterway Suitability Assessment (WSA) submitted in February 2007 by Kseas and Amergent Techs. This review was conducted following the guidance provided in U.S. Coast Guard Navigation and Vessel Inspection Circular (NVIC) 05-05. The review focused on navigation safety and maritime security risks posed by LNG marine traffic associated with the proposed Jordan Cove Energy Project and the measures needed to responsibly manage these risks. During the review, the Coast Guard consulted with a variety of stakeholders including an adhoc validation committee and the Area Maritime Security Committee. Following this review a Waterway Suitability Report (WSR) was issued in July 2008. The WSR identifies the requirements, conditions and risk mitigation measures to ensure the safe movement of these vessels.

The Applicant's WSA includes risk management strategies and associated measures that were developed for the safe navigation and security at each maritime security level, and that if properly implemented, sufficiently mitigate the identified risks associated with LNG vessel traffic for the proposed facility. These risk mitigation measures and strategies have been documented in the attached WSR. Based on my review and the full implementation by the Applicant of the measures outlined in their WSA and the attached WSR, I have determined that

Coos Bay leading up to Jordan Cove could be suitable for the type and frequency of LNG marine traffic associated with this project.

The final review and this letter are issued pursuant to NVIC 05-08, which replaced NVIC 05-05. NVIC 05-08 eliminated the term WSR and replaced it with "Letter of Recommendation (LOR) Analysis". For the purpose of clarity, the WSR is equivalent to the LOR Analysis. While this letter has no enforcement status, the determinations, analysis, and ultimate recommendation as to the suitability of this waterway as contained in this letter, would be referenced in concert with a Captain of the Port Order, should an LNG transit be attempted along this waterway without full implementation of the risk mitigation measures. Such an Order would be issued pursuant to my authority under the Ports and Waterways Safety Act of 1972, as amended by the Port and Tanker Safety Act of 1978, 33 U.S.C. § 1223, *et seq.*, among other authorities.

A copy of the LOR has been forwarded to the Applicant. Should the Applicant feel aggrieved by this decision, they may request reconsideration by me pursuant to 33 C.F.R. § 127.015(a). For your information, any request for reconsideration must be submitted in writing, within 30 days of receipt of this letter. The Applicant may also request an in person appeal if the written request would have an adverse impact on their operation.

If you have any questions, my point of contact is Mr. Russ Berg. He can be reached at the above address, phone number and e-mail.

Sincerely,

F. G. MYER
Captain, U. S. Coast Guard
Captain of the Port

Enclosures: (1) WSR
(2) WSR Supplementary Record (SSI, Not Releasable)

Copy: Jordan Cove Energy Project, L.P. w/o enclosures
Commandant, U. S. Coast Guard (CG-522, CG-541, CG-544) w/o enclosures
Commander, Thirteenth Coast Guard District (dl, dp) w/o enclosures
Commander, Coast Guard Pacific Area (Pp) w/o enclosures
Coast Guard Maintenance and Logistics Command Pacific (sm) w/o enclosures
Oregon Department of Energy w/o enclosures
Oregon Department of Fish and Wildlife w/o enclosures
Coos County Sheriff w/o enclosures
Coos Bay Fire Department w/o enclosures
Coos Bay Police Department w/o enclosures
North Bend Fire Department w/o enclosures
North Bend Police Department w/o enclosures

APPENDIX B

Jordan Cove's Letter of Intent and the U.S. Coast Guard's Waterway Suitability Report for the Jordan Cove Energy Project

ENCLOSURE(3)

Jordan Cove
Energy Project, L.P.

April 10, 2006

Captain Patrick Gerrity
Commanding Officer
USCG Sector Portland
6767 N. Basin Ave.
Portland, Oregon 97217

RE: **Jordan Cove Energy Project**
Coos Bay, Oregon
Letter of Intent

Dear Captain Gerrity:

Under the requirements of 33 CFR 127.007, I am pleased to forward this LETTER OF INTENT (LOI) for the construction of an LNG receiving terminal located at Coos Bay, Oregon. As part of this proposal, I am attaching as Enclosure (1) a Preliminary Waterway Suitability Assessment (WSA), which has been completed using the guidance contained in Enclosure (2) of Navigation and Vessel Circular No. 05-05, (NVIC 05-05) dated June 14, 2005.

This Preliminary WSA has been prepared to meet the requirement to start the "Pre-Filing" process with the Federal Energy Regulatory Commission (FERC). It is understood that a "Follow-on" WSA will be required to be submitted to you as this project matures. The "Follow-on" WSA will clearly identify credible security threats and safety hazards to LNG transportation in this port, and will identify appropriate risk management measures, as well as addressing items of concern noted in the Preliminary WSA.

In accordance with the requirements contained in 33 CFR 127.007 (d), the following information is provided:

1. The name, address, and telephone number of the owner and operator:

Jordan Cove Energy Project
125 Central Avenue, Suite 380
Coos Bay, OR 97420
Attn: Robert L. Braddock
Phone: (541) 266-7510
Fax: (541) 269-1475
E-mail: bobbraddock@attglobal.net

The name, address and telephone number of the facility: (since the facility has not been constructed, the information is the same as in item 1 above.

Jordan Cove Energy Project
125 Central Avenue, Suite 380
Coos Bay, OR 97420
Attn: Robert L. Braddock
Phone: (541) 266-7510
Fax: (541) 269-1475
E-mail: bobbraddock@attglobal.net

2. Physical location of the facility: *This information is contained in Section 3.10 of the Preliminary WSA included as Enclosure (1) to this report.*

3. Description of the facility: *This information is contained in Section 3.10 of the Preliminary WSA included as Enclosure (1) to this report.*

4. LNG vessel characteristics and frequency of shipments to and from the facility: *This information is contained in Section 3.11 of the Preliminary WSA included as Enclosure (1) to this report.*

5. Charts showing waterway channels and identifying commercial, industrial, environmentally sensitive and residential areas in and adjacent to the waterway used by the LNG vessel en route to the facility, within 15.5 miles of the facility. *This information is contained in Sections 2.5, 3.1, 3.13, 3.14, 3.15 and 3.16 of the Preliminary WSA included as Enclosure (1) to this report.*

We understand the requirement to advise you in writing within 15 days if there are any changes to the information presented in this letter in paragraphs 1 – 5 above. We do not anticipate any construction starting in the next 60 days or LNG transfer operations in the next 12 months.

I trust the information provided meets all LETTER OF INTENT requirements. Please feel free to contact me at any time to discuss this proposal, or if you require any further documentation incident to this submission.

Sincerely,

Robert L Braddock

Robert L. Braddock
Project Manager

ENCL: (1) Preliminary Waterway Suitability Assessment

U.S. Department of
Homeland Security

United States
Coast Guard

Commanding Officer
United States Coast Guard
Sector Portland

6767 N. Basin Avenue
Portland, OR 97217
Phone: (503) 240-9307
Fax: (503) 240-9586

16611
July 1, 2008

Lauren O'Donnell
Director of Gas – Environmental & Engineering, PJ-11
Federal Energy Regulatory Commission
888 First Street, N.E., Room 62-45
Washington, DC 20426

WATERWAY SUITABILITY REPORT FOR THE JORDAN COVE ENERGY PROJECT

Dear Ms. O'Donnell:

This Waterway Suitability Report (WSR) fulfills the Coast Guard's commitment under the Interagency Agreement among the Federal Energy Regulatory Commission (FERC), the Research and Special Programs Administration (RSPA), and the Coast Guard for the Safety and Security Review of the Waterfront Import/Export Liquefied Natural Gas Facilities that was signed in February 2004. Under this agreement, our agencies work together to ensure that both land and maritime safety and security risks are addressed in a coordinated and comprehensive manner. In particular, the Coast Guard serves as a subject matter expert on maritime safety and security issues.

On June 11, 2008, the Coast Guard completed a review of the Waterway Suitability Assessment (WSA) for the Jordan Cove Energy Project (JCEP) that was submitted in September of 2007. This review was conducted following the guidance provided in Navigation and Vessel Inspection Circular (NVIC) 05-05 of June 14, 2005. The review focused on the navigation safety and maritime security risks posed by LNG marine traffic, and the measures needed to responsibly manage these risks. During the review, the Coast Guard consulted a variety of stakeholders including state and local emergency responders, marine pilots, towing industry representatives, members of the Ports and Waterways Safety Committee and the Area Maritime Security Committee.

Based upon this review, I have determined that Coos Bay is not currently suitable, but could be made suitable for the type and frequency of LNG marine traffic associated with this proposed project. Additional measures are necessary to responsibly manage the maritime safety and security risks. The specific measures, and the resources needed to implement them, where applicable, are described below and in a separate supplementary report which is being provided to you under the terms and conditions established for handling Sensitive Security Information (SSI). This supplemental report includes a copy of the Jordan Cove Waterway Suitability Assessment. This determination is preliminary as the NEPA analysis has not yet been completed.

The following is a list of specific risk mitigation measures that must be put into place to responsibly manage the safety and security risks of this project. Details of each measure, including adequate support infrastructure, will need further development in consultation with the Coast Guard and state and local agencies through the creation of an Emergency Response Plan as well as a Transit Management Plan that clearly spell out the roles, responsibilities, and specific procedures for the LNG vessel and all agencies responsible for security and safety during the operation.

Navigational Measures:

<u>LNG Tanker Size Limitations:</u> Based on the Ship Simulation Study conducted by Moffatt & Nichol on March 17-20, 2008, the maximum size LNG tanker permitted to transit through the Port of Coos Bay is a spherical containment LNG carrier with the physical dimensions of a 148,000 m^3 class vessel. The ship dimensions used in the study reflect a length overall of 950 feet, beam of 150 feet and a loaded draft of 40 feet. The channel must demonstrate sufficient adequacy to receive LNG carriers for any single dimension listed. Consequently, prior to approving the transit of an LNG ship larger than 148,000 m^3, or any increase in the physical dimensions cited, additional simulator studies must be conducted in order to assure the sufficiency of the channel.

- <u>Safety/Security Zone:</u> A moving safety/security zone shall be established around the LNG vessel extending 500-yards around the vessel but ending at the shoreline. No vessel may enter the safety/security zone without first obtaining permission from the Coast Guard Captain of the Port (COTP). The expectation is that the COTP's Representative will work with the Pilots and patrol assets to control traffic, and will allow vessels to transit the Safety/Security zone based on a case-by-case assessment conducted on scene. Escort resources will be used to contact and control vessel movements such that the LNG Carrier is protected.

  While the vessel is moored at the facility there shall be a 150 yard security zone around the vessel, to include the entire terminal slip. In addition, while there is no LNG vessel moored, the security zone shall cover the entire terminal slip and extend 25-yards into the waterway.

  Resource Gap: Resources required to enforce the safety/security zone are discussed under Security Measures in the supplemental report.

- <u>Vessel Traffic Management:</u> Due to a narrow shipping channel, navigational hazards, and the proximity to populated areas, LNG vessels will be required to meet the following additional traffic management measures:
  - A Transit Management Plan must be developed in coordination with the Coos Bay Pilot Association, Escort Tug Operators, Security Assets and the Coast Guard prior to the first transit.
  - This plan must be submitted to the COTP no less than 6 months to initial vessel arrival, and followed by an annual review to ensure that it reflects the most current conditions and procedures.
  - For at least the first six months, all transits will be daylight only, unless approved in advance by the COTP.
  - The LNG Vessel must board Pilots at least 5 miles outside the sea buoy.
    - Overtaking or crossing the LNG tanker within the security zone is prohibited for the entire transit from the Coos Bay Sea Buoy to mooring the vessel at the LNG terminal.
  - Vessel transits and bar crossings will be coordinated so as to minimize conflicts with other deep draft vessels, recreational boaters, seasonal fisheries, and other Marine Events.
  - 24 hours prior to arrival, the Coast Guard, FBI, Coos Bay Pilot Association, Escort Tug Masters, and other Escort assets will meet to coordinate inbound and outbound transit details.

Resource Gaps: The Vessel Transit Management Plan must be approved by the COTP at least 60 days prior to the first vessel arrival.

- Vessel Traffic Information System /Vessel Traffic System: The Port of Coos Bay does not have the capacity to receive Automatic Identification System (AIS) signals. AIS receiving capability must be established and must have the capacity to be used by appropriate agencies, port authorities and ship husbandry companies. Additionally, the Port does not have any means for continuous monitoring the navigable waterway. In order to ensure vessel safety and security, a robust camera system capable of monitoring the entire transit route must be established. Due to weather concerns, these cameras must be equipped with the means to adequately monitor vessel traffic in wind, rain and fog conditions.

  Resource Gaps: AIS receiver and camera systems including necessary hardware, software, staffing and training. Camera system must have complete coverage of the entire transit route, capable of detecting vessel traffic in wind, rain, fog, and dark conditions. Equipment and access to data feed of video imagery must be provided to state and local emergency operations centers impacted by the project.

- Tug Escort and Docking Assist: Due to the confined channel and high wind conditions, each LNG Carrier must be escorted by two tractor tugs, which will join the vessel as soon as safe to do so. The primary tug will be tethered at the direction of the pilot. A third tractor tug is required to assist with turning and mooring. Based on the Ship Simulation Study conducted by Moffatt & Nichol on March 17-20, 2008, vessels are limited to transiting during periods of high tide and 25 knot winds or less. While unloading, all three tugs will remain on standby to assist with emergency departure procedures.

  All three tractor tugs must be at least 80 Ton Astern Bollard Pull or larger and equipped with Class 1 Fire Fighting equipment.

  Resource Gaps: Three 80 Bollard Ton Tractor Tugs with Class 1 Fire Fighting capability.

- Navigational Aids:
  - Based on the Ship Simulation Study conducted by Moffatt & Nichol on March 17-20, 2008, four aids to navigation must be added and eight aids to navigation relocated on the waterway (pg. 12-17).
  - Physical Oceanographic Real-Time System (PORTS) must be contracted with NOAA to provide real time river level, current and weather data.

- LNG Carrier familiarization training for Pilots and Tug Operators: Prior to the arrival of the first vessel, simulator training must be provided for pilots and tug operators identified as having responsibility for LNG traffic.

Safety Measures:

Emergency Response Planning: Regional emergency response planning is limited in the region. Emergency response planning resources will need to be augmented to adequately develop emergency response procedures and protocols as well as continuously update those plans as conditions change.

Resource Gap: To be determined in conjunction with local and regional response agencies through the Emergency Response Planning process.

- Vessel and Facility Inspections: LNG tankers and facilities are subject to (at a minimum) annual Coast Guard inspections to ensure compliance with federal and international safety, security and pollution regulations. In addition, LNG vessels and facilities are typically required to undergo a pre-arrival inspection, and transfer monitor.

  Resource Gap: Additional Coast Guard Facility and Vessel Inspectors.

- Shore-Side Fire-Fighting: Firefighting capability is limited in the area surrounding the proposed LNG terminal. Shore side firefighting resources and training will need to be augmented in order to provide basic protection services to the facility as well as the surrounding communities along the transit route.

  Resource Gap: To be determined in conjunction with local and regional response agencies through the Emergency Response Planning process.

- In-Transit Fire-Fighting: Firefighting capability is limited along the entire transit route for proposed LNG vessels.

  Resource Gap: A plan must be developed for managing underway firefighting, including provisions for command and control of tactical fire fighting decisions as well as financial arrangements for provision of mutual aid and identification of suitable locations for conducting fire fighting operations along the transit route. To be determined in conjunction with local and regional response agencies through the Emergency Response Planning process.

  Public Notification System and Procedures: Adequate means to notify the public along the transit route, including ongoing public education campaigns, emergency notification systems, and adequate drills and training are required. Education programs must be tailored to meet the various needs of all waterway users, including commercial and recreational boaters, local businesses, local residents, and tourists.

  Resource Gap: A comprehensive notification system, including the deployment of associate equipment and training, must be developed. To be determined in conjunction with local and regional response agencies through the Emergency Response Planning process.

- Gas Detection Capability: No gas detection capability exists at the Port of Coos Bay, along the transit route and at the site of the proposed facility. Emergency response personnel require appropriate gas detection equipment, maintenance, and training. Additionally, the use of fixed detection equipment will ensure accurate and expedited gas detection in the event of a large scale LNG release. The installation of these detectors at strategic points along the waterway must be developed.

Resource Gap: Gas Detectors, appropriate training, and maintenance infrastructure. To be determined in conjunction with local and regional response agencies through the Emergency Response Planning process.

Security Measures:

- Security Boardings, Waterway Monitoring, and Vessel Escorts: Extensive security measures will be required to provide adequate protection for LNG vessels in transit to and while moored at the facility. The details of these measures are SSI, and are outlined in a separate supplementary report.

- Facility Security Measures: LNG facilities are subject to the security regulations outlined in 33 CFR 105, and are required to submit a Facility Security Plan (FSP) for Coast Guard approval, and undergo (at a minimum) an annual Coast Guard security inspection. The facility shall also develop a plan to provide for appropriate security measures from the start of construction through implementation of the Coast Guard approved FSP.

- Sandia Study: The WSA proposes the potential to receive vessels with up to 217,000 m^3 cargo capacity. The Sandia Report is based on consequences of LNG breaches, spills and hazards associated with LNG vessels having a cargo capacity no greater than 148,000 m^3 and spill volumes of 12,500 m^3. There remains some question as to the size of hazard zones for accidental and intentional discharges and the potential increased risk to public safety from LNG spills on water for larger vessels. Based on these existing uncertainties, Jordan Cove must either complete a site-specific analysis for the largest sized LNG vessel or limit arrivals to vessels with a cargo capacity no greater than 148,000 m^3 until additional analysis addressing vessels with higher cargo capacities is completed. However, this requirement is contingent on the requirement for US Coast Guard approval to receive LNG tankers larger than 148,000 m^3.

In the absence of the measures described in this letter and the resources necessary to implement them or changes in Coast Guard policy upon which the resource decisions are based, Coos Bay would be considered unsuitable for the LNG marine traffic associated with the Jordan Cove LNG Terminal. The applicant shall be required to submit an annual update to the Waterway Suitability Assessment to the Coast Guard which shall be revalidated by the COTP and AMSC. For further information, please contact Mr. Russ Berg of Coast Guard Sector Portland at (503) 240-9374.

Sincerely,

F. G. Myer
Captain, U.S. Coast Guard
Captain of the Port
Federal Maritime Security Coordinator

Copy: Thirteenth Coast Guard District (dp)
Coast Guard Pacific Area (Pp)
Commandant, Coast Guard Headquarter (CG-52), (CG-522), (CG-544)
Maintenance and Logistics Command Pacific (Sm)

Exhibit 3

Submitted by
Jerry Havens, Distinguished Professor Emeritus
Department of Chemical Engineering, University of Arkansas
September 7, 2019

Re:
Jordan Cove Energy Project L.P.
Docket No. CP17-495-000
Response to August 28, 2019 PHMSA Data Request

My comments are not to be attributed to the University of Arkansas.

This comment expands on my earlier ones to the Public Workshop on Liquified Natural Gas Regulations Website on July 28, 2016; September 22, 2018; October 2, 2018; December 3, 2018; April 1, 2019; July 18, 2019; and August 27, 2019 - all of which I stand by.

On August 28, 2019, the U.S. Department of Transportation, Pipeline and Hazardous materials Safety Administration (PHMSA) Staff issued questions and information requests related to PHMSA's review of the siting requirements under 49 CFR Part 193,Part B ("August 28 PHMSA Request").

These comments address only JCEP's response to Scenarios MR-2 involving the use of FLACS-Fire. However, these comments are not directed to the details of the calculations (using FLACS-Fire) presented for Scenario MR-2. My purpose here is to emphasize the same concerns raised in my previous (August 27, 2019) comments, and to expand on the importance of PHMSA taking immediate corrective action.

I believe that the use of FLACS-Fire in JCEP's submission effectively circumvents the intent of 49 CFR Part 193, Part B because it has not been approved by PHMSA for such use. If I am wrong about this, I respectfully ask that PHMSA immediately notify me, and I will take the necessary corrective action.

If I am not wrong about this, I believe we are, as a result of this action, further enabling the applicant to circumvent the Regulations in a manner that will result in important decreases in the provision of Public Safety.

The current LNG regulations focus on providing public safety by requiring that the applicant provide approved science-based calculations of exclusion distances to prevent public injury beyond the plant boundaries from liquid pool fires and vapor cloud fires and explosions.

The FLACS model, which is increasingly used in applications for LNG Export Terminal Siting applications, is a complex suite of mathematical modeling methods that are advertised to address the calculation of Dispersion, Fire Radiation, and Vapor Cloud Explosion hazards.

The FLACS Model used by JCEP designed to predict dispersion has received PHMSA approval for use in applications to meet the requirements of 49 CFR 193.

The FLACS Model used by JCEP designed to predict vapor cloud explosion overpressures has not received such approval.

It is my understanding that the FLACS-Fire Model used by JCEP in the application here considered to calculate fire radiation intensity to ensure that the prescribed radiation limits do not extend beyond the property values has not received such approval.

If I am correct in the assumptions I have made here, I believe there has been a critically important failure to provide for Public Safety in the current regulations designed for siting LNG Export Terminals. The current regulations were designed for LNG Import Terminals. It is established knowledge that Export Terminals involve important hazards that are not present in Import Terminals. There has been a failure to update the Regulations accordingly. I am very concerned that the current moves to provide "Regulatory Relief While Preserving Public Safety" are going badly wrong. In my opinion, just as in the current debate about the science information about Global Warming/Climate Change, the debate about the push to expand the LNG Export business in the United States is allowing the Export Terminal applicants-for-siting to cut regulatory corners by adopting complex mathematical models that are used to determine the risks involved without proper science-based evaluation.

Submitted by
Jerry Havens, Distinguished Professor Emeritus
Department of Chemical Engineering, University of Arkansas
August 27, 2019

Re:
Jordan Cove Energy Project L.P.
Docket No. CP17-495-000
Part 193, Subpart B Siting Review Supplement

My comments are not to be attributed to the University of Arkansas.

This comment expands on my earlier ones to the Public Workshop on Liquified Natural Gas Regulations Website on July 28, 2016, September 22, 2018, October 2, 2018, December 3, 2018, April 1, 2019 and July 18, 2019 - all of which I stand by.

On August 14, 2019, the U.S. Department of Transportation, Pipeline and Hazardous materials Safety Administration (PHMSA) Staff issued questions and information requests related to PHMSA's review of the siting requirements under 49 CFR Part 193,Part B. These comments address only the first Information Request (Request 1):

> *In response to Request 2 from the PHMSA Information Request dated August 2, 2019, the analysis considered the 2-dimensional Phast output results from a jet fire occurring from release scenario LNG-17 that indicated at a flame height of 96.23 feet, the impacts from a jet fire do not extend over the 100-foot wall. Furthermore, the Phast output summary file provided for scenario LNG-17 indicates the length of the flame is 584 feet, which appears to be greater than the distance between the release location and the 100-foot wall. This means the tip of the flame as well as its thermal radiation may spread vertically along the height of the wall. Since the 2-dimensional analysis does not account for this spreading of the flame, the height not extending over the 100 foot wall is not indicative of the exclusion zone remaining onsite.*
>
> *In addition, it remains unclear whether the radiant heat from a jet fire from MR-2 will remain onsite.*
>
> *Provide an analysis that demonstrates the 1600 Btu/hr-ft^2 from jet fire scenarios LNG-17 and MR-2 would remain within the property legally controlled by Jordan Cove using a modeling software that accounts for the obstruction from plant equipment and the 100-foot wall. (emphasis added)*

JCEP provided two figures with accompanying text from which they appear to conclude that the 1600 Btu/hr-ft^2 (thermal radiation level?) from jet fire scenarios LNG-17 and MR-2 would remain within the property legally controlled by Jordan Cove. JCEP's response stated that these two scenarios were modelled using FLACS-Fire version 10.9.

It is my understanding that the currently applicable version of CFR193.2057, Thermal radiation protection, requires that thermal radiation distances must be calculated using Gas Technology Institute's (GTI) report or computer model GTI-04/0032 LNGFIRE3: A Thermal Radiation Model for LNG Fires (incorporated by reference, see 193.2013). The use of other alternate models which take into account the same physical physical factors and have been validated by experimental test data may be permitted subject to the Administrator's approval.

I am here respectfully requesting an answer to the following questions:

1. Has a request from, or on behalf of, JCEP been received by PHMSA for approval of the alternate (to LNGFIRE3) FLACS-Fire Version 10.9 model?
2. If such a request has been received, please provide a statement of PHMSA's response to the request.

From my position of working specifically on these matters of the calculations submitted by JCEP to obtain approval for the siting of the LNG export terminal in Coos Bay, Oregon since early 2015, and my four decades experience with PHMSA and other governmental regulators in trying to ensure that the regulations in force utilize good, carefully vetted, scientific tools to protect public safety, I am saddened to feel that the safety regulation process is being circumvented.

Submitted by
Jerry Havens, Distinguished Professor Emeritus
Department of Chemical Engineering, University of Arkansas
July 18, 2019

Regarding the
DRAFT ENVIRONMENTAL IMPACT STATEMENT
FOR THE
JORDAN COVE ENERGY PROJECT
Docket Nos. CP17-494-000 and CP17-495-000
of March 2019

My comments are not to be attributed to the University of Arkansas.

COMPUTER MODEL USED TO PREDICT LNG EXPORT TERMINAL VAPOR CLOUD EXPLOSION HAZARDS HAS NOT BEEN APPROVED BY PHMSA – THERE IS NEW PUBLISHED INFORMATION CONCERNING THE UNCERTAINTY IN THE FLACS EXPLOSION CALCULATIONS

This comment is intended to notify PHMSA of new developments regarding our knowledge of the risk of cascading fire and unconfined vapor cloud explosion (UVCE) accidents that could occur at the Jordan Cove Export Terminal (JCET). This comment expands on my earlier ones to the Public Workshop on Liquified Natural Gas Regulations Website on July 28, 2016, September 22, 2018, October 2, 2018, December 3, 2018, and April 1, 2019 - all of which I stand by.

As stated in my previous comments, my review of the March 2019 JCET DEIS did not disclose any detailed predictions of vapor cloud explosion (VCE) overpressure for design spills of heavy hydrocarbons, but I did locate on the FERC Website a report entitled "Facility Siting Hazard Analysis", dated October 2, 2018, which presents a collection of hazard footprints for overpressure, calculated with FLACS, predicted to result from design spills of heavier-than-methane hydrocarbons at the JCET[1]. The overpressures presented therein still appear to be significantly lower than those reported for numerous incidents that have occurred with the same materials, in similar amounts and in similar conditions. I am very concerned that such predictions might be approved by FERC in the FEIS - repeating the approval of similar predictions prepared for FERC with the same mathematical model FLACS in 2015.

Although a process for developing a written protocol for evaluation of FLACS for application to the prediction of overpressures was requested by PHMSA to be funded following the LNG Regulation Workshop of 2016[2], it appears that the plans announced at the LNG Workshop of 2016 for a required updating of 49 CFR 193 to cater for the new hazards that will be present at export terminals are at a standstill.

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[1] https://elibrary.ferc.gov/idmws/file_list.asp?accession_num=20181116-5198
Click on "Facility Siting Hazard Analysis" and download

[2] https://primis.phmsa.dot.gov/rd/mtgs/111616/WG%205%20Report-Out.pdf – See GAP #4

Sub-Model Q9

It is my understanding that the sub-model named Q9 was used in FLACS to compute the explosion overpressure predictions in the Jordan Cove DEIS. I believe those predictions may well be an order-of- magnitude too low. As the FLACS model has yet to be evaluated by subjection to a written Protocol, as currently required by PHMSA, it follows that the sub-model Q9 has not been evaluated either.

The purpose of this comment is to request that PHMSA consider a scientific review paper regarding Q9 recently published by the British Health and Safety Executive[3]. I believe this paper substantiates my concerns that there are such large uncertainties in the Q9 method, as utilized currently in FLACS, as to result in order of magnitude (too low) errors in overpressures. Such errors could result in the dismissal of the UVCE hazard for heavy hydrocarbon gas clouds considered as "Design Spills" in the recent Jordan Cove DEIS. I am very concerned that correction of these errors has the potential to change the overpressures presented in the Jordan Cove DEIS to indicate overpressures an order of magnitude higher, which would bring those predictions into substantial agreement with the extensive historical review by the British Health and Safety Laboratories presented at the LNG Regulatory Workshop in 2016. Such overpressures could well lead to destruction of the plant and extend danger to the public outside the controlled boundary.

---

[3] Stewart, J., Gant, S. and Bilio M. (2019) "A review of the Q9 Equivalent cloud method for explosion modelling", Fire and Blast Information Group (FABIG) Technical Newsletter 75, March 2019. Available from: http://www.fabig.com/video-publications/TechnicalNewsletters

Submitted by
Jerry Havens, Distinguished Professor Emeritus
Department of Chemical Engineering, University of Arkansas
April 1, 2019

Regarding the
DRAFT ENVIRONMENTAL IMPACT STATEMENT
FOR THE
JORDAN COVE ENERGY PROJECT
Docket Nos. CP17-494-000 and CP17-495-000
March 2019

My comments, directed simultaneously to FERC and PHMSA,
are not to be attributed to the University of Arkansas.

COMPUTER MODEL USED TO PREDICT LNG EXPORT TERMINAL VAPOR CLOUD EXPLOSION HAZARDS HAS NOT BEEN APPROVED BY PHMSA - PREDICTED EXPLOSION OVERPRESSURES APPEAR SERIOUSLY UNDERESTIMATED

These comments are intended to notify FERC, PHMSA, and the public of critically important developments regarding our expanding knowledge of the risk of cascading fire and unconfined vapor cloud explosion (UVCE) accidents that could occur at the Jordan Cove Export Terminal (JCET). The comments are an expansion on my earlier ones to the Public Workshop on Liquified Natural Gas Regulations Website on July 28, 2016, September 22, 2018, October 2, 2018, and December 3, 2018 - all of which I stand by. They are also intended as a response to the joint news release of August 31, 2018 by PHMSA and FERC, entitled " FERC, PHMSA Sign MOU to Coordinate LNG Reviews", from which I quote - "The MOU establishes a framework **for** coordination between FERC and PHMSA to process LNG applications in a timely and expeditious manner while ensuring decision-makers are fully informed on public impacts". I trust these comments will be helpful to the decision-makers in fully informing the public.

My concerns remain essentially the same as commented to FERC in January 2015 by James Venart and myself[1]. I believe that Government is failing to adequately provide for the risks of potentially devastating Unconfined Vapor Cloud Explosions (UVCEs) of heavier-than-methane hydrocarbons at the JCET.

I remain concerned that the predictions of explosion overpressures (determining explosion damage) presented in the 2015 JCET DEIS were an order of magnitude (factor 10) too low. Such overpressures are not conservative enough to indicate the real hazard that exists, as evidenced by numerous confirmed occurrences of devastating UVCEs involving the same heavy hydrocarbons in similar conditions.

My review of the March 2019 JCET DEIS did not disclose any detailed predictions of vapor cloud explosion (VCE) overpressure for design spills of heavy hydrocarbons. However, I did locate on the FERC Website a report entitled "Facility Siting Hazard Analysis", dated October 2, 2018, which

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[1] UNITED STATES LNG TERMINAL SAFE-SITING POLICY IS FAULTY, Comments submitted to FERC by Jerry Havens and James Venart, January 14, 2015, Docket No. CP13-483.

presents a collection of hazard footprints for overpressure, calculated with FLACS, predicted to result from design spills of heavier-than-methane hydrocarbons at the JCET[2]. The collection of calculations presented in that report presents a picture very similar to that presented in the 2015 DEIS. The overpressures presented therein still appear to be significantly lower than those reported for numerous incidents that have occurred with the same materials, in similar amounts and in similar conditions. I cannot determine to what extent these newer predictions have been utilized in the 2019 DEIS, but I am very concerned that such predictions as these might be approved by FERC in the FEIS - repeating the approval of similar predictions prepared for FERC with the same mathematical model (FLACS) in 2015. If that were to happen, I believe a serious error affecting public safety will be the result, because the unrealistically low damage predictions could be used again by FERC as a basis to dismiss the UVCE hazard at the JCET. Continued dismissal of the UVCE hazard would be a very serious error. If the magnitude of the possible overpressures are estimated using actual data (experience) available for UVCEs (rather than predicted with the FLACS theoretical model), the VCE hazard would be clearly indicated as a serious major hazard at the JCET[3]. *UVCEs at numerous similar heavy hydrocarbon handling/storage facilities have resulted in destruction of the facilities as well as injuries and deaths beyond the plant boundaries.*

Contrasting LNG Import and Export Terminal Siting Regulations

I want to state here that if either PHMSA or FERC believes that anything I present is in error I request that I be notified immediately. I will make any corrections as necessary, and I will alter my comments, as necessary, as well. My goal is to ensure that the science-based tools that are used for hazard evaluation in the regulations are applied correctly. I am very concerned that failure to ensure proper, validated, use of mathematical models for UVCE hazard evaluation could result in devastating UVCEs that, in addition to public endangerment, could cripple the industry.

In order to most effectively explain my concerns, I think it helpful to provide a very brief history of the LNG regulations. The provisions of 49 CFR 193. Liquefied Natural Gas Facilities: Federal Safety Standards were developed by PHMSA to govern the siting of LNG peak shaving terminals and import terminals. It has been accepted practice to identify for these two types of terminals only two principal hazards; pool fire hazards and vapor dispersion hazards. A third hazard, Unconfined Vapor Cloud Explosion (UVCE), is generally considered negligible for Import Terminals. This policy is based on the generally accepted fact that import terminals handle and store primarily LNG with methane contents sufficiently high that the LNG can be assumed to be pure methane. Given the very low propensity for explosion of unconfined methane-air clouds, UVCEs at LNG import terminals have historically been neglected as a hazard. As a consequence the present Regulation, 49 CFR 193, does not mandate the consideration of UVCE hazards.

With the advent of LNG export terminals in the United States the requirements for safe siting of LNG terminals have changed importantly. That is because the export terminals typically remove and store large quantities of heavier-than-methane hydrocarbons from the incoming natural gas feed stream. Furthermore, the removal of those heavy hydrocarbons typically requires the use of

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[2] https://elibrary.ferc.gov/idmws/file_list.asp?accession_num=20181116-5198
Click on "Facility Siting Hazard Analysis" and download

[3] https://primis.phmsa.dot.gov/meetings/MtgHome.mtg?mtg=111 Atkinson, G., Vapor Cloud Explosion (VCE) Historical Review, PHMSA Public Workshop on Liquefied Natural Gas (LNG) Regulations, Washington DC, 19 May 2016.

large quantities of refrigerant gases that are heavier-than-methane hydrocarbons. The storage and handling of large quantities of these heavier-than- air hydrocarbons results in a new primary hazard - vapor cloud explosions of the heavy hydrocarbon materials that could follow accidental release.

I have been involved in the development of 49 CFR 193 from its beginning in the early 1980s. My principal involvement has been as an author/evaluator of the DEGADIS model for use in predicting LNG vapor cloud dispersion. DEGADIS is approved by PHMSA for use in predicting the requirements for vapor cloud dispersion exclusion zones for LNG Import Terminals. During the last decade, and coincident with the advent of LNG Export Terminals in the United States, additional vapor dispersion models have been approved by PHMSA for use by LNG terminal companies seeking siting approval.

My comments here are restricted to the FLACS model. The FLACS model is an example of what is known as a computational fluid dynamics (CFD) model. I generally support the use of CFD models for vapor dispersion predictions because they are appropriate for dealing with complexities not catered for by simpler models such as DEGADIS. Accordingly, I supported the approval by PHMSA of the FEM3A model developed by the Lawrence Livermore National Laboratory (LLNL) and I supported the request for PHMSA approval of FLACS for vapor dispersion use. I do not object to FLACS' approval, which PHMSA granted, for vapor dispersion prediction.

FLACS has not been Evaluated or Approved by PHMSA for Explosion Prediction

This is the crux of the matter. There are now four mathematical models approved by PHMSA for vapor dispersion prediction, in order of the time approved; DEGADIS, FEM3A, FLACS, and PHAST. All four were required by PHMSA to be subjected to evaluation of their performance in demonstrating suitable agreement with experimental data available from a collection of field and wind tunnel tests of vapor dispersion.

FLACS (FLame ACceleration Simulator) is a commercial Computational Fluid Dynamics (CFD) software used extensively for atmospheric dispersion modeling and explosion modeling in the field of industrial safety and risk assessment[4]. FLACS has been subjected to the written protocol provided by PHMSA and approved by PHMSA for vapor dispersion predictions required by 49 CFR 193. PHMSA has not completed development of a written protocol for the evaluation of FLACS for explosion prediction. Consequently, FLACS has not been formally evaluated for explosion prediction and has not received approval for the evaluation of UVCE hazards (read explosion overpressures) by PHMSA.

Although it appears that a process for developing a written protocol for evaluation of FLACS for application to the prediction of overpressures was requested by PHMSA to be funded following the LNG Regulation Workshop of 2016[5], I can find no evidence that the required protocol has been completed. It appears that the plans announced at the LNG Workshop of 2016 for a required updating of 49 CFR 193 to cater for the new hazards that will be present at export terminals are currently at a standstill. The only conclusion I am able to reach is that the newly announced JCET DEIS appears to me likely to utilize predictions of explosion overpressures for the heavier-than-methane hydrocarbon design spills selected for analysis that have not been approved by PHMSA. Such a failure to adequately address the risk of UVCEs would mean that potential risks of cascading

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[4] https://en.wikipedia.org/wiki/FLACS

[5] https://primis.phmsa.dot.gov/rd/mtgs/111616/WG%205%20Report-Out.pdf – See GAP #4

violent explosions that could destroy the plant as well as extend dangers to the public beyond the facility boundary are effectively being ignored.

PHMSA Contracted for Expert Evaluation of the Risk of Unconfined Vapor Cloud Explosions

Simultaneously with my comments to FERC in 2015 I notified PHMSA of my concerns. I have also filed a total of four comments (to date) on PHMSA's LNG Regulation Workshop site. Further, there have been a series of important developments subsequent to my 2015 comments to FERC, the results of which I think are critically important to consider now.

PHMSA contracted with the British Health and Safety Laboratories (HSL) to prepare the report "Review of Vapour Cloud Explosion Incidents"[6]. Quoting excerpts from the Executive Summary of that report:[7]

> "This review of major vapor cloud incidents has been jointly commissioned by the US Pipeline and Hazardous Materials Safety Administration (PHMSA) and the UK Health and Safety Executive (HSE). The primary objective was to improve understanding of vapor cloud development and explosion in order to examine the potential for these hazards to exist or develop at LNG export plants that store substantial quantities of these flammable gases for use in the liquefaction process or as a by-product from the liquefaction ...
>
> This review has not found any historical records of LNG (methane) vapor cloud explosions in open areas with severity sufficient to cause secondary damage to tanks and pipes and consequently rapid escalation of an incident from a minor process leak to a major loss of inventory.
>
> On the other hand some LNG sites (especially export sites) also hold substantial amounts of refrigerant gases and blends containing ethane, propane, ethylene and iso-butane. Higher hydrocarbons may also be produced and stored on LNG export sites as by-products of gas condensation. There are numerous examples of Vapor Cloud Explosions (VCEs) in open areas involving these higher molecular weight materials and the storage and use of higher molecular weight hydrocarbons on LNG export sites which may, if not managed adequately, introduce an additional set of incident scenarios in which VCEs trigger rapid escalation of loss of containment. (emphasis added)
>
> This study involves a review of 24 major VCE incidents focusing on source terms, cloud development and explosion mechanics. The incidents studied are split between permanent fuel gas (C2-C4 (e.g. LPG) and volatile liquids C4-C6 (e.g. gasoline). The source terms for leaks of gases and liquids are different but once a stable current of cold heavy vapor forms, the subsequent development of LPG and gasoline clouds are similar...
>
> An important finding from the review is that a high proportion of vapor cloud incidents occurred in nil/low wind conditions. By the term "nil/low wind" we mean a wind that was so weak close to the ground that it only detrained (stripped away) a small proportion of the vapor accumulating around the source ... Rather than being picked up and moved downwind, the vapor flow in this case was gravity driven; spreading out in all directions and or following any downward slopes around the source.
>
> In many of the cases examined, 50% (12/24), there is clear evidence from the well-documented transport of vapor in all directions and/or meteorological records that the

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[6] https://primis.phmsa.dot.gov/meetings/MtgHome.mtg?mtg=111

[7] HSL Report on PHMSA LNG Regulation Workshop site.

> vapor cloud formed in nil/low wind conditions. In a further 21% (5/24), the pattern of vapor suggests nil/low wind conditions but there is insufficient data available to be sure … incidents in nil/low wind conditions apparently make up the majority of historical records of the most serious VCEs … In nil/low wind conditions the cloud continues to grow throughout the time that the tank takes to empty… The maximum area covered by the flammable cloud is typically several hundred times greater in nil/low winds condition than in light winds.
>
> The implication of this type of analysis is that if the density of ignition sources is constant and quite low in the area around the tank the chances of ignition in nil/low wind conditions would be hundreds of times greater for a given release. This illustrates why nil/low wind conditions dominate records of major vapor cloud incidents even though the weather frequency is low. Losses of containment in nil/low wind conditions are also particularly dangerous because a highly homogeneous cloud can be formed that may spread by gravitational slumping (without significant dilution) for hundreds of meters… A very large cloud that is all close to the stoichiometric ratio increases the risk of flame acceleration to a high pressure regime capable of seriously damaging storage and process facilities, when compared with clouds that are entraining air because of wind-driven dilution. This is because fundamental burning rates fall off rapidly for concentrations away from the stoichiometric. Once a high pressure regime is established explosions are not confined to congested areas of a site. In many of the cases reviewed almost all the footprint of the cloud was exposed to pressures in excess of 2000 mbar (29 psi). In at least one case the cloud detonated, causing extremely severe damage over the area covered by the cloud)." (emphasis added)

PHMSA Conducted a Public Workshop on Liquefied Natural Gas (LNG) Regulations

The Workshop was conducted in Washington, DC in May 2016. Quoting excerpts from PHMSA's Statement of Mission (from the Workshop Website):

> "Historically, most LNG facilities were peak shavers built to liquefy and store natural gas to be degasified and injected back into the pipeline during periods of peak demand … However, due to the recent abundance of domestic shale gas, LNG export terminals are now being constructed that liquefy vast volumes of natural gas. These facilities require significantly greater quantities of refrigerants to liquefy the natural gas than the amount typically used at peak shavers… Most refrigerant gases and blends used at the export facilities contain ethane, propane, ethylene, and iso-butane and are referred to as heavy hydrocarbons. These gases are similar to gases that have resulted in VCEs at petrochemical facilities…
>
> The understanding of VCEs is evolving. PHMSA recognizes that significant quantities of heavy hydrocarbons present different risks than methane and seeks to better understand that risk. Prior to investigative work on the Buncefield accident, the prevailing understanding was that vapor clouds formed outdoors were unlikely to explode if ignited. Today it is understood that VCEs involving higher hydrocarbons have occurred in outside areas. This paper advances our understanding further. PHMSA sponsored the "Review of Vapour Cloud Explosion Incidents" report with the primary objective to improve the scientific understanding of vapour cloud development and explosion in order to more

> reliably assess hazards at large Liquid Natural Gas (LNG) export facilities... The aim of reviewing the particular incidents in this report is the extensive forensic evidence available that provides the information needed to study how the vapor cloud formed and ignited, the amount of overpressure exerted, and other information about the mechanism of VCE. This research was performed by the Health and Safety Laboratory (HSL) under a subcontract with the Oak Ridge National Laboratory, a United States Department of Energy (DOE) facility, and was supported by the United States Department of Transportation Pipeline and Hazardous Materials Safety Administration (DOT PHMSA and DOE) and the United Kingdom Health and Safety Executive (HSE). The research's objective was to improve understanding of vapor development and explosions in order to more reliably assess hazards and safety measures at facilities that contain significant quantities of heavy hydrocarbons...
>
> The technical review of the report was performed by uncompensated subject matter experts... The purpose of this independent review was to provide candid and critical comments to make the report as sound as possible... The review, comments, and draft manuscript remain confidential to protect the integrity of the deliberative process. The panel reviewed multiple drafts of the report, held several conference calls, and convened a meeting on May 17th (2016) in Washington, D.C. A presentation about the draft report was given at a public meeting, PHMSA's Public Workshop on LNG Regulations, on May 19th, 2016, in Washington, D.C. ..." (emphasis added)

The 2018 PHMSA /FERC MEMORANDUM OF UNDERSTANDING

PHMSA is responsible for developing the regulations that specify the means of ensuring public safety in siting LNG terminals. The applicable regulation is 49 CFR 193, Liquefied Natural Gas Facilities: Federal Safety Standards. The present regulation was developed in the early Eighties to regulate LNG peak shaving and import terminals. Consequently, the present PHMSA regulation does not address the "new" hazards of vapor cloud explosions of heavier-than-methane hydrocarbons that are present in large quantities at LNG export terminals. So, during the period following my comments to FERC in 2015 on the UVCE hazard, and until very recently, I failed to understand why the 2015 JCET DEIS included an address of the UVCE hazard (not required by 49 CFR 193) by presenting the extensive predictions of explosion overpressure for heaver-than-methane hydrocarbon/air clouds that could be formed following accidental release at JCET. I remain uncertain why that action was taken, but I am increasingly concerned that the UVCE hazards present in the operation of LNG export terminals are effectively being ignored. My concern is that the order-of-magnitude-too-low predictions of the overpressures used by FERC to evaluate the VCVE hazard in the environmental impact statements for the JCET might result in the continued dismissal of the importance of this hazard for the JCET.

On August 31, 2018, the Federal Energy Regulatory Commission (FERC) and the Hazardous Materials Safety Administration within the U.S. Department of Transportation announced the signing of an agreement to coordinate the siting and safety review of FERC-jurisdictional LNG facilities. Quoting therefrom:

"The Memorandum of Understanding (MOU) establishes a framework for coordination between FERC and PHMSA to process LNG applications in a timely and expeditious manner while ensuring decision-makers are fully informed on public safety impacts. The MOU provides that PHMSA will review LNG project applications to determine whether a proposed facility complies

with the safety standards set forth in PHMSA's regulations, and that PHMSA will issue a letter to FERC stating its findings regarding such compliance. FERC will then consider PHMSA's compliance findings in its decision on whether a project is in the public interest." (emphasis added)

It is my understanding that the JCET DEIS issued in 2019 does not state that FERC received an LOD (letter of determination) from PHMSA that presented its findings regarding compliance with the safety standards set forth in its regulations. It is further my understanding that the FERC/PHMSA MOU effectively requires PHMSA to issue such an LOD by the time the FEIS is completed.

My review of the Reliability and Safety section of the DEIS disclosed no direct reference to the UVCE hazard. It is as if the problem had either been decided as lacking further need of address or that some further address might be forthcoming by the time the EIS is completed.

I respectfully request that I be provided an answer to the following question: Given PHMSA's announcement in 2016 at the Public Workshop on LNG Regulation that 49 CFR 193 appeared to require updating to cater for the new (UVCE) hazards that attend Export Terminal operations, why has that announcement not led to any further analysis and evaluation in the 2019 JCET DEIS?

Unless that question can be answered satisfactorily, it appears that critical safety recommendations by PHMSA requiring changes to 49 CFR 193, backed up by extensive advice from the scientific expert community, are being ignored.

Who Required the UVCE Hazard to be Addressed in the 2015 JCET DEIS?

The only government source I have found for guidance regarding calculations of overpressure required to be presented in the 2015 JCET DEIS is in "Guidance Manual for Environmental Report Preparation, Volume II, LNG Facility Resource Reports 11 & 13 Supplemental Guidance, DRAFT, December 2015", prepared by FERC. Section 13.H.3, "Hazard Analysis Reports" of that draft appears to be the source of the requirement for explosion overpressure that appeared in the 2015 JCET Environmental Impact Statements. The requirement for explosion overpressures remains in the Guidance Manual for Environmental Report Preparation, FINAL, dated February 2017.

It is my understanding that the Draft FERC document providing guidance to JCET for providing VCE overpressure calculations was not based on the requirements of 49 CFR 193. It appears that FERC may have recognized the need to evaluate the UVCE hazards that could attend the operation of the JCET, and that those hazards should be considered in the JCET DEIS. I have no information about why FERC included the requirement to address UVCE hazards in their Guidance Document for preparation of Environmental Impact Statements. In any case, the "requirement" in FERC's Guidance Manual for Environmental Reports appears to demonstrate FERC's awareness of the importance of addressing the UVCE hazard.

The fact remains that the predictions of overpressure that were provided for the JCET DEIS in 2015 were stated therein to be made with the FLACS model, and although FLACS is approved for vapor dispersion calculations required by 49 CFR 193, it is my understanding that FLACS still has not been either evaluated or approved by PHMSA for explosion overpressure determination. If this is the case, then a major course-correction seems required, because comparisons of those (order-of-magnitude-too-low) overpressure predictions with documented measurements of overpressure data for a large number of UVCE events involving the same hydrocarbons, in similar amounts, and in similar atmospheric conditions, will demonstrate that the predictions utilized in the JCET environmental impact statements are in serious error.

If this problem is not addressed, it appears likely that such errors accompanied by FERC's approval thereof will ignore the scientific expert advice that resulted from the PHMSA Workshop conducted in 2016. The effect will be to ignore extensive accident experience that demonstrates the potential for cascading explosions that could destroy the plant and possibly extend damages to the public beyond the facility boundary.

CONCLUSIONS

49 CFR 193 Liquefied Natural Gas Facilities: Federal Safety Standards does not currently provide for adequate consideration of the hazards of Unconfined Vapor Cloud Explosion (UVCE) hazards that attend LNG Export Terminals handling and storing large quantities of heavier-than-methane hydrocarbons.

PHMSA conducted the Public Workshop on Liquefied Natural Gas (LNG) Regulations in Washington, DC, 19 May 2016. The principal purpose of the Workshop was stated to be the intention to address the need for updating 49 CFR 193 in order to cater for any new hazards that could be involved in siting LNG Export Terminals. The Workshop clearly identified the UVCE hazard as being the most important hazard present at Export Terminals that was not currently addressed adequately by 49 CFR 193.

PHMSA initiated a program to address the needs for changes in the regulation to provide for UVCE hazards. It appears that no progress has been forthcoming.

The new Draft Environmental Impact Statement (DEIS) for the Jordan Cove Export Terminal, just issued, continues to seriously underestimate vapor cloud explosion overpressures (damage) that could occur following credible releases of heavy hydrocarbons at the JCET site. The latest predictions that I am aware of appear to be an order of magnitude lower than are indicated by physical evidence of numerous documented UVCEs that have occurred worldwide with the potential to cause injuries and deaths to persons and result in destruction of the facility.

Comment by Jerry Havens
Distinguished Professor Emeritus
University of Arkansas

I am speaking as a concerned scientist and citizen.
My comments are not to be attributed to the University of Arkansas.

These comments are my fourth in a series submitted to the website established for the Public Workshop on Liquefied Natural LNG Regulations conducted in Washington, DC in May 2016. I appreciate the availability of this website for receiving comments from the public relating to the PHMSA's intention to update 49 CFR 193, Liquefied Natural Gas Facilities: Federal Safety Standards. However, I am very concerned that failure to ensure that the hazards attending LNG export terminals are adequately addressed will have catastrophic consequences.

The Workshop website includes two documents which are critically important because they explain clearly to all stakeholders the critical need for the regulations to be updated and effectively prescribe a path forward that would alleviate my concerns. Unfortunately, the website does not appear to have received the attention it deserves – to date the site has received only about a dozen comments, four of which are mine. The first document clearly defines the principal need that the Workshop was designed to address – a science-based evaluation of severe heavier-than-methane vapor cloud explosion (VCE) hazards that can exist in LNG export terminals. The second document, commissioned by PHMSA and presented at the Workshop, clearly provides that need.

I am concerned that comments that I filed with FERC in 2015 regarding the Environmental Impact Statement for the Jordan Cove Export Terminal in Oregon and the subsequent Health and Safety Executive Report "Review of Vapor Cloud Explosion Incidents" presented at the Workshop in 2016 are being ignored. In my opinion, a potential error in overpressure calculations presented in the Jordan Cove EIS portends the possibility of a VCE explosion that could destroy the plant and endanger the Public beyond the facility boundary.

Excerpts from PHMSA's Statement of Mission (from the Workshop Website)

"Historically, most LNG facilities were peak shavers built to liquefy and store natural gas to be degasified and injected back into the pipeline during periods of peak demand ... However, due to the recent abundance of domestic shale gas, LNG export terminals are now being constructed that liquefy vast volumes of natural gas. These facilities require significantly greater quantities of refrigerants to liquefy the natural gas than the amount typically used at peak shavers... Most refrigerant gases and blends used at the export facilities contain ethane, propane, ethylene, and iso-butane and are referred to as heavy hydrocarbons. These gases are similar to gases that have resulted in VCEs at petrochemical facilities...

The understanding of VCEs is evolving. PHMSA recognizes that significant quantities of heavy hydrocarbons present different risks than methane and seeks to better understand that risk. Prior to investigative work on the Buncefield accident, the prevailing understanding was that vapor clouds formed outdoors were unlikely to explode if ignited. Today it is understood that VCEs involving higher hydrocarbons have occurred in outside areas. This paper advances our understanding further. PHMSA sponsored the "Review of Vapour Cloud Explosion Incidents" report with the primary objective to improve the scientific understanding of vapour cloud development and explosion in order to more reliably assess hazards at large Liquid Natural Gas (LNG) export facilities... The aim of reviewing the particular incidents in this report is the extensive forensic evidence available that provides the information needed to study how the vapor cloud formed and ignited, the amount of overpressure exerted, and other information about the mechanism of VCE. This research was performed by the Health and Safety Laboratory (HSL) under a subcontract with the Oak Ridge National Laboratory, a United States Department of Energy (DOE) facility, and was supported by the United States Department of Transportation Pipeline and Hazardous Materials Safety Administration (DOT PHMSA and DOE) and the United Kingdom Health and Safety Executive (HSE). The research's objective was to improve understanding of vapor development and explosions in order to more reliably assess hazards and safety measures at facilities that contain significant quantities of heavy hydrocarbons...

The technical review of the report was performed by uncompensated subject matter experts... The purpose of this independent review was to provide candid and critical comments to make the report as sound as possible... The review, comments, and draft manuscript remain confidential to protect the the integrity of the deliberative process. The panel reviewed multiple drafts of the report, held several conference calls, and convened a meeting on May 17th (2016) in Washington, D.C. A presentation about the draft report was given at a public meeting, PHMSA's Public Workshop on LNG Regulations, on May 19th, 2016, in Washington, D.C. ..."

Excerpts from the Executive Summary of "Review of Vapour Cloud Explosion Incidents"

"This review of major vapor cloud incidents has been jointly commissioned by the US Pipeline and Hazardous Materials Safety Administration (PHMSA) and the UK Health and Safety Executive (HSE). The primary objective was to improve understanding of vapor cloud development and explosion in order to examine the potential for these hazards to exist or develop at LNG export plants that store substantial quantities of these flammable gases for use in the liquefaction process or as a by-product from the liquefaction ...

This review has not found any historical records of LNG (methane) vapor cloud explosions in open areas with severity sufficient to cause secondary damage to tanks and pipes and consequently rapid escalation of an incident from a minor process leak to a major loss of inventory.

On the other hand some LNG sites (especially export sites) also hold substantial amounts of refrigerant gases and blends containing ethane, propane, ethylene and iso-butane. Higher hydrocarbons may also be produced and stored on LNG export sites as by-products of gas condensation. There are numerous examples of Vapor Cloud Explosions (VCEs) in open areas involving these higher molecular weight materials and the storage and use of higher molecular weight hydrocarbons on LNG export sites which may if not managed adequately introduce an additional set of incident scenarios in which VCEs trigger rapid escalation of loss of containment.

This study involves a review of 24 major VCE incidents focusing on source terms, cloud development and explosion mechanics. The incidents studied are split between permanent fuel gas (C2-C4 (e.g. LPG) and volatile liquids C4-C6 (e.g. gasoline). The source terms for leaks of gases and liquids are different but once a stable current of cold heavy vapor forms, the subsequent development of LPG and gasoline clouds are similar…

An important finding from the review is that a high proportion of vapor cloud incidents occurred in nil/low wind conditions. By the term "nil/low wind" we mean a wind that was so weak close to the ground that it only detrained (stripped away) a small proportion of the vapor accumulating around the source … Rather than being picked up and moved downwind, the vapor flow in this case was gravity driven; spreading out in all directions and or following any downward slopes around the source.

In many of the cases examined, 50% (12/24), there is clear evidence from the well-documented transport of vapor in all directions and/or meteorological records that the vapor cloud formed in nil/low wind conditions. In a further 21% (5/24), the pattern of vapor suggests nil/low wind conditions but there is insufficient data available to be sure … incidents in nil/low wind conditions apparently make up the majority of historical records of the most serious VCEs… In nil/low wind conditions the cloud continues to grow throughout the time that the tank takes to empty… The maximum area covered by the flammable cloud is typically several hundred times greater in nil/low winds condition than in light winds.

The implication of this type of analysis is that if the density of ignition sources is constant and quite low in the area around the tank the chances of ignition in nil/low wind conditions would be hundreds of times greater for a given release. This illustrates why nil/low wind conditions dominate records of major vapor cloud incidents even though the weather frequency is low. Losses of containment in nil/low wind conditions are also particularly dangerous because a highly homogeneous cloud can be formed that may spread by gravitational slumping (without significant dilution) for hundreds of meters… A very large cloud that is all close to the stoichiometric ratio increases the risk of flame acceleration to a high pressure regime capable of seriously damaging storage and process facilities, when compared with clouds that are entraining air because of wind-driven dilution. Thjis is because fundamental burning rates fall off rapidly for concentrations away from the stoichiometric . Once a high pressure regime is established explosions are not confined to congested areas of a site. In many of the cases reviewed almost all the footprint of the cloud was exposed to pressures in excess of 2000 mbar (29 psi). In at least one case the cloud detonated, causing extremely severe damage over the area covered by the cloud). (emphasis added)"

When is the LNG Regulation Update Expected?

It has been more than two and a half years since the Public Meeting on LNG Regulation was held. My attempts to get information on the schedule for Regulation updating have not been encouraging. I have learned that PHMSA has addressed the need for a written protocol to assess the verity and utility of the computer-calculated explosion overpressure predictions that were the means of addressing the vapor cloud explosion (VCE) hazard in the Environmental Impact Statement(s) filed for the Jordan Cove Terminal in Oregon. I should note that these comments are directed primarily to the environmental impact statements relating to the Jordan Cove Project, which I have previously commented on; however, the scientific information presented on the Workshop website that I am referring to should be considered applicable to LNG Export Terminals in general. I understand that the development of a written protocol (for explosion model verification) requires that funding be expedited. I also understand the difficulties faced by the Regulatory Agencies in the present political climate. Meanwhile, LNG export terminals are being approved and some are operating. I am concerned that errors are being made in the calculation of overpressures in the design spills that are being considered in environmental impact statements for LNG export terminals now processing applications for siting. Such errors can put these very expensive facilities at risk of severe vapor cloud explosions that could result in cascading loss of containment events that could destroy the facility and present important hazards to the public beyond the plant boundaries. Accordingly, I am convinced of an urgent need for updating of the LNG regulations.

Please let this comment serve as my request that funding be provided as soon as possible to PHMSA to determine whether the calculations now being presented for LNG facility siting can be evaluated by testing against the applicable explosion events documented in the HSE report. In my opinion the HSE report contains sufficient validated scientific data for numerous severe VCEs involving the same or similar fuels and amounts thereof. I believe that a careful, science-based, evaluation of the calculations of overpressures in VCEs that have been presented in the Jordan Cove proceedings using the HSE report will provide a method for dealing with this urgent problem that is not cost prohibitive. I believe the problems underlying my concern have been addressed carefully in the HSE report. I conclude that actions required to alleviate these concerns are doable and can be expedited using the HSE report that has been commissioned by PHMSA .

Submitted by Jerry Havens, November xx, 2018, to
US Department of Transportation Pipeline and Hazardous Materials Safety Administration

Comment by Jerry Havens
Distinguished Professor Emeritus
University of Arkansas

I am speaking as a concerned scientist and citizen.
My comments are not to be attributed to the University of Arkansas.

These comments are a further addition to my comments to the Public Workshop on Liquefied Natural LNG Regulations site on July 28, 2016 and September 22, 2018.

I stated in my comments of September 22, 2018 that I am very concerned that our current regulatory measures concerning siting of LNG export terminals be developed by decision-makers that are fully informed regarding the public safety impacts involved.

Based on information I have learned since September 22, 2018, I want here to clarify my understanding of the process that took place in the preparation of the Environmental Impact Statements for the Jordan Cove LNG Export Terminal, and I respectfully request that PHMSA inform me of any faults in that understanding.

In 2015 FERC published a draft notice of their intent to update their guidance document on preparation of environmental impact statements. The earlier guidance document (2002) did not include any consideration of explosion overpressure hazards. The draft (dated 2015) clearly specified the direction to applicants to prepare calculations of VCE explosion overpressures that could result following the Design Spills considered, and the draft was approved and issued in 2017 – still containing the directions to the applicant to prepare the explosion overpressure hazards calculations.

To my knowledge, PHMSA's regulations on LNG Terminal siting did not in 2015 and still do not require Vapor Cloud Explosion (VCR) overpressure calculations.

The FLACS Model was approved for vapor cloud dispersion exclusion zones by PHMSA based on FLACS' satisfactorily meeting the requirement of PHMSA's written protocol.

The written protocol used to approve FLACS for calculating vapor cloud dispersion zones does not address the suitability of FLACS for calculating VCE overpressures.

I am very concerned that the afore-mentioned information could indicate that the FLACS model used for calculating the VCE overpressures presented in the Jordan Cove LNG Export Terminal Environmental Impact Statements has not received adequate scientific peer review.

I appreciate this site remaining available for comments relating to the 2016 PHMSA Public Workshop on Liquefied Natural Gas (LNG) Regulations.

Submitted by Jerry Havens, October 2, 2018, to
US Department of Transportation Pipeline and Hazardous Materials Safety Administration

Comment by Jerry Havens
Distinguished Professor Emeritus
University of Arkansas

I am speaking as a concerned scientist and citizen.
My comments are not to be attributed to the University of Arkansas.

These comments are an expansion of my earlier comments to the Public Workshop on Liquefied Natural LNG Regulations site on July 28, 2016, which I stand by. They are also intended as a response to the joint news release of August 31, 2018 by PHMSA and FERC:

FERC, PHMSA Sign MOU to Coordinate LNG Reviews

Quoting the MOU, "The MOU establishes a framework for coordination between FERC and PHMSA to process LNG applications in a timely and expeditious manner while ensuring decision-makers are fully informed on public safety impacts ".

I understand the importance to us all of expeditious and timely handling of LNG Export Terminal applications, but I am very concerned that our current regulatory measures be developed by decision-makers that are fully informed regarding the public safety impacts involved. I realize the gravity of this statement, and I have struggled with the decision to put such questions of uncertainty on the table. But I have been unable to satisfy myself that my concerns are unwarranted. Therefore, I appreciate this opportunity to state my concerns.

Please let me repeat that I stand fully behind the comments I submitted to this site on July 28, 2016, as well as all of my previous comments submitted to FERC and PHMSA. But more importantly, I want to clearly identify here my increasing concerns that our regulatory process is failing to satisfactorily consider fully the accident consequences that attend the operation of LNG Export Terminals that must be considered in the public interest. Please consider the following statements, which I trust are factual. If PHMSA notifies me that I am in error, I will promptly refile accordingly.

- The current LNG regulation 49 CFR 193 was developed for application to the evaluation of hazards attending Import Facilities.
- 49 CFR identifies only two hazard exclusion zone requirements; a vapor dispersion zone and a fire radiation zone. The regulations require that the maximum lateral extent of these zones must not exceed the distance to the property boundary.
- The current regulation does not address vapor cloud explosion hazards. My understanding of the basis for this policy is the long-accepted premise that LNG vapor (being essentially methane, that is, not containing heavier (higher molecular weight) hydrocarbons such as propane, butane, etc.), will not explode if uncontained.

- For import terminals, there are normally no situations where there is significant risk of release of large amounts of heavier-than-methane hydrocarbons.
- But, for export terminals, the gases entering the facility for liquefaction may (and typically do) contain significant amounts of high-explosion-risk hydrocarbons that must be stored and handled, thus presenting new risks not ordinarily attending import terminals.
- The requirement for only two exclusion zones, dispersion and thermal radiation zones, for import terminals does not address the risks of explosion of unconfined gas air clouds that can occur at export terminals.
- My comments to FERC and PHMSA on this subject have been directed thus far primarily to the Jordan Cove Export Terminal proposed for the coast of Oregon. The remaining points in these comments are largely presented for consideration with the Jordan Cove Facility only. However, it should be anticipated that such hazards could attend any of the LNG export terminals currently operating or under consideration throughout the world.
- As I understand it, there is no requirement at present in 49 CFR 193 to address the unconfined vapor cloud explosion (UVCE) risk.
- However, as exemplified by the Draft and Final Environmental Impact Statements for Jordan Cove, the applicants included calculations to provide for the formation of very large clouds of heavier hydrocarbon gases than methane which are known to cause damaging explosion overpressures. It is my understanding that the calculation of the overpressures was done with a Computer Code called FLACS. The results of the calculations were then used to justify the statement in the Environmental Impact Statements that the explosion damage would not extend off-site. Along with Professor James Venart of the University of New Brunswick (now deceased) I filed comments with FERC questioning the accuracy of those conclusions in 2015.
- Subsequently, PHMSA held a public workshop in Washington in mid-2016 which announced PHMSA's intent to consider the need for updating the LNG regulations for proper consideration of the hazards that attend LNG export terminal operations.

The Current Situation (as I understand it)

It appears that the FLACS Computer Model used in support of Jordan Cove applications was used to calculate the vapor cloud explosion overpressures that could have been realized for the design spills considered. My understanding is that the calculations using the FLACS model are important to the final decision by FERC to grant approval to both the DEIS and the FEIS for Jordan Cove. For various reasons, the project did not proceed, but it has been announced that a new DEIS will be issued in February of 2019.

In view of the importance of the facts presented, coupled with the policy now adopted by PHMSA for such codes as FLACS to be designated **Proprietary** using their designation as Critical Energy Infrastructure Information (CEII), it appears to me that the public interest is not being served by the Agency's failure to sufficiently investigate the scientific validity of FLACS for determining the damage that might result from the very spills of heavier than methane hydrocarbons that Jordan Cove argued could be released, specifically mixed refrigerant hydrocarbons and ethylene, both of which have been shown to cause violent Unconfined Vapor Cloud Explosions.

Here are three more inputs which I believe support my concerns:

- LNG Regulation 49 CFR 193 is based on the determination of the extents of exclusion zones for vapor dispersion and fire (thermal) radiation using mathematical models which must be approved by PHMSA.
- As I understand it, vapor dispersion models are now approved by PHMSA only if the models meet the requirements of PHMSA-specified written protocols designed for the purpose.
- To my knowledge there has not been made available to the public a protocol that must be met for PHMSA's approval for the use of FLACS to predict vapor cloud explosion overpressures. This leaves me with the concern that the FLACS model has not been sufficiently evaluated for such regulatory use, considering the very high stakes involved.

Thank you for the opportunity to express my concerns about this situation, which I believe is of critical importance to us all.

Comment by Jerry Havens
Distinguished Professor of Chemical Engineering
University of Arkansas

I am speaking as a concerned scientist.
My comments are not to be attributed to the University of Arkansas.

I attended the LNG workshop at DOT Headquarters in Washington on May 18 and 19, 2016. My comments are directed to the plans previewed by PHMSA at the workshop for updating the federal regulatory requirements for safe siting of LNG facilities; especially relating to the workshop presentations made by Drs. Graham Atkinson and Simon Gant of the British Health and Safety Laboratories (HSL) regarding predictive modeling of flammable vapor cloud formation, dispersion, and explosion hazards.

I understand that HSL is under contract to PHMSA to provide an assessment of specific needs that should be addressed by PHMSA for its planned updating of LNG Regulation 49 CFR 193. I do not know the specific requirements of the contract with HSL, but it seemed strongly suggested at the workshop that HSL is considering at least two critical needs for LNG facility siting regulation evaluation and updating:

- Unresolved questions about the potential at LNG storage terminals for unconfined vapor cloud explosion (UVCE), with emphasis on the increased potential for severe explosions involving heavier-than-methane hydrocarbons used and stored in large amounts in LNG export terminals. (Workshop presentation by Dr. Atkinson)
- Protocols for approval of mathematical models for LNG vapor cloud formation, dispersion, and explosion potential, particularly for heavier-than-methane hydrocarbons. (Workshop presentation by Dr. Gant)

My comments focus on the methods used to determine consequences of UVCEs that could follow the design spills required to be considered by 49 CFR 193. I believe the following three issues (in caps), all of which are closely coupled in the determination of vapor cloud explosion potential, are of highest priority for updating the LNG regulations.

MATHEMATICAL MODELS FOR VAPOR DISPERSION CONFINED BY FENCES AND UVCE OVERPRESSURE POTENTIAL REQUIRE THOROUGH SCIENTIFIC VETTING

The main purpose of my comments is to request PHMSA to address concerns that have been raised that some of the mathematical modeling methods currently in use can produce results that severely underestimate vapor cloud explosion hazards (consequences) to the public. I am very concerned that PHMSA's current procedure for determining the hazards attending large-scale LNG Export Terminals, including the present protocol for approval of vapor dispersion models for such use, is seriously flawed, particularly regarding UVCE hazards.

Proprietary Models

The current model approval process relies on provision to PHMSA by the applicant (for model approval) of evidence that the proposed model meets PHMSA requirements for scientific correctness as well as requirements for satisfactory model agreement with a PHMSA supplied list of field and laboratory experiments that have been documented. The most serious flaw in the current procedure, in my opinion, is that because the protocol allows approval of modeling methods that are proprietary, and thus not subject to independent scientific-peer review, neither PHMSA nor the public can confidently determine whether the models are suitable for purpose. The result is that the public is not provided the following information about the hazard-modeling process, all of which is necessary to make a science-based evaluation of the model predictions that form the basis for FERC's approval or disapproval of proposed LNG terminals:

- Details of data input to the model(s),
- Detailed results produced by the model(s), and,
- most importantly, a transparent description of the methods used in the models that is suitable for examination and scientific review to ensure that the methods are not used improperly.

The use of proprietary models denies the public an effective means of ensuring that errors in model application are not committed accidentally or intentionally. Such a process portends danger to the public. There is no question that the hazards attending the handling and storage of extremely large quantities of potentially flammable/explosive materials in LNG facilities, if the hazard determinations are not accurate, could result in catastrophic damages extending beyond facility boundaries.

PHMSA has a single means of ensuring that the decisions for approval of the safety provisions claimed are not subject to error – a scientific peer review process. There must be a means developed to insure that the public is provided information sufficient to independently verify the accuracy and applicability of the model predictions that determine FERC's decision for or against LNG facility approval. The importance of requirements for model transparency can only increase as the scientific tools for predicting hazardous materials risks and consequences become more complex and difficult for evaluation by the regulators and the public.

Past Experience: "Sub-Model" SOURCE5

A brief review of one of PHMSA's documented actions taken to correct misuse of hazard-models illustrates the difficulties the agency faces in enforcement of model use that is based on correct science and is accurate. The "case" described below also provides a pertinent example of the critical need to ensure that so-called "sub-models" (subordinate parts of the parent models) that are required to quantify the risk and/or consequences of the "design" spill are also based on correct science and are accurate. This is particularly important presently; some of the issues that I believe are now being handled incorrectly and which were described in my comments to FERC in January/February 2015 regarding the DEIS for the Jordan Cove LNG Export Terminal are due to use of such sub-models.

The vapor dispersion models approved for determination of vapor cloud exclusion zones by PHMSA require specification as input the rate at which the gas enters the atmosphere. Historically, the largest "design spills" for which vapor cloud exclusion zones must be predicted are liquid spills into impoundments, necessitating estimation of the evaporation rate from the LNG (liquid) released as input to the vapor dispersion model. Until about 2010, during which time the LNG vapor dispersion model DEGADIS was used widely, a sub-program called SOURCE5 was used to compute gas input rate to the dispersion model. There appeared statements in the scientific literature as well as comments to Draft Environmental Impact Statements that SOURCE5 contained assumptions that were erroneous and that resulted in severe underestimation of the "source term" (the gas rate introduced to the atmosphere) which led to severely underestimated vapor cloud dispersion distances.

PHMSA responded and processes were put in place to provide scientific review of several sub-models, including SOURCE5. One of the resulting scientific reports that contributed to PHMSA's decision to prohibit further use of SOURCE5 was prepared by the British Health and Safety Laboratory (HSL). See Ref. 1 below. For brevity, I quote a single brief statement from Appendix A of HSL's report which I believe says everything that is necessary to justify, indeed require, PHMSA's decision to prohibit further use of SOURCE5:

> *In summary we find that the suite of models embodied in SOURCE5 do not have a sound physical basis. In fact it is doubtful that one can get an accurate picture of a scenario as complicated as those considered here if one restricts oneself to simple algebraic equations such as those considered by SOURCE5. Some of the predictions of the model, especially the lack of dilution of the vapour before it achieves the bund wall height, are expected to result in markedly optimistic prediction of hazards.*

I used this short excerpt because it so effectively summarized HSL's finding. Lest the reader be misled by the brevity and straightforward simplicity of this statement that justified PHMSA prohibiting further use of SOURCE5, I think a few remarks are in order. Readers willing to take the time to examine the HSL Report from which the excerpt is quoted will find that the examination of the model by HSL was thorough and painstaking. The expertise and knowledge required for an assessment of complex mathematical models resides in relatively few independent organizations, and the resulting action prohibiting further use of SOURCE5 could not have been achieved without PHMSA's request to a neutral scientific body for advice and interpretation. I appreciate the agency's concern that the amount of time and effort required by the model evaluation by HSL was expensive to the U.S. taxpayer. However, such costs are necessary as part of any government regulatory process that relies on expert scientific advice for decision making, particularly if those decisions directly impact public safety. Without such actions taken by the regulatory authority, the public cannot be confident of predictions that FERC accepts to approve or disapprove a facility.

THE PRACTICE OF CONFINEMENT OF VAPOR CLOUDS WITH GAS-IMPERMEABLE FENCES SHOULD BE EVALUATED FOR POTENTIAL TO INCREASE EXPLOSION DAMAGE

The use of gas-impervious vapor fences is relatively new to the industry; it appears to be resulting more frequently associated with requests for approval for siting of very large facilities which cannot economically provide satisfactory exclusion distances to the facility property line without resort to such "vapor cloud mitigation practices". The majority of LNG Export Terminals now being considered have requested approval by FERC of vapor-impervious fences placed strategically to limit flammable vapor cloud travel beyond the applicant's property line. Such practices raise important (unanswered) questions about the increase in the severity of vapor cloud explosions that can result from such partial confinement. Based on my review of the Jordan Cove project DEIS, it appears that FERC has not considered the potential of such fences, some of which are 40 feet tall and constructed with reinforced concrete, to increase explosion overpressure damage. In my opinion this neglect of explosion science knowledge is wrong.

CURRENT MODELS FOR EXPLOSION DAMAGE OF VAPOR CLOUDS ARE INSUFFICIENTLY TESTED AND MAY LEAD TO NONCONSERVATIVE HAZARD PREDICTIONS

After I learned of the planned PHMSA workshop and that PHMSA had contracted with HSL to evaluate some of the concerns I had raised in my comments to FERC, I developed a better understanding of the situation which I believe should be considered by PHMSA as they proceed with the regulation updating process. I believe the issues described here deserve highest priority, since unconfined vapor cloud explosions involving heavier-than-methane hydrocarbons handled and stored in large quantities in LNG export facilities pose the potential for catastrophic cascading explosion damages resulting in complete destruction of the facility and potential for danger to the public beyond the facility boundaries.

Focusing on Jordan Cove EIS Critical Issues: Effects of Vapor Fences and Use of Proprietary Models to Predict Explosion Overpressure

Expert advice for preparation of draft environmental impact statements is generally provided to applicants for siting approval (such as Jordan Cove) by consultants who are practiced in making such determinations using computer modeling methods. Such calculations are now almost exclusively made using complex mathematical modeling tools – the use of computational fluid dynamics (CFD) computer models has become widespread in the LNG industry/regulatory community in the last two decades. This practice, however sophisticated and rapidly developing it may be, is relatively new and untested for application to the strongly coupled complex phenomena of atmospheric dispersion and combustion/explosion dynamics. Experimental verifications of such model predictions as complex as those currently appearing in environmental impact statements is increasingly expensive and difficult to achieve.

In my opinion, the reality of the situation is this: The prediction of explosion overpressure damage that could result if a very large design spill formed a flammable vapor cloud in near-calm conditions and confined by vapor fences is presently fraught with uncertainty; so much so that the scientific community has insufficient confidence in such predictions unless they are verified, at least in part, by experiment. But these new "complex" models are the product of private research and development efforts, in the present case by consulting companies that must deal directly (for the project applicant) with PHMSA and FERC. The result is that such tools are now being approved by PHMSA with a proprietary designation. This is understandable, if not necessarily justified, as the companies are motivated to protect their investment in the required model development process.

It is this author's experience that until the current model protocol process was instituted (accepting proprietary models for regulatory use), there has always been a strong reluctance by regulators to allow such models that are not available (at reasonable cost) to the public, or the public's agent, for careful scientific scrutiny. SOURCE5, although developed by private interests, was not prohibitively expensive and could be obtained for careful analysis with a reasonable effort by the public. That availability enabled the criticisms that led to the model's careful scientific vetting and the prohibition of its further use. The new complex models being adopted are prohibitively expensive to the public and protected as proprietary as well. There must be some means of ensuring that such complex, untested, calculations are thoroughly vetted by independent scientific parties responsible to PHMSA. In my opinion, proceeding with the current hazard evaluation processes now being approved by FERC cannot be justified.

Low or No--Wind Condition Concerns Made Worse with Cloud Confinement

Revisiting the Jordan Cove DEIS in preparation of these comments, I verified that the vapor cloud travel distances that were determined using the recently approved FLACS model, essentially none of which reach beyond the JC property lines, resulted not from dispersion (or lack thereof) but from the use of vapor fences that confine the cloud to the property controlled by the applicant. The vapor cloud does not proceed beyond the boundaries because it is stopped by a vapor fence. Because the cloud cannot penetrate the fence, it accumulates on the site. Although the fences are not continuous (laterally), they prevent the cloud from advancing beyond most of the boundaries. The result is confinement of the gas on the site, where the depth (thickness) tends to increase until the spill ends and the liquid all evaporates. Then, under very low or no-wind conditions, the gas cloud pretty much sits there (which can be a long time if there is no wind to increase vertical diffusion of the gas) unless it is ignited. But, if it is ignited and the flammable concentration range of the gas includes large parts of the cloud, the condition is set up for a catastrophic explosion.

The Volume of the Gas Cloud that is within the Flammable Concentration Range is a Strong Determinant of the Damaging Explosion Overpressure

The confinement of the cloud when it is formed with very little wind (to increase dispersion) can result in the cloud becoming highly concentrated (in flammable gas) throughout. In all four of the catastrophic explosions described in my comments to FERC (and those described by Dr. Atkinson at the Workshop), there were very large parts of the cloud with gas concentrations in the flammable range. The gas concentration distribution in the cloud strongly determines the severity of the fire or explosion that can result if the cloud is ignited. If the entire cloud is below the lower flammability concentration of the gas, none of it will ignite and there will be no fire or explosion. If the source of ignition is in a region of the cloud where the gas concentration is above the upper flammability limit, ignition will not occur at that location. If ignition occurs in a cloud region where the concentration lies between these limits and there are nearby regions where there are higher concentrations (above the upper flammability limit) the cloud will continue to burn through those regions. In any case the flame advance will only be stopped when the concentration of the cloud (at that location) drops below the lower flammable limit.

Revisiting FLACS and Sub-Model Q9 Used for Jordan Cove EIS

There exists evidence in the open scientific literature that the FLACS vapor-dispersion mathematical model, which includes a specific sub-model called Q9 that is used in part to calculate explosive overpressures, has not been subjected to a satisfactory scientific peer-review process designed to prevent its misuse. In preparation for these comments, I found a publication in the Institution of Chemical Engineers (IChemE) Symposium Series which presents an evaluation of the combined use of FLACS and Q9 for explosion modeling (See Ref. 2 below).

There are striking similarities in the IChemE paper with statements that appeared in criticisms of SOURCE5. Again, for brevity, I have selected brief comments from the IChemE paper about Q9 that indicate serious questions about its overall applicability to the prediction of UVCE explosion overpressure damage in complex plant environments:

> *Q9 is a volume measure which accounts for the effects of gas concentration by weighting the volume with the effect of burning velocity and expansion ratio. Experiments showed that burning velocity varies with concentration ... For hydrocarbons, burning velocity is maximum at or near stoichiometric concentration of 1 and dropping off rapidly as gas concentration is rich ... or lean ..., reaching zero at UFL and LFL.*
>
> *We found that Q9 measures are being used increasingly by consultants. We are concerned that there has not been work to verify that this approach is indeed correct. Our observation is that there appears to be little fundamental understanding of the Q9 measures by consultants we encountered. Its application is based on a belief that since there is a varying gas concentration in a gas cloud formed from pressurized gas release, assuming a uniform gas cloud concentration is thus 'over-conservative', and using Q9 would remove this perceived 'over-conservatism'. As we see... this is not necessarily so.*
>
> *Superficially, Q9 seems to be the most accurate measure out of the three (we reviewed) as it accounts for the well known effect of gas concentration on flame speed and expansion ratio. It may be a surprise that our results showed that the Q9 measure performs poorly. ... one should not confuse complexity and accuracy.*
>
> *Size of the gas cloud – Limiting the flammable gas cloud to a smaller effective volume reduces the effect of flame acceleration over a larger distance and over a longer period of time that that produced by larger cloud volumes and could lead to lower and the wrong distribution of overpressure .... Another reason for psssible underestimation of flammable volume is that volumes with rich gas mixtures can be diluted with air or with lean gas mixtures during the course of a gas explosion, rendering the rich mixture closer to the stoichiometric ratio of 1. Applying the Q9 method blindly, it is possible to reach a conclusion that a very large leak of flammable gas would not pose a hazard* (emphasis added).
>
> *Any methods used should be verified against experimental data as far as possible. It should be the duty of the model developer or user of the model to verify any new methods against available data ...*
>
> *This work does not support the use of Q9* (emphasis added).

While the referenced IChemE Symposium paper is not equivalent to a thorough scientific peer review, it does qualify as an Industry/Academia-led evaluation of current methods for determining flammable gas volumes to be considered in explosion modelling. Most importantly, the paper provides results of a technical expert-evaluation of the Q9 model for estimating equivalent stoichiometric volumes of the flammable cloud volumes that were predicted for the heavy hydrocarbon design spills presented in the Jordan Cove Export Terminal EIS. Similar queries about SOURCE5 were dealt with by PHMSA's request to an independent scientific body for assessment. I believe the questions raised here about Q9 (as used with FLACS) deserve similar scrutiny, and I hope that PHMSA will commission such a review.

A Closing Comment on Accidental vs. Intentional Events

There were suggestions during the Workshop that incorporation of quantitative risk assessment (QRA) procedures were being considered by PHMSA for updating 49 CFR 193, perhaps by incorporation of LNG-QRA procedures in NFPA 59A.

I believe it is just as important that the regulations begin to address the burgeoning problem of the potential for intentional acts against LNG facilities to cause extremely serious fire and explosion cascading events.

It is clear that reliance on design of LNG facilities to minimize the probability (measure of likelihood) of accidental occurrences is turned on its head when intentional acts are considered. A simple fact plagues all of the energy industry, including the nuclear power and weapons sectors; it is relatively easy to assemble an explosive device that can be made to explode. Designing the same device to ensure that it doesn't explode is another matter entirely.

We can start by doing a better job in applying our scientific knowledge to minimize the extent to which we provide opportunities to those inclined to take advantage. The incorrect use of our scientific tools, so as to mistakenly conclude that the design under consideration is a benign one, leads us in the wrong direction.

Conclusions

The concerns laid out here exemplify why it is impossible for complex mathematical models used in regulatory determinations of questions bearing on public safety, in the absence of transparent independent scientific review, to be fairly and adequately vetted for such use. These concerns were laid out by Professor Jim Venart, now deceased, and me in response to the Draft Environmental Statement (DEIS) for the proposed Jordan Cove LNG Export Terminal in Coos Bay, Oregon. See Ref 3 and 4. I stand by my comments submitted to FERC, which I subsequently provided PHMSA for their information. While FERC acknowledged my comments when the FEIS was issued for the Jordan Cove Export Terminal Project, their reply was unsatisfactory in that it did not address the technical questions for which I had requested answers.

This is more than a debate about scientific theories of the hazards of UVCEs. It is not about "opinions" regarding the hazards of UVCE. My comments to FERC provided verified information that at least four catastrophic UVCE events, all occurring under conditions that clearly justify their description as worst-case accidents (therefore normally considered highly improbable), have occurred in the past decade. See Ref 3 and 4. Those incidents, and additional ones, were also described by Dr. Atkinson at the workshop.

There must be increased transparency of PHMSA approved mathematical modeling methods, especially those used for public-safety-regulation purposes, to prevent the public being misled. In the absence of such transparency there is little likelihood that more detailed and extensive alterations to the regulation will address the primary problem underlying these concerns.

So, my comments focus on a single question - Are the mathematical models which are being used as a basis for approving construction of LNG terminals, with the present focus on Export rather than import, being subjected to the necessary scientific scrutiny to ensure that the hazards involved are being correctly identified? I do not believe they are.

References

1. LNG source term models for hazard analysis, A review of the state-of-the-art and an approach to model assessment, Appendix A – Model Assessment Reports for GASP and SOURCE5; Dr DM Webber, Dr SE Gant, Dr MJ Ivings & SF Jagger, Health and Safety Laboratory, Harpur Hill, Buxton, Derbyshire SK17 9JN (2010)
2. Simplified flammable gas volume methods for gas explosion modeling from pressurized gas releases. A comparison with large scale experimental data. V.H.Y. Tam[1], M. Wang[1], C.N. Savvides[1], E. Tunc[2], S. Ferraris[2], and J.X. Wen[2]; [1]EPTG, BP Exploration, Chertsey Road, Sunbury-on-Thames, TW16 7LN, UK; [2]Faculty of Engineering, Kingston University, Friars Avenue, London, SW15 3DW, UK; IChemE Symposium Series No. 154, 2008
3. 1-14-2015 filing submitted to FERC by Jerry Havens and James Venart under CP13-483. http://elibrary.FERC.gov/idmws/file_list.asp?accession_num=20150114-5038
4. 2-6-2015 filing submitted to FERC 2-6-2015 - Supplementary Comment with Questions by Jerry Havens and James Venart under CP13-483. http://elibrary.FERC.gov/idmws/file_list.asp?accession_num=20150206-5040

Exhibit 4

From: Springer, Laura M LCDR/U.S. Coast Guard
Sent: Tuesday, May 15, 2018 12:39 PM
To: Jody McCaffree
Cc: Crowell, Ben W LCDR/U.S. Coast Guard; Griffitts, Thomas CAPT/U.S. Coast Guard; Dunn, Brian/U.S. Coast Guard
Subject: RE: [Non-DoD Source] FW: Connecting re Jordan Cove LNG Export Project

Good Day,
Thank you for your concern, the Letter of Recommendation is the USCG's input into this process and FERC is the final permitting authority. The draft Environmental Impact Statement will be put out for comment and FERC welcomes these comments (www.FERC.gov & docket #CP17-495-000).

I have made record of your comments. Please remember to include them and any additional comments when FERC issues their draft EIS. Also, please note that a limited access area (safety zone) has not yet been determined for this project and if drafted will be put out for public comment.

Respectfully,
LCDR L.M. Springer

From: Dunn, Brian/U.S. Coast Guard
Sent: Tuesday, May 15, 2018 12:16 PM
To: Jody McCaffree
Cc: Springer, Laura M LCDR/U.S. Coast Guard; Crowell, Ben W LCDR/U.S. Coast Guard
Subject: FW: [Non-DoD Source] FW: Connecting re Jordan Cove LNG Export Project

Ms. McCaffree,

The Coast Guard point of contact is LCDR Laura Springer at Marine Safety Unit Portland. I have copied her, so she will have the information you have provided. She can be reached by e-mail at [redacted] or by phone at [redacted].

Brian L. Dunn
US Coast Guard Bridge Program (CG-BRG)
[redacted]

From: Jody McCaffree
Sent: Monday, May 14, 2018 12:11 PM
To: Springer, Laura M LCDR/U.S. Coast Guard
Subject: FW: Connecting re Jordan Cove LNG Export Project
Attachments:
LNG Hazard Zones of Concern FEIS 4.7-3 Revised -3 (4).pdf (224KB);
029FERC_Exb32_Explosive-LNG-issues-grab-PHMSA-attent.pdf (621KB)

FYI…

From: Jody McCaffree
Sent: Monday, May 14, 2018 12:06 PM
To: Springer, Laura M LCDR/U.S. Coast Guard
Cc: Dunn, Brian/U.S. Coast Guard; Crowell, Ben W LCDR/U.S. Coast Guard; Jody McCaffree
Subject: FW: Connecting re Jordan Cove LNG Export Project
Attachments:
LNG Hazard Zones of Concern FEIS 4.7-3 Revised -3 (4).pdf (224KB);
029FERC_Exb32_Explosive-LNG-issues-grab-PHMSA-attent.pdf (621KB)

Please advise as to who is currently handling LNG hazards and the safety and security of the Jordan Cove LNG for the Coast Guard because I get tired of constantly sending this information over and over again only to be ignored.

Sincerely,

Jody McCaffree
PO Box 1113
North Bend, OR 97459
[redacted]

From: Jody McCaffree
Sent: Monday, May 14, 2018 11:10 AM
To: 'Laura.M.Springer@uscg.mil'
Subject: Complaint - Request for LNG Hazard contact person

Dear Lt. Cmdr. Laura Springer:

I just read your announcement regarding the Coos Bay being suitable for the Jordan Cove LNG project. This should be shocking news to the general public. We would like to know what you did with the July 1, 2008 Coast Guard assessment and how without any real changes to the Coos Bay channel you now are ignoring your prior recommendations for safety and security? Why is the Coast Guard ignoring the gas industries SIGTTO recommendations for the safe siting of LNG facilities? Why are you ignoring the FAA's May 7, 2018 thirteen (13) determinations of *Presumed Airport Hazards* with respect to the Jordan Cove Project? The FAA determined Jordan Cove's ships are a hazard but the Coast Guard has not? Amazing! Why would you place so many school children in harm's way in the Coos Bay area? Why would you put our airport at such risk?

Your recent announcement states that the Coast Guard received official notification January 9, 2017. That is not exactly true and the Coast Guard should offer a retraction. This project has been in the works since 2004. Jordan Cove submitted a Letter of Intent, pursuant to 33 C.F.R. § 127.007, and a Waterway Suitability Assessment ("WSA") for its original LNG import project in April 2006. The U.S. Coast Guard ("USCG") issued a Water Suitability Report on July 1, 2008, and provided a Letter of Recommendation on April 24, 2009. On December 28, 2012, JCEP submitted an amended and updated Letter of Intent to the USCG for the prior export project proposal under Docket No. CP13-483. On August 5, 2016, the USCG accepted the annual 2015 review of the WSA update as an LNG export project. Jordan Cove submitted the 2016 annual update of the WSA to the USCG on November 23, 2016.

I did my best to try to talk with Coast Guard personnel at Jordan Cove's latest round of Open Houses held on Tuesday, March 21, 2017 at the Mill Casino in North Bend. It was obvious from those conversations that the current Coast Guard personnel were not interested in what I had to say and for the most part were pretty much clueless about LNG hazards.

I suggest you include the general public and non-biased LNG hazard experts in with your consultations before you decide whether something is safe or not. We do not need another New Carissa fiasco like the Coast Guard created in 1999. Only this time it would be far, far worse.

I would like to know who is in charge of LNG hazards for the Coast Guard and where I might be able to file an official complaint. As a cooperating agency with the FERC you should really be paying attention to what has been filed under the current FERC dockets for Jordan Cove (CP17-495-000; CP17-494-000; and PF17-4-000)

I have asked to be notified concerning these matters in the past but to date I have yet to receive any notifications from the Coast Guard.

Sincerely,

Jody McCaffree
PO Box 1113
North Bend, OR 97459
[redacted]

From: Jody McCaffree
Sent: Monday, November 20, 2017 11:46 AM
To: Brian Dunn/U.S. Coast Guard
Cc: Crowell, Ben W LCDR/U.S. Coast Guard
Subject: Connecting re Jordan Cove LNG Export Project

To: Brian Dunn United States Coast Guard [redacted]

Dear Mr. Dunn:

I came across your contact information in a letter that the Federal Energy Regulatory Commission (FERC) sent out on October 12, 2017 under Accession No. 20171012-3062. I do not know if you are the Coast Guard personnel responsible for overseeing the safety and security of the Jordan Cove LNG export project or not but I am passing along the following information sent on the 18th to Lieutenant Commander Crowell. These issues along with others are critical and must be thoroughly addressed with respect to the proposed Jordan Cove LNG export project before that project is allowed to proceed.

I look forward to discussing these and other important matters with you.

Sincerely.

Jody McCaffree
PO Box 1113
North Bend, OR 97459
[redacted]

From: Jody McCaffree
Sent: Saturday, November 18, 2017 11:23 AM
To: Crowell, Ben W LCDR/U.S. Coast Guard
Subject: Connecting re Jordan Cove Charleston Fire Station Meeting

Dear Lieutenant Commander Crowell:

I connected with you yesterday at the Jordan Cove Charleston Fire Station meeting and presentation.

At yesterday's presentation, Peter Schaedel, Jordan Cove's marine director from their Houston Office, stated that the Coast Guard would be handling all the safety and security for LNG transits in and out of the Coos Bay, including safety along the shoreline. Several things that Mr. Schaedel stated were not true and I would like to be in communication with the current contact in the Coast Guard who is handling all the safety and security for the proposed Jordan Cove LNG vessel transits. There are safety concerns that need to be addressed before Jordan Cove is given the green light in any way.

According to a September 9, 2003 CRS Report for Congress titled, "*Liquefied Natural Gas (LNG) Infrastructure Security: Background and Issues for Congress*,"[1] by Paul W. Parfomak, Specialist in Science and Technology Resources, Science, and Industry Division:

Page CRS-17:

> *...The Coast Guard Program Office estimates that it currently costs the Coast Guard approximately $40,000 to $50,000 to "shepherd" an LNG tanker through a delivery to the Everett terminal, depending on the duration of the delivery, the nature of the security escort, and other factors.*[2] ***State and local authorities also incur costs for overtime police, fire and security personnel overseeing LNG tanker deliveries. The state of Massachusetts and the cities of Boston and Chelsea estimated they spent a combined $37,500 to safeguard the first LNG shipment to Everett after September 11, 2001.***[3] ***Based on these figures, the public cost of security for an LNG tanker shipment to Everett is on the order of $80,000, excluding costs incurred by the terminal owner****...*

On July 1, 2008, the Coast Guard completed a review of the Waterway Suitability Assessment (WSA) for the Jordan Cove Energy Project and **determined that the Coos Bay was not**

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[1] http://www.au.af.mil/au/awc/awcgate/crs/rl32073.pdf

[2] U.S. Coast Guard, Program Office. Personal communication. August 12, 2003. This estimate is based on boat, staff and administrative costs for an assumed 20-hour mission

[3] McElhenny, John. "State Says LNG Tanker Security Cost $20,500." Associated Press. November 2, 2001. p1.

currently suitable, but could be made suitable for the type and frequency of LNG marine traffic associated with the LNG project. Coast Guard mitigation measures included **limiting the LNG carrier to the physical dimensions of a 148,000 m3 class vessel.** The ship dimension used in the study reflected an overall length of 950 feet and a beam of 150 feet with a loaded draft of 40 feet. (*See WSA Report*)

The Coast guard determined that the channel must demonstrate sufficient adequacy to receive LNG carriers for any single dimension listed. The Coos Bay is only dredged to 37 feet currently. LNG ships would transit the bay during high slack tides, the same tides used by the fishing fleet.

The Coast Guard established a Safety/Security Zone for LNG vessels both while the vessel is moored and even when the vessel is not moored. When the LNG vessel is at the docking facility there would be a 150 yard security zone around the vessel to include the entire terminal slip and when there is no LNG vessel moored, the security zone would cover the entire terminal slip and extend 25-yards in the waterway. (CG-WSA page 2) In addition, the Coast Guard has also set a moving safety/security zone for the LNG tanker ship that extends 500-yards around the vessel but ends at the shoreline. **No vessel may enter the safety / security zone without first obtaining permission from the Coast Guard Captain of the Port.** [4] <u>This safety and security zone would encompass the entire bay in some areas.</u>

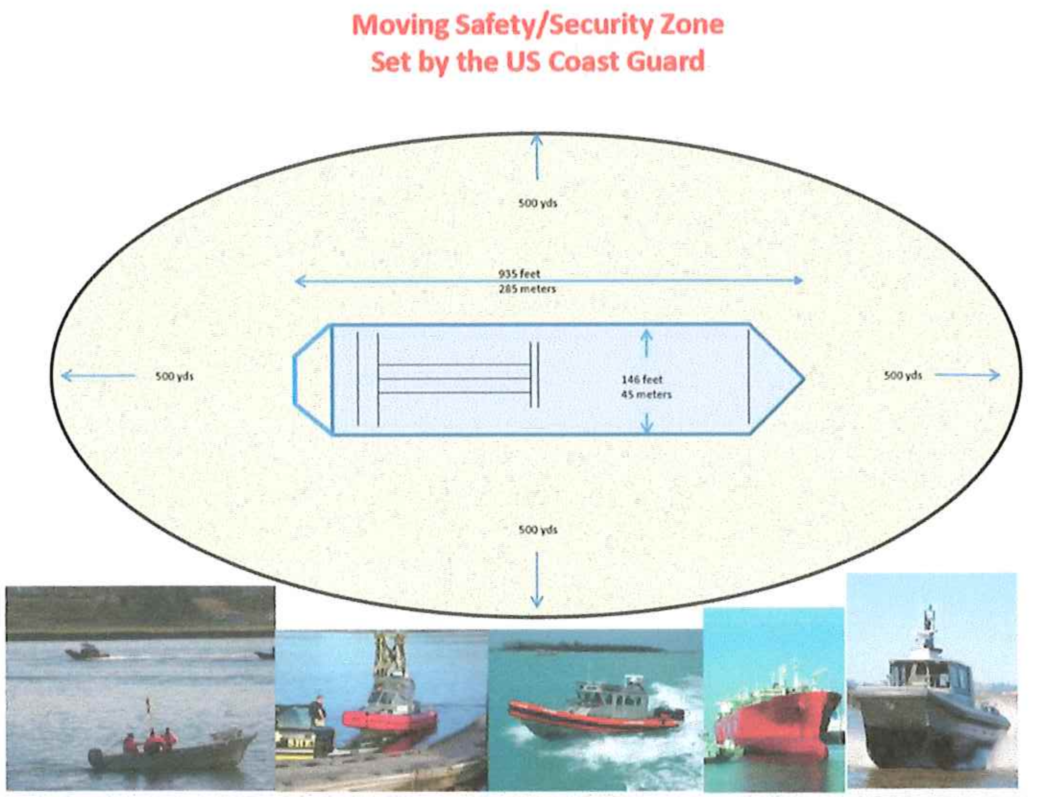

Diagram above from Jordan Cove March 2012 Open House

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[4] Coast Guard - LOR / WSR / WSA for Port of Coos Bay / Jordan Cove Energy Project: https://homeport.uscg.mil/mycg/portal/ep/contentView.do?contentTypeId=2&contentId=63626&programId=12590&%20pageTypeId=16440&BV

JORDAN COVE LNG EXPORT VOLUMES

The proposed Jordan Cove Energy Project applied (Sept 21, 2017) to the Federal Energy Regulatory Commission (FERC) to export 7.8 million metric tons of LNG. This amounts to around 1 Bcf/d of exported natural gas.

However, Jordan Cove has publicly stated that they plan on increasing that volume to 9 million metric tons of LNG. This amounts to around 1.2 Bcf/d of exported natural gas.

Jordan Cove has approvals from the Canadian National Energy Board (NEB) to "export" 1.55 Bcf/d of natural gas and from the U.S. Dept of Energy (DOE) to "import" this volume from Canada.

Even though the U.S DOE has approved Jordan Cove importing 1.55 Bcf/d of gas from Canada (11.6 million metric tons LNG per year), the U.S. DOE has **only given Jordan Cove permission to export 1.2 Bcf/d of gas to Free Trade Agreement Nations (9 million metric tons LNG per year)** and .8 Bcf/d of that 1.2 Bcf/d has been approved to go to Non-Free Trade agreement nations IF JORDAN COVE IS ABLE TO COMPLY WITH ALL THE CONDITIONAL REQUIREMENTS FOUND IN DOE ORDER 3413. So far that has not happened, so they don't have approval yet to export to Non-Free Trade Agreement Nations.

Below is how this volume of LNG being exported from Coos Bay calculates out with respect to potential harbor shipping disruptions.

Jordan Cove states in their Resource Report #1 Page 13:

> *The number of ship calls at the LNG vessel berth* ***has increased to 110 to 120. This number was previously 90 to 100.***

Once again, Jordan Cove has deliberately underestimated their LNG shipping impacts. See calculations below:

Calculating 148,000 cubic meter LNG ship at –
600 to 1 conversion from Natural Gas and determining how many shipments that would mean is below:

148,000 cubic meters LNG ship = 5,226,570.675 cubic feet of LNG

5,226,570.675 X **600** = 3,135,942,405 cubic feet of natural gas per shipment

7.8 million metric tons of LNG yearly = 379.86 billion cubic feet of NG (7.8 X 48.7)
(1 million metric tons LNG = 48.7 billion cubic feet NG
(https://www.extension.iastate.edu/agdm/wholefarm/html/c6-89.html)

379,860,000,000 cubic feet of gas yearly shipped by JCEP :/: 3,135,942,405 cubic feet of gas per shipload = **121 shipments needed per year which = 242 harbor disruptions at high slack tide**

due to shipping impacts involving the LNG vessel both coming in and going out of the harbor.

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9 million metric tons of LNG yearly = 438.3 billion cubic feet of NG (9 X 48.7)
(1 million metric tons LNG = 48.7 billion cubic feet NG
(https://www.extension.iastate.edu/agdm/wholefarm/html/c6-89.html)

438,300,000,000 cubic feet of gas yearly shipped by JCEP :/: 3,135,942,405 cubic feet of gas per shipload = **139.76 shipments needed per year which = 279.52 harbor disruptions at high slack tide due to shipping impacts involving the LNG vessel both coming in and going out of the harbor.**

This is considerably higher than Jordan Cove's 110 to 120 shipments that are stated in their recent Resource Report #1 (page 13) that has been filed with the FERC.

If Jordan Cove was to export the entire 1.55 Bcf/d of LNG from Canada it would amount to the following harbor disruptions.

1.55 Bcf/d X 365 days in a year = 565.75 Bcf/year of exported gas

565,750,000,000 cubic feet of gas yearly shipped by JCEP :/: 3,135,942,405 cubic feet of gas per shipload = **180 shipments needed per year which = 360 harbor disruptions at high slack tide due to shipping impacts involving the LNG vessel both coming in and going out of the harbor.**

SAFETY GUIDELINES

One of the reasons there is such as good safety record involving LNG Carriers worldwide is due to the fact that the current Ports in operation have developed their docking facilities for these LNG terminals strictly following the guidelines laid out by the *Society of International Gas Tanker & Terminal Operators* (SIGTTO)[5].

Examples of SIGTTO guidelines not addressed adequately include:

1) **Approach Channels. Harbor channels should be of uniform cross-sectional depth and have a minimum width, equal to five time the beam of the largest ship**
2) **Turning Circles. Turning circles should have a minimum diameter of twice the overall length of the largest ship, where current effect is minimal. Where turning circles are located in areas of current, diameters should be increased by the anticipated drift.**
3) **Tug Power. Available tug power, expressed in terms of effective bollard pull, should be sufficient to overcome the maximum wind force generated on the largest ship using the terminal, under the maximum wind speed**

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[5] **Site Selection & Design for LNG Ports & Jetties – Information Paper No. 14 -** Published by *Society of International Gas Tanker $ Terminal Operators Ltd* / 1997

permitted for harbor maneuvers and with the LNG carrier's engines out of action.

4) **Site selection process should remove as many risks as possible by placing LNG terminals in sheltered locations remote from other port users. Suggest port designers construct jetties handling hazardous cargoes in remote areas where ships do not pose a (collision) risk and where any gas escaped cannot affect local populations. Site selection should limit the risk of ship strikings, limiting interactive effects from passing ships and reducing the risk of dynamic wave forces within mooring lines.**
5) **Building the LNG terminal on the outside of a river bend is considered unsuitable due to fact that a passing ship may strike the berthed carrier if the maneuver is not properly executed.**
6) **SIGTTO Examples given for reducing risk factors beyond normal operations of ship/shore interface include LNG terminal patrols of the perimeter of the offshore safety zones with guard boats and to declare the air-space over an LNG terminal as being a restricted zone where no aircraft is allowed to fly without written permission.**
7) **Restriction of the speed of large ships passing close to berthed LNG carriers.**

Also some of the safety guideline preventative measures found in the Sandi National Laboratories Report – "*Guidance on Risk Analysis and Safety Implications of Large Liquefied Natural Gas (LNG) Spill Over Water*" – Dec 04:

Guidelines (Pg 64) include: [6]

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

On January 14, 2015, and February 6, 2015, Jerry Havens, Distinguished Professor of Chemical Engineering at University of Arkansas, and James Venart, Professor Emeritus of Mechanical Engineering at University of New Brunswick, published two papers regarding the Jordan Cove LNG Export Terminal Draft Environmental Impact Statement under FERC Docket No. CP13-483. **Professor Havens and Professor Venart found significant discrepancies and problems with Jordan Cove's hazard analysis for their LNG Export facility and determined the hazards had been significantly underestimated.** Safety measures incorporated into the proposed Jordan Cove former LNG Export terminal actually increased the chance of a catastrophic failure and presented a far more serious public safety hazard than regulators had

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[6] Without an emergency response plan to review it is hard to know if some of these recommendations have been met. At the FERC hearing held in Coos Bay on December 8, 2014, U.S. Coast Guard Captain of the Port stated that the Coast Guard has "***no intention to close the waterway during LNG shipments.***"

analyzed and deemed acceptable. Adding liquefaction equipment to proposed LNG Import terminals increases the hazard risks of these facilities as these documents explain.

Copies of 1-14-2015 and 2-6-2015 filings submitted to FERC by Professor Havens and Professor Venart can be linked to here:

- 1-14-2015 - Jerry Havens Ph.D and James Venart Ph.D under CP13-483 http://elibraryFERC.gov/idmws/file_list.asp?accession_num=20150114-5038
- 2-6-2015 - Supplementary Comment with Questions by Jerry Havens Ph.D and James Venart Ph.D under CP13-483. http://elibraryFERC.gov/idmws/file_list.asp?accession_num=20150206-5040

I have provided links below to some of the publications that these two professors have published. These are high level professionals in the area of Chemical Engineering and Chemical Hazards, just in case you may not be familiar with their work.

Published Research work of Jerry Havens University of Arkansas - Department of Engineering
http://www.researchgate.net/profile/Jerry_Havens

Published Research work of James E.S. Venart - University of New Brunswick - Department of Mechanical Engineering
http://www.researchgate.net/profile/James_Venart

In their Feb 6, 2015, filing to the FERC, Professor Havens and Professor Venart asked specific questions of the FERC. **THOSE QUESTIONS HAVE YET TO BE ANSWERED.** The FERC, the U.S. Department of Transportation and the Coast Guard need to make sure those questions are answered adequately and scientifically. Thousands of people living in the Coos Bay area depend on it.

LNG VESSEL HAZARDS

It is all spelled out in the scientific literature that if a LNG tanker ship was to be breached and only 1/2 of one of the (4 to 5) LNG tanks (or 3 to 4 million gallons of LNG) was to leak out into the water and a pool fire was to develop, people up to a mile away would be at risk of receiving 2nd degree burns in 30 seconds. **This is because heat flux levels of 5kW/m2 would go out as far as a mile away from the fire.** If the Jordan Cove LNG Export Project was to actually make it through permitting and be built, 16,922 people would live in the Jordan Cove LNG hazard zones of concern according to the Jordan Cove former Import FERC EIS (Page 4.7-3) and also the former Export Draft EIS (Page 4-980). The former Jordan Cove LNG Export Draft EIS page 4-7 states:

> *The waterway for LNG vessel marine traffic would traverse 7.5 miles of the existing navigation channel within Coos Bay. The navigation channel is zoned "Deep-Draft Navigation Channel." in the CBEMP. The navigation channel, which is generally 300-feet-wide and 37-feet-deep, is maintained by the COE on behalf of the Port.*

LNG tankers with up to a 40 foot draft would exit our narrow Bay carrying around 39 million gallons of LNG but there is little concern given for our safety by local officials. Both the cities of North Bend and Coos Bay have signed agreements indemnifying Jordan Cove should there be an LNG accident. The City of North Bend has also passed a Resolution and written letters of support for the Project prior to the completion of the NEPA process and also prior to Final Decisions being made on Jordan Cove's Land Use Permits. Coos County Commissioner John Sweet has also done the same.

Jordan Cove's FERC former Draft Export EIS Page 2-76 states:

> *LNG to be exported from the Jordan Cove terminal to overseas markets would be transported in vessels specially designed and built for that task. Jordan Cove expects that its terminal would be visited by about 90 LNG vessels per year. These vessels would be loaded with LNG at the terminal and deliver the cargo to customers, most likely around the Pacific Rim.* ***LNG vessels would be under the ownership and control of third-parties, not Jordan Cove****, and* ***would not be regulated by the FERC.*** (Emphasis added)

This is not acceptable as it places our entire area at an extreme hazard risk and liability.

Structures close to an LNG pool fire, should one develop, could actually self-ignite from the high heat flux levels. This is not my words but comes directly from the December 2004 Sandia Report, ***"Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water."*** [7] The large hazardous burn zones associated with these LNG faculties are also confirmed by other Government and independent studies as well. [8] In 2005 the Port of Long Beach and the California Public Utilities Commission had an analysis done entitled, "*An Assessment of the Potential Hazards to the Public Associated with Siting an LNG Import Terminal in the Port of Long Beach.*" [9] The analysis resulted in the Port of Long Beach no longer approving the proposed LNG facility.

LNG tankers would transit only 6/10ths of a mile from children attending Sunset and Madison schools. The tankers and cargo ships would transit within 1,350 feet of the shoreline areas of the community of Empire, 2,150 feet of the shoreline areas of the community of Barview, 1,900 to 2,300 feet of the Charleston breakwater, and 2,100 to 3,100 feet of the North Bend Airport. This is well within the LNG hazard zone distances that have been established by the many government and scientific reports.

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[7] "*Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water.*"

[8] United States Government Accountability Office, Report to Congressional Requesters, Maritime Security; "*Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification*", February 2007; GAO-07-316: http://www.gao.gov/new.items/d07316.pdf

U.S. Department of Energy report to Congress, "*Liquefied Natural Gas Safety Research*" ; May 2012 : http://energy.gov/sites/prod/files/2013/03/f0/DOE_LNG_Safety_Research_Report_To_Congre.pdf [NOTE: Based on the data collected from the large-scale LNG pool fire tests conducted, thermal (fire) hazard distances to the public from a large LNG pool fire will decrease by at least 2 to 7 percent compared to results obtained from previous studies. In spite of this slight decrease, people up to a mile away are still at risk of receiving 2nd degree burns in 30 seconds should a LNG pool fire develop due to a medium to large scale LNG breach event.

[9] "*An Assessment of the Potential Hazards to the Public Associated with Siting an LNG Import Terminal in the Port of Long Beach*" By Dr. Jerry Havens, September 14, 2005 - http://www.ecosakh.ru/data/im_docs_62_ocenka_ugroz_v_svyazi_s_razmescheniem_SPG%28angl.yaz.%29.pdf

I am sure the Coast Guard is well aware of these hazard issues, but as resident who would be living in one of these proposed LNG hazard zones, I wanted to confirm this and encourage the Coast Guard to take ALL the measures that are absolutely necessary to ensure our safety. Our tax dollars should not have to pay for these proposed safety measures either. This should be Jordan Cove's responsibility.

Sincerely,

Jody McCaffree
Po Box 1113
North Bend, OR 97459
[redacted]

REFERENCES

[1] http://www.au.af.mil/au/awc/awcgate/crs/rl32073.pdf

[2] U.S. Coast Guard, Program Office. Personal communication. August 12, 2003. This estimate is based on boat, staff and administrative costs for an assumed 20-hour mission

[3] McElhenny, John. "State Says LNG Tanker Security Cost $20,500." Associated Press. November 2, 2001. p1.

[4] Coast Guard - LOR / WSR / WSA for Port of Coos Bay / Jordan Cove Energy Project: https://homeport.uscg.mil/mycg/portal/ep/contentView.do?contentTypeId=2&contentId=63626&programId=12590&%20pageTypeId=16440&BV

[5] **Site Selection & Design for LNG Ports & Jetties – Information Paper No. 14** - Published by *Society of International Gas Tanker $ Terminal Operators Ltd* / 1997

[6] Without an emergency response plan to review it is hard to know if some of these recommendations have been met. At the FERC hearing held in Coos Bay on December 8, 2014, U.S. Coast Guard Captain of the Port stated that the Coast Guard has "***no intention to close the waterway during LNG shipments.***"

[7] "*Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water.*"

[8] United States Government Accountability Office, Report to Congressional Requesters, Maritime Security; "*Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification*", February 2007; GAO-07-316: http://www.gao.gov/new.items/d07316.pdf

U.S. Department of Energy report to Congress, "*Liquefied Natural Gas Safety Research*" ; May 2012 : http://energy.gov/sites/prod/files/2013/03/f0/DOE_LNG_Safety_Research_Report_To_Congre.pdf [NOTE: Based on the data collected from the large-scale LNG pool fire tests conducted, thermal (fire) hazard distances to the public from a large LNG pool fire will decrease by at least 2 to 7 percent compared to results obtained from previous studies. In spite of this slight decrease, people up to a mile away are still at risk of receiving 2nd degree burns in 30 seconds should a LNG pool fire develop due to a medium to large scale LNG breach event.

[9] *"An Assessment of the Potential Hazards to the Public Associated with Siting an LNG Import Terminal in the Port of Long Beach"* By Dr. Jerry Havens, September 14, 2005 - http://www.ecosakh.ru/data/im_docs_62_ocenka_ugroz_v_svyazi_s_razmescheniem_SPG%28angl.yaz.%29.pdf

Jordan Cove LNG Tanker Hazard Zones (FEIS Page 4.7-3)

Zone 1 (yellow) - No one is expected to survive in this zone. Structures will self ignite just from the heat.
Zone 2 (green) - People will be at risk of receiving 2nd degree burns in 30 seconds on exposed skin in this zone.
Zone 3 (blue) - People are still at risk of burns if they don't seek shelter but exposure time is longer than in Zone 2.
Map does not include the hazard zones for the South Dunes Power Plant and the Pacific Connector Gas Pipeline.

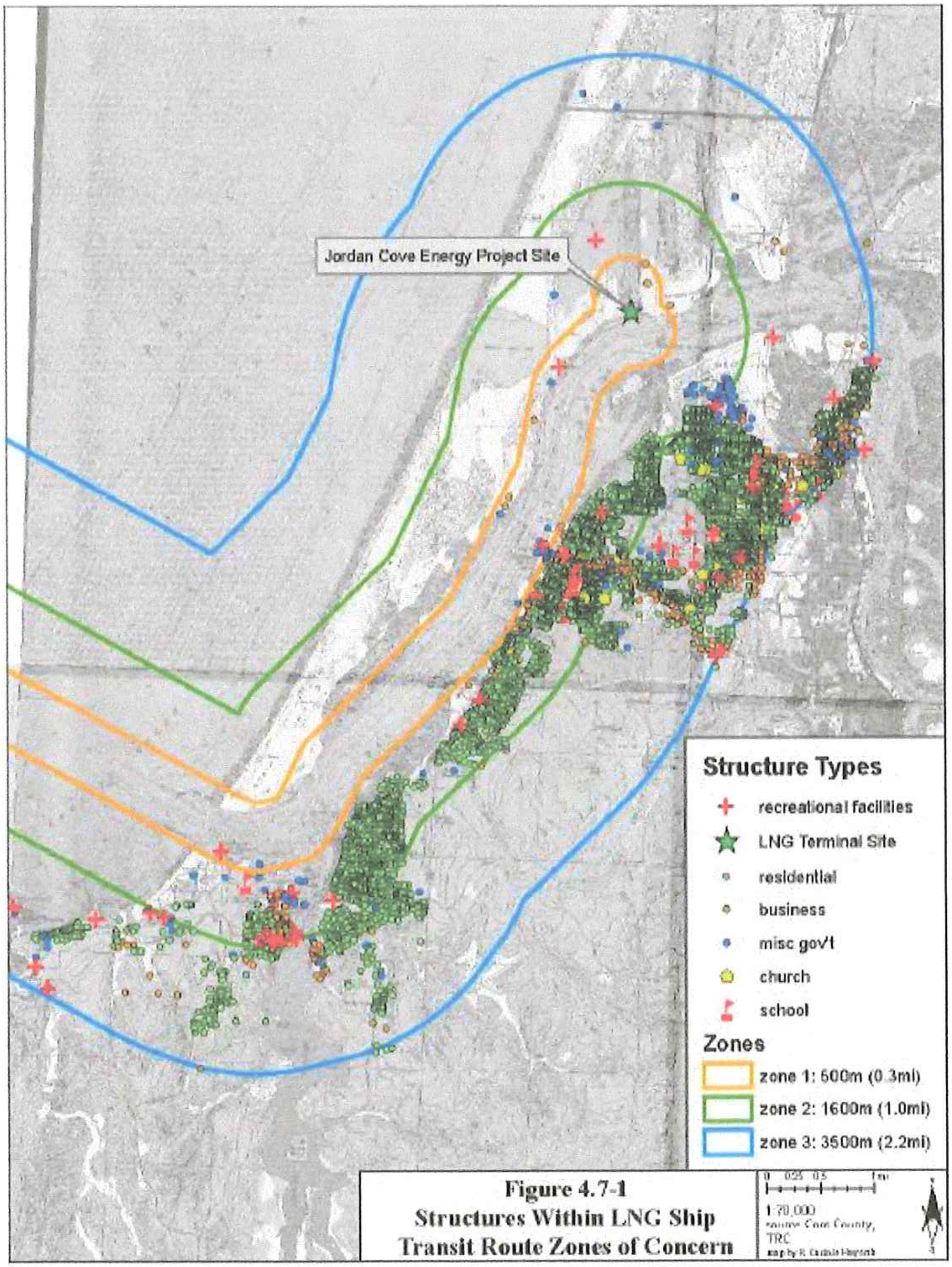

Figure 4.7-1
Structures Within LNG Ship Transit Route Zones of Concern

source Coos County, TRC

NATURAL GAS:
Explosive LNG issues grab PHMSA's attention

Jenny Mandel, E&E reporter

EnergyWire: Tuesday, June 7, 2016

Smoke pours from petroleum storage tanks following a 2009 explosion at the Caribbean Petroleum Corp. refinery in San Juan, Puerto Rico. The blast and fire damaged 17 of the 48 tanks at the site, and flames burned for nearly 60 hours. Photo courtesy of the U.S. Chemical Safety and Hazard Investigation Board.

The Department of Transportation's May 19 workshop on liquefied natural gas (LNG) safety started with a bang.

At DOT's headquarters in Washington, D.C., the agency's Pipeline and Hazardous Materials Safety Administration (PHMSA) hosted an in-depth discussion of what went wrong during a March 2014 explosion at an LNG facility in Plymouth, Wash., that led to five injuries and $72 million in property damage (*EnergyWire*, May 6).

The decision by PHMSA to conduct a broad review of its LNG safety rules -- and kick it off with an unusually open discussion of a fiery accident -- suggests the agency has taken to heart the saltiest criticisms tossed from Capitol Hill. "PHMSA is not only a toothless tiger, but one that has overdosed on Quaaludes and is passed out on the job," Rep. Jackie Speier, a Democrat from San Francisco, said during a congressional hearing in April 2015.

She pointed to the lethal and destructive natural gas pipeline accident in San Bruno, Calif., in 2010. In its aftermath, PHMSA came under fire for being slow to update its safety regulations. Late last year, a leaking Aliso Canyon underground gas storage facility outside Los Angeles, operated by Southern California Gas Co., prompted hand-wringing that regulators were underprepared.

If gas pipelines and storage fields come with risk, researchers are increasingly concerned that the expanding footprint of big LNG export terminals and other facilities along the U.S. coast are also potentially deadly.

LNG is jam-packed with energy. Natural gas is turned into a liquid by supercooling it to minus 260 degrees Fahrenheit, which shrinks its volume 600-fold and makes it easier to transport across the ocean.

Natural gas and its liquid form are flammable and explosive in confined spaces, but researchers say it's not prone to exploding when released in large, open areas. That's not the case for other heavy hydrocarbons such as propane and ethane, which can be stored at large LNG export facilities.

The concern among researchers and regulators grappling with how to regulate LNG safety is the potentially deadly mix of liquid fuels at an LNG site.

Things that go boom

At the DOT workshop last month, a presentation by Graham Atkinson, a principal scientist in the Major Hazards Unit of the Health and Safety Lab in Buxton, England, focused on what happens when heavy hydrocarbons explode.

The audience listened, riveted, as Atkinson showed photos -- some not previously seen by the public -- from industrial accidents linked to liquefied petroleum gas (LPG), LNG, gasoline and other petrochemicals.

Four of the incidents took place within the last decade and were explosions of so-called unconfined vapor clouds that led to a series of cascading events that ultimately destroyed the facilities.

Researchers looked at 24 vapor cloud explosions but focused their attention on four major industrial accidents -- at gasoline storage sites in Buncefield, England, in 2005; Jaipur, India, in 2009; San Juan, Puerto Rico, in 2009; and at an LPG storage site at Venezuela's Amuay refinery in 2012.

In work funded by PHMSA through a contract with the Energy Department's Oak Ridge National Laboratory, Atkinson's team reviewed photos and videos from the accidents and conducted tests with gasoline in a range of spill conditions. The team focused on how vapor clouds form in low wind conditions and when barriers keep gases from fully dispersing.

Atkinson said an accident can happen under two conditions. One is a small leak that, after as little as 15 minutes with no wind, can cause a massive explosion that resembles a bomb blast with no epicenter. Devastation is spread evenly across the range of the vapor cloud.

An unconfined vapor cloud explosion at a gasoline storage site in Buncefield, England, in 2005 left bomblike devastation across a wide area. Photo courtesy of the U.K. Health and Safety Laboratory.

The other accident scenario is a large leak on a windy day, when cloud dispersion from the wind cannot keep up with the volume of gas released. That, too, creates a cloud-sized explosion zone. The shape of the plume can be mapped from the destruction.

Pictures from San Juan, Buncefield, Amuay and Jaipur show cars twisted and burned, bombed-out buildings, and flaming storage tanks.

"Fuel tanks are efficiently set on fire in the area covered by the vapor cloud," Atkinson noted, estimating that 95 percent of tanks exposed to the vapor clouds were set on fire. "It means it's a real tough job for all the emergency services. They're dealing with [potentially] 20 tanks set on fire. It's an almost unmanageable situation."

The researchers also looked at cases in which flash fires turned into explosions, finding that in some cases a confined space or a congested intersection of piping turned a fire into a blast.

"In all but one of the incidents reviewed, when a very large cloud was formed, there was a severe explosion," Atkinson said.

In low wind conditions, vapor clouds that accumulated from small, sustained leaks caused blast damage and fatalities 765 yards -- nearly half a mile -- or more from the source.

And if a large cloud of gasoline or LPG accumulates, a "severe explosion" is likely, Atkinson said.

'20 minutes'

After Atkinson spoke, a leader in the LNG industry quickly tried to wrestle control of the discussion, emphasizing that LNG doesn't carry the same risks as the non-methane fuels he had focused on.

Cheniere Energy Inc. is developing the Sabine Pass LNG export terminal in Cameron Parish, La. The terminal already has one processing train up and running to liquefy LNG, and construction plans include four more; the plant is the first modern LNG export facility in the United States (*EnergyWire*, May 3).

Pat Outtrim, vice president of government affairs for Cheniere, questioned Atkinson on his presentation in a rapid-fire series of yes-or-no questions.

Atkinson agreed with Outtrim that the heavy hydrocarbons tested have different properties from methane, and that the alert and emergency shutdown equipment at the facilities studied were absent, nonfunctioning or not able to alert the right people quickly.

But he disagreed with the notion that his results aren't applicable to LNG facilities.

Ethane blends, propane, isobutane and ethylene, as well as hundreds of metric tons of condensates like pentanes and hexanes, might be present at an LNG export site. The explosion research "shows just how important the detection and response protocols are," Atkinson told Outtrim. Vapor cloud explosions like those demonstrated "can't happen at an LNG facility if you detect [a leak] early and shut it down right away," he said.

The takeaway for the LNG industry should include consideration of automatic equipment shut-offs, Atkinson told *EnergyWire*.

"Twenty minutes can be enough to cause a problem," he said. If equipment shut-offs are manual, the staff needs to be well-trained. If sensors indicate a leak, "the response can't be, 'Oh, I need to go tighten it up.'"

"Problems tend to come from people. There are just so many cases where [warning lights] start flashing and people just go to pieces," he said.

One more challenge? Explosion events often occur at night, when wind speeds slow as the air cools. So plant personnel can go from keeping watch over a sleepy facility in the small, dark hours to a rapidly evolving emergency.

"When they decide what's sensible to automate, they ought to think about these factors and take it into account," Atkinson said.

The new LNG era

Still, automated controls are probably not the big worry that set PHMSA down the path of researching old accidents -- especially since many of a plant's most important controls have physical fail-safe mechanisms in case the electronics fail.

So why did PHMSA dedicate so much time to discussion of the hazards tied to gasoline, LPG and other hydrocarbons that are afterthoughts at most LNG installations?

A critique by two longtime LNG researchers offers some insight.

Jerry Havens and James Venart submitted public comments to the Federal Energy Regulatory Commission in January 2015 on a proposal to build the Jordan Cove LNG terminal in Coos Bay, Ore.

Havens has worked on LNG safety issues throughout his 40-year career and authored two of the computer models whose use was long required by federal regulators to assess the hazards of proposed LNG facilities. Venart was the longtime director of the Fire Science Centre at the University of New Brunswick in Canada, and studied industrial heat exchange and catastrophic explosions.

The Jordan Cove project proposed a liquefaction plant capable of processing up to 6.8 million metric tons per year of natural gas.

Havens and Venart said they were concerned that regulations governing LNG import terminals had been guided by the premise that LNG, as methane, poses less danger than other gas liquids and petroleum fuels. But with LNG export terminals designed and constructed under regulations used for simpler LNG import facilities, Havens and Venart warned that regulators were overlooking dangers.

A 2009 vapor cloud explosion and ensuing fire at an Indian Oil Corp. facility in Jaipur, India, destroyed the plant and damaged homes more than a mile away, according to an investigation report. Photo courtesy of the U.K. Health and Safety Laboratory.

"We believe the [Jordan Cove draft environmental impact statement] fails to provide for protection of the public from credible fire and explosion hazards," the researchers said.

The mix of refrigerants used to chill the gas and the heavy hydrocarbon impurities in pipeline gas that are stripped out and stored on-site pose a threat, they said.

"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," Havens and Venart said.

The researchers also raised concerns that Jordan Cove and other proposed facilities would use concrete "vapor walls" to trap a gas cloud on the property and keep the fire hazards from breaching the property lines. But such walls would cause methane and other gases to build up into concentrated vapor clouds several meters deep, increasing the explosion risk.

With densely packed processing equipment on the site and a vapor fence trapping hydrocarbons, "one could hardly design the releases to better maximize the potential for catastrophic explosion hazard," Havens and Venart added.

FERC finalized Jordan Cove's EIS in September. It made no mention of Havens and Venart's comments.

Michael Hinrichs, a spokesman for the Jordan Cove project, noted in an email that "dispersion modeling, safety and security were all thoroughly analyzed and accepted by the FERC, [the Department of Transportation] and PHMSA to be within compliance." The three agencies, he said, "have all upheld the current modeling as meeting the safety criteria for the industry."

The Jordan Cove project's fate has since been thrown up in the air by an unexpected FERC decision to reject the project despite the favorable review by agency staff, pointing to a lack of firm contracts for LNG off-take (*EnergyWire*, April 19).

But Havens continues to be concerned. In a paper at the Health and Safety Laboratory -- where researcher Atkinson works -- in April, he argued that regulators are "doing it wrong" when it comes to gauging the explosion hazards of large hydrocarbon clouds.

Havens said PHMSA may be relying on the wrong computer models to assess explosion risks. Most of its results are classified for security reasons.

Divided responsibilities

At the workshop in May, Kenneth Lee, who directs PHMSA's engineering and research division within the Office of Pipeline Safety, declined to say what specific regulatory changes are on the table for an upcoming overhaul of the LNG rulebook, or even what the key questions are, deferring to public input from the meeting to shape the process (*EnergyWire*, May 20).

But the workshop itself, in providing a platform to discuss heavy hydrocarbon risks, points to the potential for new requirements for LNG export facilities. How those requirements might be designed remains to be seen.

Industry has welcomed small tweaks to PHMSA's rules that would bring them up to date, more easily encompass new technologies and be more in line with standards used by regulators in other jurisdictions. But any changes that added new hurdles to the process of siting LNG facilities -- which primarily falls under FERC jurisdiction -- could face opposition from developers. They could raise difficult questions about Sabine Pass LNG and the four other LNG export terminals under construction.

For its part, PHMSA pledges that the coming rulemaking process will be transparent. "We take comments that you submit very seriously," said Julie Halliday, a member of the agency's engineering and research division who coordinated much of the meeting, in a discussion of the next steps. "We will address those points that you submit."

Still, she noted that PHMSA's authority over LNG facility siting is limited. "We don't actually have authority for siting within our regulations," she said, describing the agency's role in that process as working out the public safety "exclusion zones" that extend around the core of the facility.

"It's about a setback. It's not telling you whether you can site a facility at a certain location," she added, noting that other agencies control that question. "If FERC doesn't have jurisdiction to site a facility, it's the local jurisdiction."

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Exhibit 5

United States Government Accountability Office

GAO

Report to Congressional Requesters

February 2007

MARITIME SECURITY

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

GAO

Accountability * Integrity * Reliability

GAO-07-316

GAO
Accountability·Integrity·Reliability
Highlights

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

Why GAO Did This Study

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

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

What GAO Recommends

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

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

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

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

February 2007

MARITIME SECURITY

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

What GAO Found

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

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

LNG Tanker Passing Downtown Boston on Its Way to Port

Source: GAO.

Exhibit 6

U.S. DEPARTMENT OF
ENERGY

Liquefied Natural Gas Safety Research

Report to Congress
May 2012

United States Department of Energy
Washington, DC 20585

Message from the Assistant Secretary for Fossil Energy

The Explanatory Statement accompanying the Consolidated Appropriations Act, 2008[1] and the House Report on the House of Representatives version of the related bill[2] requested the Department of Energy to submit a report to Congress addressing several key liquefied natural gas (LNG) research priorities. These issues are identified in the February 2007 Government Accountability Office Report (GAO Report 07-316), *Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification*.

In response to this request, the Department of Energy tasked Sandia National Laboratories (SNL) with expanding the scope of the Department's LNG safety research program to address the research priorities identified in GAO Report 07-316. To accomplish this, SNL performed LNG field research and testing and conducted advanced computational modeling, simulation, and analyses over a three year period from May 2008 through May 2011. This report contains the findings, results, and conclusions of this research.

I am pleased to submit the enclosed report entitled, *Liquefied Natural Gas Safety Research Report to Congress*. The report was prepared by the Department of Energy's Office of Fossil Energy and summarizes the progress being made in this important area of research. This report is being provided to the following Members of Congress:

- **The Honorable Joseph R. Biden, Jr.**
  President of the Senate
- **The Honorable John Boehner**
  Speaker of the House of Representatives
- **The Honorable Daniel K. Inouye**
  Chairman, Senate Committee on Appropriations
- **The Honorable Thad Cochran**
  Vice Chairman, Senate Committee on Appropriations
- **The Honorable Dianne Feinstein**
  Chairman, Senate Subcommittee on Energy and Water Development
  Committee on Appropriations
- **The Honorable Lamar Alexander**

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[1] Explanatory Statement accompanying Public Law 110-161 (Dec. 26, 2007) at page 570.

[2] H.Rept. 110-185 accompanying Energy and Water Development Appropriations Bill, 2008 (H.R. 2641) at page 73.

Ranking Member, Senate Subcommittee on Energy and Water Development
Committee on Appropriations

- **The Honorable Harold Rogers**
  Chairman, House Committee on Appropriations
- **The Honorable Norm Dicks**
  Ranking Member, House Committee on Appropriations
- **The Honorable Rodney P. Frelinghuysen**
  Chairman, House Subcommittee on Energy and Water Development
  Committee on Appropriations
- **The Honorable Pete Visclosky**
  Ranking Member, House Subcommittee on Energy and Water Development
  Committee on Appropriations

If you need additional information, please contact me or Mr. Jeff Lane, Assistant Secretary, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Charles D. McConnell

Executive Summary

The February 2007 Government Accountability Office Report (GAO Report 07-316), *Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification*, identified several key Liquefied Natural Gas (LNG) research priorities highlighted by a GAO-convened panel of experts on LNG safety in order to provide the most comprehensive and accurate information for assessing the public safety risks posed by LNG tankers transiting to LNG facilities. To address these issues, Congress provided funding to the Department of Energy (DOE) to expand their LNG safety research program to focus on the major LNG research priorities contained in the GAO report. Sandia National Laboratories (SNL) supported the DOE in this effort starting May 2008 through May 2011 by conducting a series of large-scale LNG fire and cryogenic damage tests, as well as detailed, high performance computer models and simulations of LNG vessel damage resulting from large LNG spills and fires on water.

The key findings from these efforts include the following:

- For the large breach and spill events considered, as much as 40 percent of the LNG spilled from the LNG vessel's cargo tank is likely to remain within an LNG vessel's structure, leading to extensive cryogenic fracturing and damage to the LNG vessel's structural steel. In addition to the cryogenic damage, the heat fluxes expected from an LNG pool fire would severely degrade the structural strength of the inner and outer hulls of an LNG vessel. The extent of the cryogenic and fire damage on an LNG vessel resulting from large spills and associated pool fires would significantly impact the LNG vessel's structural integrity, causing the vessel to be disabled, severely damaged, and at risk of sinking.
- Current LNG vessel and cargo tank design, materials, and construction practices are such that simultaneous, multi-cargo tank cascading damage spill scenarios are extremely unlikely, though sequential multi-cargo tank cascading damage spill scenarios may be possible. Should sequential cargo tank spills occur, they are not expected to increase the hazard distances resulting from an initial spill and pool fire; however, they could increase the duration of the fire hazards.
- Based on the data collected from the large-scale LNG pool fire tests conducted, thermal (fire) hazard distances to the public from large LNG pool fires will decrease by at least two to seven percent compared to results obtained from previous studies.
- Risk management strategies to reduce potential LNG vessel vulnerability and damage from breach events that can result in large spills and fires should be considered for implementation as a means to eliminate or reduce both short-term and long-term impacts on public safety, energy security and reliability, and harbor and waterways commerce. Approaches to be considered should include implementation of enhanced operational security measures, review of port operational contingency plans, review of emergency response coordination and procedures, and review of LNG vessel design, equipment and operational protocols for improved fire protection.

LIQUEFIED NATURAL GAS SAFETY RESEARCH

Table of Contents

I. Legislative Language

This report responds to legislative language set forth in the Explanatory Statement accompanying the Consolidated Appropriations Act, 2008 (2008 Act)[3] and the House Report on the House of Representatives version of the related bill[4].

The Explanatory Statement, at page 570, provides as follows:

> *"… The Department is directed to submit to the House and Senate Committees on Appropriations a report on liquefied natural gas (LNG), as outlined in the House report…"*

House Report 110-185, at page 73, similarly requested the Department of Energy to address several key LNG research priorities in a liquefied natural gas report:

> *"… Liquefied Natural Gas (LNG) Report.—The February 2007 Government Accountability Office report, 'Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification,' found that the most likely public safety impact of an LNG spill is the heat hazard of a fire, but disagreed with the specific heat hazard of a fire and cascading damage failure conclusion, which is used by the Coast Guard to prepare Waterway Suitability Assessments for LNG facilities. Additionally, GAO found that the Department's 'recently funded study involving large-scale LNG fire experiments addresses some, but not all, of the research priorities identified by the expert panel.' Therefore, the Committee directs the Department to incorporate the following key issues, as identified by the expert panel, into its current LNG study: cascading failure, comprehensive modeling (interaction of physical processes), risk tolerability assessments, vulnerability of containment systems (hole size), mitigation techniques, the effect of sea water coming in as LNG flows out, and the impact of wind, weather, and waves."*

II. LNG Cargo Tank Breach and Spill Analyses

For this study, the larger classes of Moss and Membrane LNG vessels were analyzed. The dimensions of the vessels considered are summarized in Table 1. The sizes selected span many of the LNG vessels used in the U.S., including the largest LNG vessels in operation today.

Table 1. Dimensions of Moss and Membrane LNG Vessels Evaluated

Dimension	Moss	Membrane
Length	280 m (924 ft)	330 m (1090 ft)
Breadth	45 m (150 ft)	54 m (178 ft)
Draft	10.4 m (34 ft)	11.5 m (38 ft)
LNG Cargo Capacity	140,000 m^3	260,000 m^3

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[3] Explanatory Statement accompanying Public Law 110-161 (Dec. 26, 2007).

[4] H.Rept. 110-185 accompanying Energy and Water Development Appropriations Bill, 2008 (H.R. 2641) at page 73.

The geometric models, which were created using detailed structural drawings of actual LNG vessels, are shown in cross-sections in Figures 1 and 2.

Figure 1. Moss LNG Vessel cross-section.

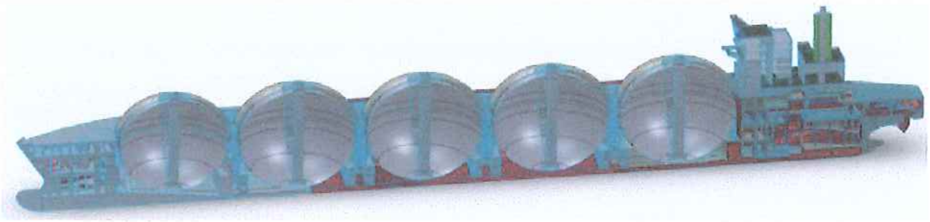
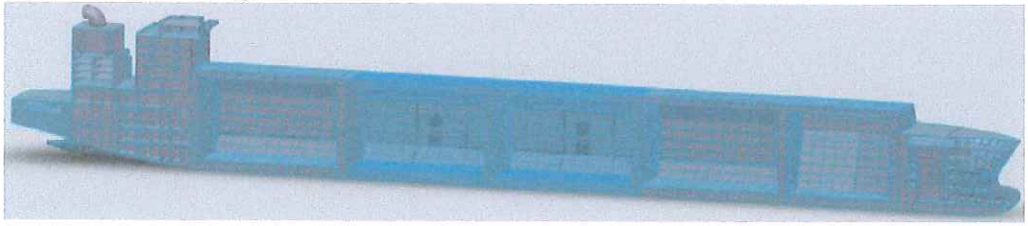


Figure 2. Membrane LNG Vessel cross-section.



LNG Cargo Tank Breach Analyses

Many potential accidental and intentional damage scenarios have been considered for LNG hazard analyses in previous DOE-directed public safety analyses for large LNG spills over water, including Hightower et al., 2004 and Luketa et al., 2008. For this study, Sandia reassessed threats and potential credible event scenarios for LNG marine transportation with marine safety, law enforcement, and intelligence agencies. The evaluations considered a wide range of possible threats. These included accidents, as well as intentional events such as attacks with shoulder-fired weapons, explosives, and attacks by small to medium size boats and aircraft. Potential threats and possible breach events are always site-specific and will vary depending on the location of the LNG vessel, such as inner harbor, outer harbor, or offshore Deep Water port.

The breach sizes calculated were based on detailed, two- and three-dimensional, shock physics/structural interaction and damage models. The breach modeling included detailed representations of the LNG vessel's structural design and materials of construction, cargo tank construction and materials, and the location and energy content of the threats identified. The range of breach sizes calculated for specific threats are presented in classified reports, but Table 2 provides a summary of the range of the cargo tank breach sizes considered for this study. To simplify integration with the structural geometry and construction of LNG vessels, square holes were assumed in all analyses.

Table 2. LNG Cargo Tank Breach Sizes Considered

Type	Breach Area	Breach Dimension
Very Small	0.005 m^2	(0.25 ft x 0.25 ft)
Small	0.5 m^2	(2.3 ft x 2.3 ft)
Medium	2-3 m^2	(5.0 ft x 5.0 ft)
Large	5 m^2	(7.3 ft x 7.3 ft)
Very Large	15 m^2	(12.7 ft x 12.7 ft)

The breach events evaluated can occur at a range of locations. While many accidental and intentional threats fall into the very small and small breach size categories, the major focus of the spill and damage analyses were for medium to very large hole sizes that are difficult to analyze without the use of high performance modeling and computing capabilities.

LNG Spill Analyses

To determine the extent of LNG flow during a breach event, three-dimensional computational fluid dynamics (CFD) analyses of the internal and external flow of LNG from a breach of Moss and Membrane LNG cargo tanks were performed for the small through very large hole sizes. The spill analyses considered the entire flow physics of the problem, including the draining of the breached cargo tank, the timing and flow of the LNG internal and external to the vessel, and LNG vaporization during a spill. The flow modeling and analysis conducted are presented in detail in Figueroa et al., 2011. Figures 3 and 4 show examples of LNG flow analyses conducted for the Moss and Membrane LNG vessels.

Figure 3. Moss LNG vessel spill and internal flow analysis example.

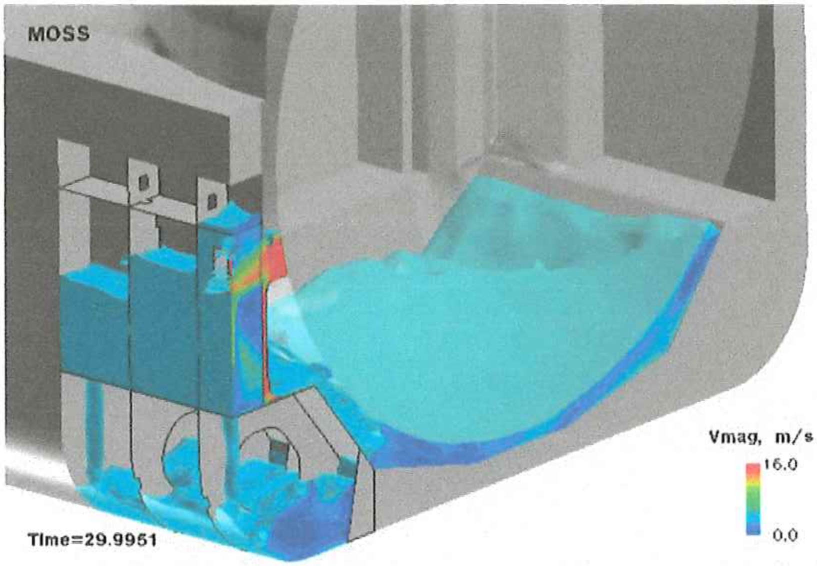
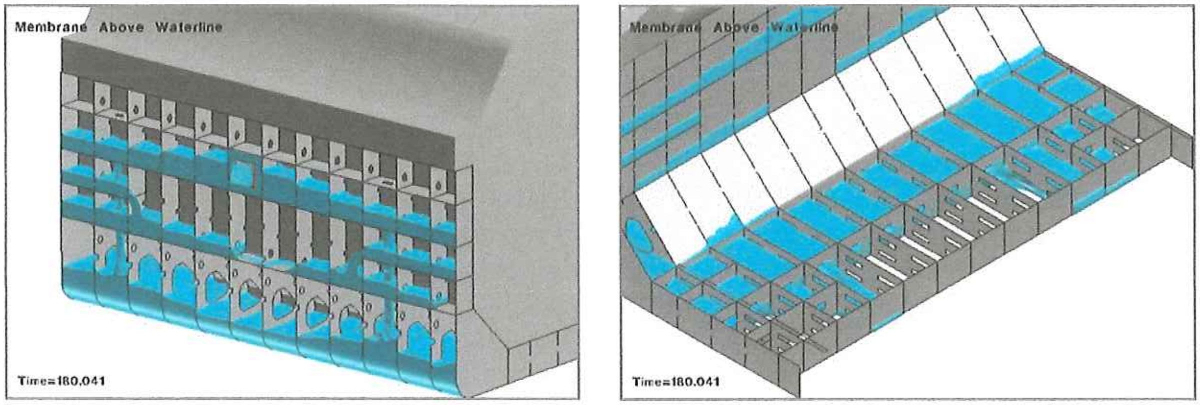


Figure 4. Membrane LNG vessel spill and internal flow analysis examples.



The spill analyses indicate that for the larger breach and spill events, as much as 40 percent of the cargo tank LNG volume will likely remain within the LNG vessel. The spill and flow analyses show that for medium and larger spills, the internal flow of LNG into a Moss LNG vessel will be completed within ten to fifteen minutes, at which time the remaining LNG will all flow out onto the water. For a Membrane LNG vessel, LNG flow within the vessel for medium to larger spills will be completed in about 10 minutes, and then the remaining LNG will flow out onto the water. For smaller breach events, the spills are smaller and the spill durations longer.

The results for the external flow analyses showed that for the larger breach events, LNG pool diameters between 180 m to 350 m can be expected for the Moss LNG vessels, while LNG pool diameters between 205 m to 330 m can be expected for the Membrane LNG vessels. Smaller breach events result in spills of much smaller volumes of LNG and have much smaller pools.

The flow results obtained should be considered as providing qualitative information on the general pattern, timing, and magnitude of the internal and external LNG flows for different breach and spill events.

III. Large LNG Pool Fire Experimental Results

The focus of the efforts for this part of the study was to improve the understanding of the physics and hazards of large LNG spills and fires on water. The key LNG pool fire issues to be addressed included:

- Determining the Surface Emissive Power (SEP) of large LNG pool fires;
- Determining the fuel vaporization rate of LNG fires on water; and
- Determining the flame height to diameter ratios for large LNG pool fires.

This effort was accomplished through the collection of data obtained during a series of LNG pool fire tests on water. A summary of the test data collected is presented here, while the detailed test data and results are presented in Blanchat et al., 2010.

Shown in Figure 5 is the large scale LNG pool fire test site. The site design included: 1) using soil excavated from the creation of a two meter deep, 120 m diameter pond to create a 310,000 gallon compacted soil LNG storage reservoir; 2) covering the reservoir with a double insulated cover and insulated liner to minimize LNG vaporization; 3) use of prefabricated reinforced concrete pipes to transport the LNG from the base of the reservoir to the center of the pool; and 4) use of simple, liftable plugs to allow gravity-driven high LNG flow rates from the reservoir to the pool. This approach enabled LNG flow rates representative of large spills, while minimizing the need for cryogenic rated high flow volume pumps, associated hardware, and fire rated LNG storage tanks.

Figure 5. Large-scale LNG pool fire test site.

Numerous cameras, spectroscopic diagnostics, and heat flux sensors were used to obtain extensive heat flux, flow rate, and fire size data from the resulting fires for each test. The spreading pool fire area was photographed with the aid of gyroscopically stabilized cameras deployed in U.S. Air Force helicopters.

Figures 6 and 7 are pictures of the two large LNG pool fires, conducted in February 2009 and December 2009.

Figure 6. LNG Test 1 – 21 m diameter LNG spill and pool fire.

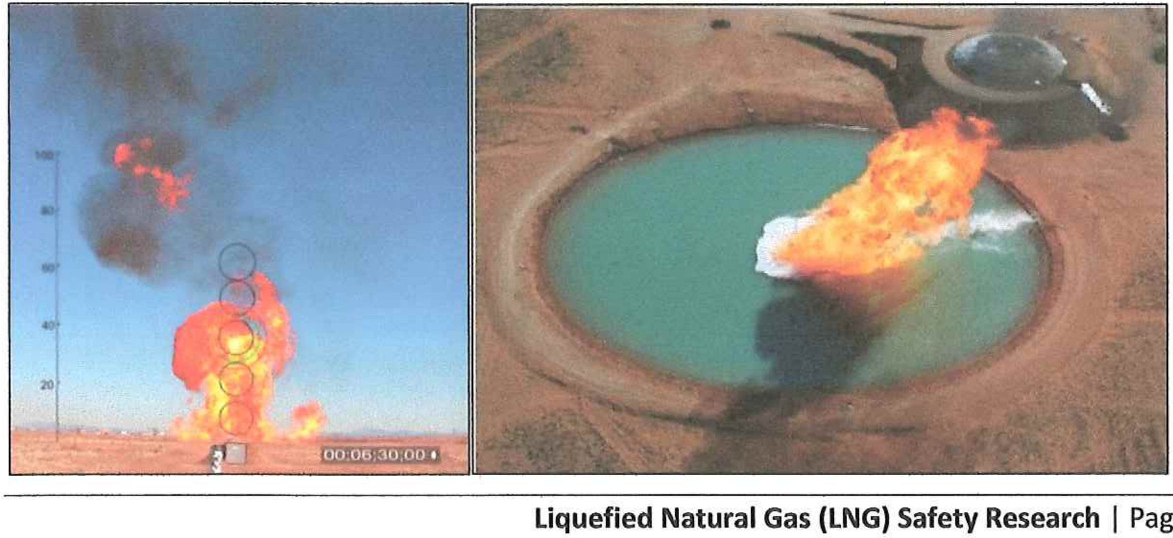


Figure 7. LNG Test 2 – 83 m diameter LNG spill and pool fire.

A summary of the major pool fire parameters measured during these tests are provided below in Table 3.

Table 3. Large LNG Pool Fire Data

Test	Volume Discharged (gallons)	Avg. Flame Height (m)	Flame Diameter (m)	Wind Speed (m/s)	Flame Tilt (degrees)	Vap. Rate (kg/m^{2}s)	Surface Emissive Power (kW/m^2) (narrow/wide)
1	15,000	70	20.7	4.8	50	0.15	238/277
2	52,000	146	56 (83 m spill)	1.6	Negligible	Not obtained	316/286

The thermal radiation spectra as a function of height and time were acquired using a scanning mid-infrared (1.3-4.8 µm) spectrometer. Analyzed spectra determined that the dominant contributor to the thermal radiation was from broadband soot emission. The overall thermal radiation reaching the spectrometer was attenuated by atmospheric water and CO_2 which resulted in a decrease in intensity at different wavelength bands. In LNG Test 2, at ~40 m to 103 m above the ground surface, the data is fairly consistent with spectra-derived flame temperatures of between 1300-1600°C and emissivity values between ~0.3 -0.4.

In both of the tests conducted for this study, there was no evidence of smoke shielding. There were a few instances when small amounts of smoke were seen in LNG Test 2 during the production of large scale vortices that rolled up from the base of the flame when the fire exhibited a puffing behavior. Very little smoke shielding was also observed in pool fire data obtained from a previous, smaller scale (~10 m diameter) test conducted by SNL.

The trend in the data from these tests indicate that the SEP for LNG fires on water level off at about ~280-290 kW/m^2 and might be expected for spreading pools with diameters in the range of 100 m. This is a reasonable value for use in hazard calculations for structures, such as the LNG vessel or shoreline areas, adjacent to or near the fire. Larger LNG fires would likely have some smoke shielding in the upper portions of the flame plume that will lower the overall flame-average SEP for far afield objects.

The collected data showed some unique and unexpected results. Specifically, the fire diameter was not the same size as the spreading pool diameter, as had been assumed by most analyses to date. Previous studies with stagnant pools in pans resulted in fire diameters the same size as the pool diameter. However, in all such studies, the pans had edges that can result in flame stabilization that would not be available in open water scenarios. The data collected further showed that in both very light and significant cross-winds, the flame will stabilize on objects projecting out of the fire, suggesting the vessel itself will act as a flame anchor.

Flame Height-to-Diameter Testing

To develop a flame height-to-diameter correlation, a large (3 m diameter) gas burner was used to create fully turbulent methane fires at the Sandia Thermal Test Complex, which more closely simulates large fire behavior. The data collected was compared with other common height-to-diameter correlations conducted for smaller and less turbulent fires. The Sandia data collected suggests that the fire height for large LNG spills would be much lower than often used in many fire hazard analyses. The Sandia data suggest the fire height-to-diameter ratios for LNG pool fires greater than 300 m in diameter would be less than 1.5 and would approach 0.7 for LNG pool fires about 1,000 m in diameter. Previously, many studies used a constant height-to-diameter ratio of 1.5. The data from the two large LNG pool fire tests conducted as part of this study closely match the gas burner flame height-to-diameter correlation identified.

IV. LNG Vessel Thermal/Structural Analyses

This section provides a summary of the development of LNG vessel structural steel thermal material property data, LNG vessel cryogenic fracture and fire damage testing and analysis, and development of cryogenic and fire thermal loading models needed to identify the time varying thermal stress states on a vessel structure during a large LNG spill and fire. The detailed material testing, and thermal damage testing and analysis efforts conducted are presented in two technical reports Kalan and Petti, 2011 and (Figueroa et al., 2011).

LNG Vessel Structural Steel Material Property Testing

It is well known that many structural steels are susceptible to low temperature brittle fracturing and high temperature softening. In order to perform the thermal (both cryogenic and high temperature) structural damage analyses required for LNG vessels during a spill and fire, information on vessel structural steel material properties and material response at extreme temperatures (from -161°C for cryogenic LNG temperatures and up to 1000°C for LNG fire temperatures), as well as suitable damage models were required. In both cases, neither existing data nor appropriate damage models existed for LNG vessel steels for this range of temperatures. Therefore, a series of material property and material failure tests were performed on two American Bureau of Shipping (ABS) steels representative of the structural steels used in standard LNG vessel construction. The data collected was used to develop cryogenic fracture and fire-induced structural damage models based on vessel structural features, stress states, and temperatures. The material and cryogenic fracture and damage response testing is summarized here, but is discussed in detail in Kalan and Petti, 2011.

ABS Grades A and EH round bar tensile test data were collected at temperatures ranging from -161°C to 800°C. In addition, notched tension specimens and Charpy V-notch testing was performed from -191°C (far below the brittle transition region) to -24°C (above the brittle transition region) for both ABS steels. The tensile test data showed low residual strength (20 percent of yield strength) of LNG vessel steels at LNG fire temperatures for extended periods. The Charpy V-notch energy absorption test results showed low fracture toughness for both materials at cryogenic LNG temperatures, highlighting the susceptibility to fracture of LNG vessel structural steels if contacted by LNG for any extended period.

LNG Vessel Cryogenic Fracture Testing

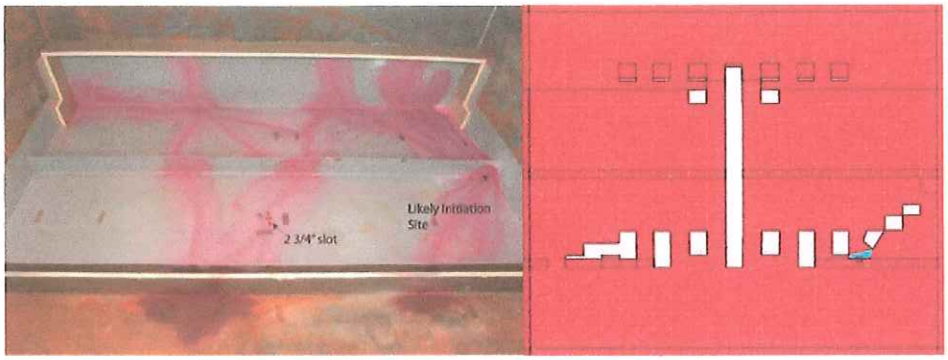
In order to predict how structural sections of an LNG vessel would respond to contact with cryogenic LNG, we conducted a series of large scale LNG spill and fracture tests on ABS Grades A and EH steels. Three series of fracture tests were conducted that included testing of large steel plates that were constrained on their edges, and the testing of large, welded, three dimensional, steel structures representative of LNG vessel structural elements and vessel construction approaches. For these tests, a region in the center of the plate or structure was cooled with liquid nitrogen, which was used for safety considerations. However, testing conducted with LNG showed similar cool down rates of the steel as using liquid nitrogen. The cooling rate and cooling distribution from each test was monitored at several locations on the plates and structures using thermocouples, and fractures were identified after each test. The tests were conducted with prescribed flaw sizes, boundary conditions, and flow rates to provide extensive, high quality data to develop and validate a cryogenic fracture and damage model.

From the fracture data collected, a vessel fracture damage model was developed and was used to predict structural fracture for several simulated LNG vessel structural elements. The development and validation of the cryogenic damage model is discussed in detail in Petti et al., 2011. For verification of the fracture and damage model, a finite element model of a large test structure was developed, and a cryogenic flux was applied to the model that represented the cooling rate data measured in the large structure tests. The cracking observed was compared to the fracturing predicted from the structural model. What was important was to predict the general direction, amount, and propagation of fractures and cracks through structural elements based on the identified temperature and stress states.

Figure 8 shows a comparison of model predictions and test data, and shows that the general extent and direction of cracking is similar relative to crack directions and elements damaged.

These efforts verified that damage could be estimated based on the LNG flow, temperature, and the stress state of the vessel structure.

Figure 8. Comparison of damage analysis to experimental test results.



LNG Vessel Structural Cooling Evaluation

The internal and external regions of the LNG vessel's structure that come into contact with spilled LNG become cooled. To determine cooling rates, experimental data was obtained from a series of structural steel cooling experiments. LNG was pooled on ¾ inch thick carbon steel plates with various surface coatings that included bare steel, primed only, and primed and painted surfaces. The tested surface coatings used consisted of primers and paints used on LNG vessels. The temperature response of the test plates was used to estimate convective heat transfer coefficients. The data and supporting analyses lead to an estimation of lower and upper bound heat transfer coefficients of 400 and 1080 W/m^2-K. The test data also showed that cooling occurs essentially only in the area in contact with the LNG. Based on this data, the regions identified from the flow analysis that come into contact with LNG were reduced linearly in temperature from 20°C to -148°C over 10 minutes.

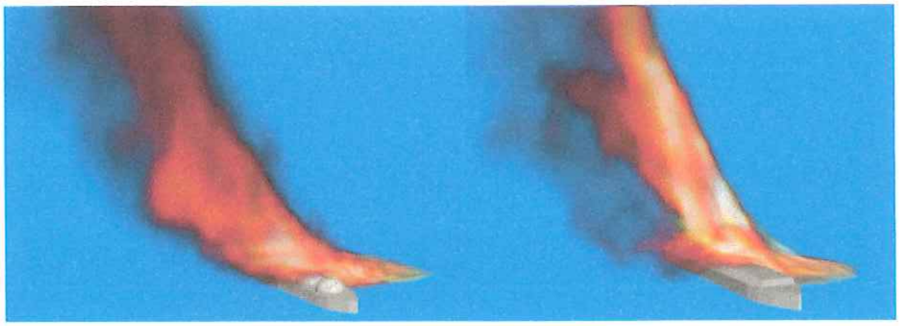
The cooling of LNG vessel steel in contact with seawater was also evaluated. The cooling rates were determined using a finite difference heat transfer analysis. The analysis calculated ice growth depending on the water/ice or water/vessel interface temperature. At interface temperatures below the freezing point of seawater (-1.9°C), the analysis allowed ice to accumulate. For a case with a reasonable external current velocity (1 knot) and for a wide range of bulk seawater temperatures, it was determined sufficient ice forms to insulate the outer hull and allow it to cool to temperatures approaching the temperature of the LNG. The cooling rate calculated was close enough to the cooling rate value determined for air to support using the same cooling rates for vessel steels above and below the waterline contacted by LNG.

LNG Vessel Structural Heating Evaluation

LNG vapors burn at temperatures of about 1500°C, which will negatively impact an LNG vessel's structural integrity if a fire lasts for a significant period of time. For medium to larger spills, the flow analysis indicated the maximum pool diameters would be approximately 180 m to 350 m. Using these pool diameters, pool fire analyses were conducted to estimate the thermal heating rate of the LNG vessel's structural steel. Fuego, a CFD fire code developed and used by Sandia, was used to estimate the envelope of an LNG fire on LNG vessels under various environmental, wind, and humidity conditions. Historical wind speed information was obtained from the National Data Buoy Center (www.ndbc.noaa.gov) for various harbors in the U.S. and was evaluated to obtain a typical wind speed for these harbors. Based on this data, an average wind speed of 9 m/s (20 mph) was considered directed toward the LNG vessels.

As shown in Figure 9, the analyses suggest that in average winds, fire can overlay onto the vessels and impact the tops and sides of the vessels, which should be included in evaluating vessel and cargo tank damage and integrity during a fire.

Figure 9. Large pool fire impacts on Moss and Membrane vessels.



The surface emissive power obtained from the large LNG pool fire experiments was used to define the LNG pool fire heating rates to the LNG vessel structures. Based on these analyses, the temperatures of the outer hulls were calculated to reach approximately 1000°C, while the inner hulls can reach about 775°C. These results compare favorably with vessel hull heating data collected from cargo tank insulation damage testing discussed later in this report. The results suggest that the outer and inner hull structural elements exposed to LNG pool fires for more than 10-20 minutes can experience about a 75 to 80 percent reduction in strength.

V. LNG Vessel Cascading Damage Analyses

The key LNG vessel damage issues Congress wanted addressed as part of this study included:

- Improved understanding of cryogenic fracture and damage to LNG vessels;
- Improved understanding of fire damage to LNG vessels; and
- Improved understanding of the potential for cascading damage from a large spill.

A summary of the cryogenic and fire related vessel damage analyses and the potential for cascading damage to the vessel from an initial spill is presented in this section, while the detailed modeling and analysis results are presented in Petti et al., 2011. The focus of the LNG vessel cascading damage analysis efforts was to use detailed vessel structural and thermal damage models, along with high performance computing resources, to improve the ability to assess and predict cascading damage potential to an LNG vessel from an initial spill.

LNG Vessel Structural Analysis Model Development

For the final vessel cascading damage analyses, detailed finite element structural analysis models were created for both the Moss and Membrane LNG vessels. For the structural analyses, elements with 0.1 m (4 inch) edge lengths were used in the regions where damage and fracturing could potentially occur to allow all of the major structural elements, including the longitudinal stiffeners attached to the inner and outer hulls, to be modeled explicitly in detail. In regions outside of the areas of potential fracturing, the elements were gradually increased to a maximum of approximately 1 m, with most elements in the 0.3 m to 0.5 m range. This helped to reduce the structural analysis complexity and computing resources needed. This approach produced two structural models, each with between four and five million elements.

To ensure the proper mass distributions, both the steel density and the thickness of the shell elements need to be defined as input parameters in the structural models. In the detailed mid-ship sections of the vessel, the thickness of the steel plating was set to the as-built thicknesses since all of the major structural elements were modeled explicitly. For the less detailed fore and aft sections, where the longitudinal stiffeners were not modeled explicitly, the thickness of the inner and outer hulls was increased to account for both the global and local stiffness lost by not including these members. In addition to the thickness of the steel plating, the densities of the blocks in various sections of the vessels were adjusted to account for various non-structural items including LNG cargo, cargo tank insulation, piping, machinery, anchors, fuel, water, etc.

LNG Vessel Damage Analysis Approach

From the spill and flow analyses conducted, the medium to very large breach events give very similar overall LNG flow results within the vessel structures, with the major difference being some variation in the timing of cooling of different regions. For this reason, a single detailed structural damage analysis was performed for each type of LNG vessel. For these analyses, gravitational loads, exterior seawater hydrostatic loads, and internal LNG cargo tank hydrostatic loads were applied to the vessel structural models to first obtain the initial stress states of the vessels. ABS Grade A and EH steels were used to model the structural steel in each vessel. For regions with lower fracture toughness materials (ABS Grades A, B, D, and E) ABS Grade A properties were used, and in regions with higher fracture toughness materials (ABS Grades AH32, AH36, DH32, DH36, EH32, and EH36) ABS Grade EH properties were used. This was done to simplify the structural model input and quality assurance checks needed. The initial load condition chosen was the Summer Arrival Condition where the LNG cargo tanks are 97 percent filled for the Moss LNG vessel and 98.5 percent filled for the Membrane LNG vessel.

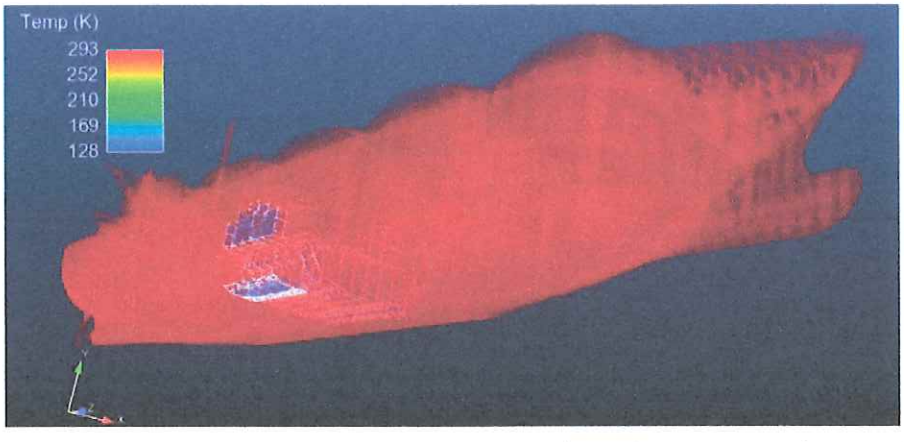
After establishing the initial load and stress states and vessel stability and draft of the structural analysis models for these conditions, temperature changes were applied to the structural models in accordance with the LNG flow, cooling rate, and fire heating rate values discussed in previous sections of this report. These thermal changes, along with the initial stress states and structural steel material properties, were used to track the progression of calculated damage (summarized below) for the LNG vessel. All vessel damage analyses were conducted using high performance computing resources, and the structural damage models were run using approximately 500 parallel computer nodes, each with multiple processors.

Moss LNG Vessel Medium to Large Spill Damage Analysis

The flow analysis showed widespread LNG contact with steel plate surfaces within 30 seconds of a large breach event. As the flow progressed, different regions started to cool at different times. These delays were used to simulate the timing of the flow of LNG within the space surrounding the cargo tank for up to approximately 14 minutes. Beyond that time, the LNG has filled the internal spaces and spills out onto the water. The initial analysis assumed that spilled LNG would not come into contact with the LNG vessel's structure just above the bilge area. However, in some cases the LNG could come into contact with this area. Because of this, the final structural damage results presented include damage in the bilge area in estimating the worst case damage scenarios.

An example of the resulting structural cryogenic damage from a large cargo tank breach and spill is shown in Figure 10.

Figure 10. Example of Moss vessel damage due to cryogenic LNG flow.

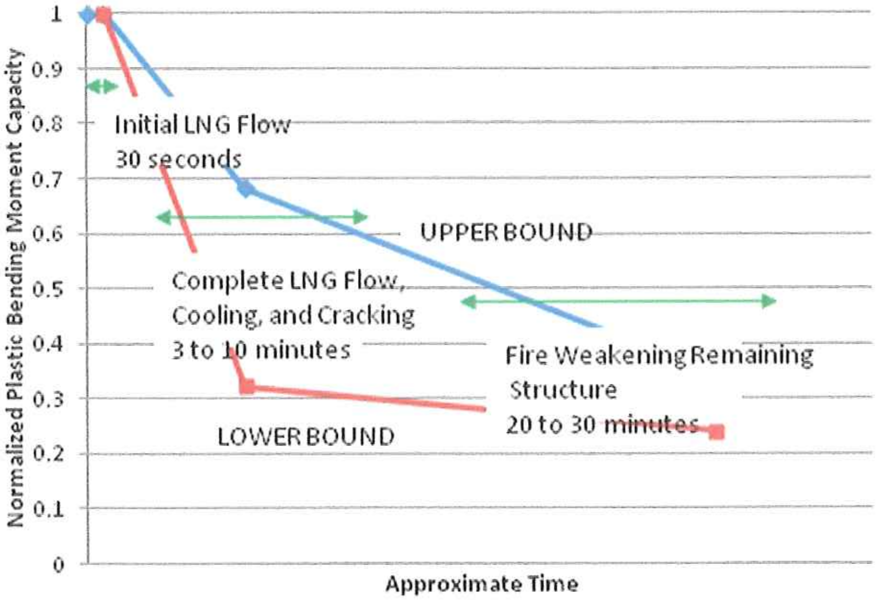


The white colored elements indicate the structural elements that reached the critical fracture damage criterion. The transparent view of the vessel shows both the cryogenic cracking and damage in the outer and inner hull surrounding the cargo tank. The significant damage to the inner hull causes the outer hull to deform upward into the vessel as the hydrostatic pressure from the seawater is no longer resisted by the damaged vessel's inner and outer hulls. The estimated displacement of the outer hull could be as much as one meter. The analysis predicts cryogenic cracking will occur throughout the portions of the vessel that were exposed to LNG flow. No damage was predicted to occur in regions beyond where the LNG flowed.

Based on the cryogenic structural damage analysis, much of the inner hull near a large breach event was damaged. As a result of the pool fire, much of the vessel's structure near the fire on both the side and top of the vessel will reach temperatures of between 775°C and 1000°C for the inner and outer hulls. At these temperatures, the vessel's structural steels are severely weakened, having less than 25 percent of their original strength, and will deform significantly.

Based on the combined cryogenic and fire damage estimated, the plastic bending moment capacity for the Moss LNG vessel as a function of time is presented in Figure 11.

Figure 11. Moss LNG vessel reduction in plastic bending moment capacity for large spills.



The plastic bending moment capacity is defined as the bending moment that would lead to the entire cross-section of the vessel yielding and creating essentially a plastic *hinge*. The plastic bending moment capacity is often used in extreme event risk analyses to evaluate the level of residual structural capacity following an extreme event.

The moment capacity is normalized by the full undamaged plastic moment capacity of the section. The cryogenic damage causes an approximate 30 to 70 percent reduction within

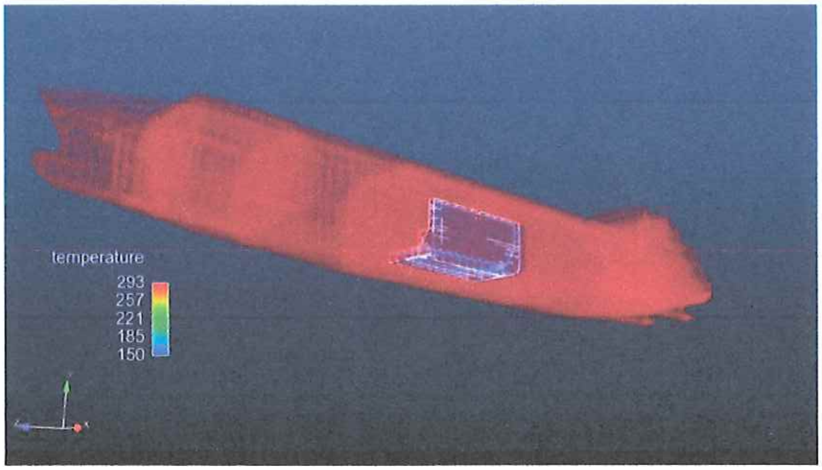
3 to 10 minutes, with the fire causing an additional 10 to 20 percent reduction between 20 and 30 minutes. However, the upper bound capacity estimates assume that the cross-section is in a condition to obtain the full strength of the materials without section buckling. However, the cryogenic damage modeling shows local buckling and material displacement that suggests that the lower bound moment capacity could occur since the sections of the inner and outer hull at the top of the vessel are affected by the fire and have little resistance to tension.

Based on the reduction in plastic moment capacity, the vessel is judged to have essentially no remaining structural strength in the affected region, and will most likely be disabled, severely damaged, and at risk of sinking. Based on the flow and damage analysis, the LNG vessel's structural design limits the LNG flow to the initially damaged region, and the four remaining cargo tanks not breached during the initial event should be unaffected by the cryogenic damage. Also, because the Moss cargo tanks are independent and do not rely on the vessel's hull structure for support, a simultaneous release of LNG from the undamaged cargo tanks due to cascading failure is considered highly unlikely.

Membrane LNG Vessel Medium to Large Spill Damage Analysis

The flow results were used to develop a series of cooled regions for the cryogenic damage analysis. Widespread LNG flow between the inner and outer hulls occurs within 2 and 3 minutes, with subsequent filling of the compartments. At approximately 6 to 10 minutes into the spill, a significant portion of the ballast tank and areas between the inner and outer hulls are filled. While complete filling of the ballast compartments and areas between the double hulls does not occur, the open spaces are small and would contain cold LNG vapor and therefore, the entire ballast tank was included as one large, cooled region. Finally, the same assumptions were made for the Membrane vessel as the Moss vessel regarding cooling rates below the waterline and the eventual entrainment of seawater into the vessel for some breach events and their inclusion in the damage conclusions. Figure 12 shows an example of the Membrane vessel with temperatures and damage plotted.

Figure 12. Example Membrane vessel damage due to cryogenic LNG flow.

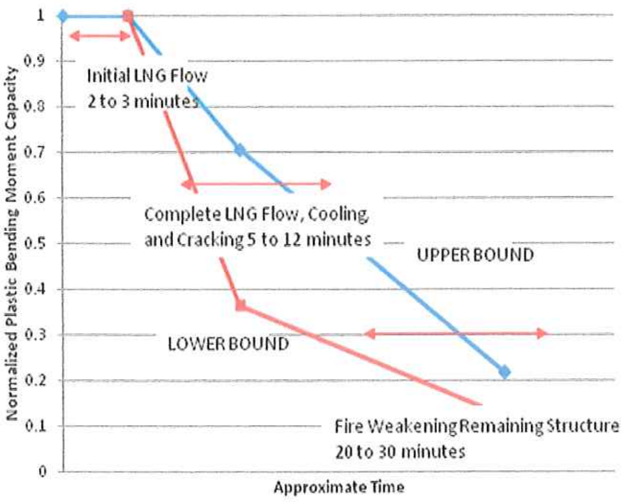


The white colored elements indicate the cryogenic fractures calculated after reaching the critical strain criterion during cooling. The transparent view shows both the cracking in the outer hull and inner hull surrounding the cargo tank. Here, the extent of the damage to vessel structure surrounding the breached cargo tank can be seen. The analysis predicts cracking will occur throughout the entire cooled region, which reflects those portions of the vessel that were exposed to LNG flow.

The damage was predicted to occur primarily near the cooled region boundaries. This is likely an artifact of the sharp gradient from cool to warm material along this boundary. Once the cracks occurred in the structural model, these elements were removed, and much of the stress was reduced in the interior of the cooled region, preventing further apparent damage. The cryogenic fracture and cracking in an actual event is expected to extend throughout much of the cooled region, especially in areas of flaws or stress concentration such as welds, corrosion, and so on. As with the Moss vessel analysis, no damage was predicted to occur in regions outside of the cooled areas. The effective damage to the Membrane LNG vessel is initially localized on one side of the vessel. The majority of the inner and outer hull was damaged, severely reducing the ability of the vessel to resist hydrostatic loads from the surrounding seawater. Unlike the Moss LNG vessel, in which the LNG cargo tank is structurally independent from the inner hull, the Membrane LNG vessel's inner hull provides the structural support for the cargo tank. With the damage to the inner hull, the cargo tank in the affected region will likely not be capable of fully containing the LNG cargo that remains below the breach. This would lead to additional inner hull damage and expanding damage of the inner hull to both sides of the vessel.

From the fire analysis, much of the vessel structure near the fire on both the side and top of the Membrane LNG vessel could reach temperatures of between 775°C and 1000°C for the inner and outer hulls. Since the LNG vessel's inner hull and internal structural members provide the structural support for the Membrane cargo tanks, thermal degradation of both the outer and inner hulls from an LNG pool fire would likely cause damage to the cargo tanks. Based on the cryogenic and fire damage estimated, the reduced cross-sections and weakened materials analysis results were used to estimate the plastic bending moment capacity for the Membrane vessel as a general function of time and are shown in Figure 13.

Figure 13. Membrane LNG vessel reduction in plastic bending moment capacity for large spills.



The cryogenic damage causes an approximate 40 to 70 percent reduction within 5 to 12 minutes (including several minutes to account for the slower flow calculated for the Membrane vessel design) with the fire causing a 80 to 90 percent total reduction in the plastic bending moment capacity between 20 and 30 minutes. The fire has a more significant effect on the Membrane vessel section modulus due to the greater amount of structural cross-section that is exposed to the fire.

The damage to the vessel also introduces concerns related to a reduced buckling capacity for structural regions in compression. The sections of the inner and outer hull at the top of the vessel are affected by the fire and have little resistance to tension. Based on the reduction in plastic bending moment capacity, the vessel is judged to have essentially no remaining structural strength in the affected region, and will most likely be disabled, severely damaged, and at risk of sinking.

Based on the flow and damage analysis, the LNG vessel's structural design limits the LNG flow to the initially damaged region. Although the four remaining cargo tanks were not calculated to have been breached during the initial event, the Membrane cargo tanks are integrated tanks and rely on the vessel's hull structure for support, and the release of their cargo is slightly more uncertain. One of the tanks adjacent to the initially breached tank was calculated to experience cracking in the corner of the inner hull exposed to LNG. The breach of this adjacent tank is possible, but not certain. Even so, if this adjacent tank were to experience a leak, it would most likely progress slowly and/or occur during the fire portion of the event when the fire would weaken the vessel structure in the adjacent tank. This would have the effect of extending the duration of an initial fire, but not increasing the size of the pool fire to any significant degree.

LNG Vessel Damage from Smaller Spills

For very small breach events (0.005m^2 Breach Area; 0.25 ft x 0.25 ft Breach Dimensions; from Table 2), which could occur from a number of credible intentional or accidental events, the spill rates will be more than a factor of 1,000 times less than that of the larger breach events considered. This puts small spills into categories that would typically fall within current spill detection and safety systems and allow a significantly extended response time for both Moss and Membrane LNG vessels. The large reduction in spill rates, cryogenic damage and fire damage potential suggests that should a smaller breach event occur, both Moss and Membrane LNG vessels would have sufficient time to transit to an appropriate anchorage location and work with the Coast Guard and other public safety agencies to perform a damage assessment and initiate appropriate action.

For small breach events (0.5 m^2 Breach Area; 2.3 ft x 2.3 ft Breach Dimensions; from Table 2), the physics of the flow conditions will reduce the LNG flow rate into an LNG vessel by a factor of approximately six, relative to the larger LNG spills, and the full cryogenic cooling and damage of all the compartments between the LNG hulls for each vessel type could take as much as six times as long. However, based on the flow analysis conducted for these holes, the LNG flow internal to the vessel reaches the keels of the LNG vessels only a few minutes later than for the larger spills. This suggests that for spills from small breach events, the full cryogenic damage could take from 10 minutes to 60 minutes longer than for the larger spills. Unfortunately, the fire damage will still occur over the original time period calculated, and therefore the overall reduction in structural capability will most likely occur within one hour of the event.

VI. Additional Cascading Damage Analyses

A number of additional cascading damage issues were addressed in this study, including:

- Cargo tank insulation damage during a fire;
- Overpressure of an LNG cargo tank during a fire;
- Impact of Rapid Phase Transitions (RPTs) during a spill; and
- LNG vaporization, deflagration, and associated damage during a spill.

A summary of the testing and analysis efforts conducted to assess the potential impacts of these kind of cascading damage scenarios is presented in this section, while the detailed test data and analyses are presented in Blanchat et al., 2011, Morrow, 2011, and Figueroa et al., 2011.

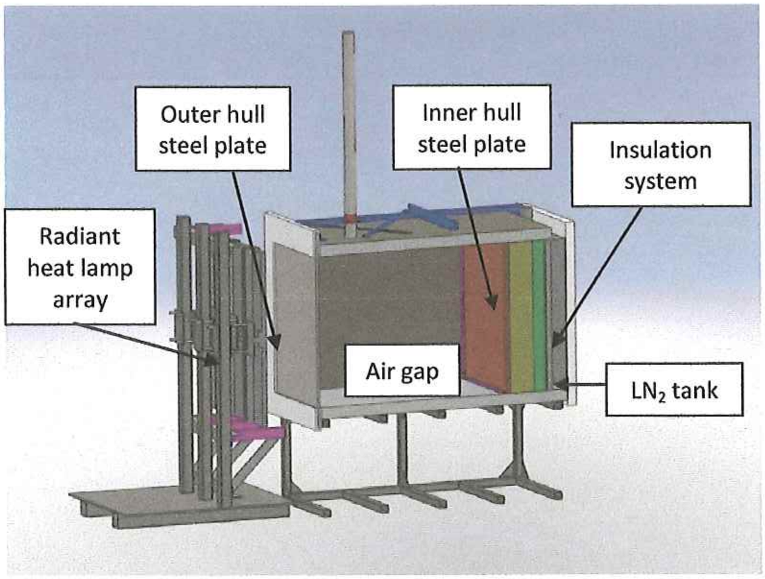
LNG Cargo Tank Insulation Fire Damage Testing

To assess the thermal resistance of LNG cargo tank insulation materials and systems in a fire, large-scale thermal damage experiments and testing were conducted on four major LNG cargo tank insulation systems (two Moss and two Membrane systems), which represent most of the current LNG insulation systems being used in U.S. ports. The testing of each insulation system was coordinated through LNG vessel designers and cargo tank insulation system manufacturers, and each insulation system tested was either provided by the insulation manufacturers or was fabricated at Sandia to the insulation system design and construction specifications provided by the manufacturers. LNG vessel representatives witnessed their insulation system test setup, experiments, data collection and evaluation, and participated in post-test insulation system inspection.

The experiments were designed to test the insulation systems for the fire durations expected from a large LNG spill. Based on the latest information on large-scale LNG spills and associated fires (Luketa et al., 2008), fires from 20 to 40 minutes long might be possible. Therefore, all the insulation systems were tested for at least 40 minutes. All tests were performed using a radiant heat assembly that allowed identical and reproducible heat flux boundary conditions for each test. All tests were performed to yield a continuous incident heat flux to the outer hull (for the membrane) or weather cover (for the Moss) insulation systems of ~270 kW/m^2. This value was based on preliminary, flame-averaged steady-state surface emissive powers measured in the large-scale LNG pool fire tests previously discussed and presented in (Blanchat et al., 2010).

The insulation tests were conducted in the test apparatus shown in Figure 14.

Figure 14: LNG cargo tank insulation testing layout.



It was approximately one meter by one meter square, and approximately two meters long and designed to allow testing of large representative LNG insulation panel systems with minimal edge effects such that a thermal environment representative of a large fire could be created. The testing apparatus included a radiant heat lamp assembly, mild steel plates representing Membrane LNG vessel outer and inner hulls or the Moss LNG vessel weather cover, an air gap inerted with nitrogen during testing, the insulation system being tested, and an aluminum tank filled with liquid nitrogen (LN$_2$) to represent a cold LNG cargo tank boundary condition. Liquid nitrogen was used for safety reasons, since it is not flammable, and has a similar temperature as LNG.

A summary of all the insulation test results are shown in Table 4. Heat flux was measured by heat flux gauges attached to the tank and by evaluating the change in the liquid nitrogen boil-off rate in the LN_2 tank.

Table 4. LNG Cargo Tank Insulation System Fire Damage Test Results

LNG Vessel	Insulation Type	Thickness	Fire Survivability	LN_2 Tank Heat Flux
Moss	Extruded polystyrene panel	~300 mm	> 40 min	< 7 kW/m^2
Moss	Polyurethane foam/ phenolic resin foam composite panel	~300 mm	> 40 min	< 5 kW/m^2
Membrane	Polyurethane foam and plywood panel	~300 mm	> 40 min	< 5 kW/m^2
Membrane	Perlite-filled plywood boxes	~500 mm	> 40 min	< 5 kW/m^2

LNG Cargo Tank Pressure Safety Relief Valve Evaluation

There has been much discussion on the impacts of a large LNG pool fire on increasing vaporization of LNG in undamaged tanks and the capacity of the current pressure safety relief valves to handle this increased vaporization. The concern is that if pressure builds up during a fire and cannot be adequately handled by the pressure safety relief valve systems, then a cargo tank could become over-pressurized, fail, lead to additional LNG spills, and increase hazards. A particular concern was Moss LNG cargo tanks, since some Moss insulation systems were considered to be quite vulnerable to high temperature degradation.

The significant reduction in heat transfer levels measured in the insulation damage testing discussed previously indicates that during the tests, charred insulation and soot formation is interfering with flux between the weather cover and the liquid nitrogen tank. Several possibilities exist; the atmosphere between the two surfaces could be acting as a participating media blocking heat flow. Alternatively, a very thin layer of insulation is left on the surface of the tank interfering with heat flux, or the charred insulation continues to act as a heat flux barrier along with the undamaged insulation. These possibilities suggest that different heat flux models should be considered and assessed.

Therefore, three models were considered as a way to bracket the potential range of heat flux values that an LNG cargo tank could experience during a fire. The estimates of heat flux to the cargo tank based on the experimental data and analysis from the cargo tank insulation damage testing suggests a potential range of values from 3-7 kW/m^2, with a most likely minimum value of ~5 kW/m^2. This value would be representative of a simple radiation heat transfer value. In considering both a participating media heat transfer analysis and a free convection heat transfer analysis for a Moss LNG cargo tank, the analyses support maximum heat flux estimates of up to 10 kW/m^2. Based on the fire modeling information, these heat flux values can be assumed to occur during free convection over the full tank surface area, including the area of the cargo tank below the main deck of the LNG vessel.

From the analyses, a heat flux of 5 kW/m^2 will result in an average pressure equivalent to the normal operating pressure of the cargo tank (~1.3 psig). A heat flux of 10 kW/m^2 will result in an average pressure of ~2.8 psig, and for the free convection case, a pressure of ~14.7 psig. Moss LNG cargo tanks are constructed to a design pressure which significantly exceeds the highest estimated pressure from the above scenarios. While the increased heat flux will cause some vaporization of the LNG in the vessel's cargo tanks, the cargo tank pressure relief valves are adequately sized to handle the resulting vapor production rates. Due to the combination of adequately sized cargo tank pressure relief valves and cargo tank design standards, there is a minimal likelihood of a Moss LNG cargo tank being damaged from a fire due to vapor over pressurization.

This approach was compared to an analysis performed by the Society of International Gas Tanker and Terminal Operators (SIGTTO) in 2009. This was an industry-wide study conducted to assess LNG cargo tank safety relief valve performance in the face of a large pool fire. The SIGTTO approach used standard handbook sizing algorithms and simplifying assumptions on fire/vessel interactions and cargo tank insulation damage rates, but reached similar conclusions. Overall, the testing and analyses suggest that the Moss LNG cargo tank insulation materials currently used can provide protection of the cargo tanks in a fire, and LNG vaporization would not increase to a level that would exceed the pressure safety relief valve capacity or damage the LNG vessel's cargo tanks. These analyses are presented in greater detail in Morrow, 2011.

LNG Vaporization and Deflagration Analysis

During an LNG spill, as the cryogenic LNG flows over the relatively warm structural steel within an LNG vessel, the LNG will begin to vaporize. Likewise, if a breach is at, near, or below the waterline, the LNG will also vaporize when it comes in contact with the relatively warm water. In both cases, the methane generated is flammable within a certain concentration range by volume in air (5 to 15 percent). Below five percent concentration, the vapor is too lean to burn, and above 15 percent concentration there is not enough air to sustain combustion.

During the spill flow analyses conducted, LNG vaporization and concentrations were also calculated. This provided an estimate of the amount and timing of the vapor generated and the likelihood of ignition, especially between the double hulls. In evaluating the calculated vaporization data, the combustible vapor concentrations varied spatially and temporally in each compartment and the ignitable concentrations in any region only lasted a few to ten seconds. Therefore, it is unlikely that ignition of methane vapors would occur inside the double hull compartments.

LNG Spill on Water Rapid Phase Transition Damage Analysis

A Rapid Phase Transition (RPT) is a phenomenon observed when two liquids of very different temperatures come into contact. LNG spilled onto water and undergoing a series of RPTs can create localized overpressures that look, sound, and behave like a small explosions. Where the explosive pressure is confined or where it is near structural elements, severe structural damage can occur.

In a review of the existing RPT information and data from LNG spills on water, the primary observation is that RPTs generally occur when LNG is either poured at high velocity onto water, or when water is sprayed at high velocity onto LNG. Therefore, we used the LNG flow results to identify and evaluate events with high LNG mixing rates. The results show that only a few events cause significant mixing. Those events that create the most mixing, and therefore the greatest likelihood of RPTs, occur relatively far away from an LNG vessel's outer hull. Therefore, the direct or additional damage of an RPT or a series of RPTs on the LNG vessel's outer hull is possible, but would likely cause minimal additional damage to the vessel.

VII. Large LNG Pool Fire Hazard Analyses

In this section we provide summarized thermal hazard distances resulting from large LNG spills and pool fires on water using solid flame models while the information is presented in detail in Luketa, 2011. The LNG pool fire hazard analysis parameters used in the 2004 and 2008 Sandia LNG reports (Hightower, et al. 2004) (Luketa, 2008) were based on LNG pool fire data of much smaller scale. In keeping with the principle of using the best available data, the parameters in those reports have been updated to reflect the newly acquired LNG pool fire and cascading damage data from this study. The former and updated fire parameter values are noted in Table 5 and are appropriate for use with common Solid Flame Fire Models. These types of models are suggested for their ease of use in estimating general hazard distances for a range of spills (Luketa, 2011).

Table 5: Recommended Nominal Values for Solid Flame Model

Nominal value	*2004 and 2008 Sandia LNG reports*	*Current report*
Burn rate (m/s)	3.0×10^{-4}	3.5×10^{-4}
Flame height (m)	Moorhouse correlation	Sandia correlation
SEP (kW/m^2)	220	286
Transmissivity	0.8	Wayne formula

As in the 2004 and 2008 Sandia reports, it must be emphasized that hazard distances from an LNG spill and fire will change depending on site-specific environmental conditions and breach scenarios, and site-specific analyses should be considered when appropriate.

Table 6 provides predicted thermal hazard distances for intentional events using the updated parameters and the same scenario matrix for hole sizes and tanks breached as presented in the 2004 Sandia report, which are contained in Table 7. The average pool size is calculated using the same approach as in the 2004 report, and the discharge coefficients also have not changed. Note the calculated pool diameter for the nominal cases are representative of pool diameters of 180 m to 350 m calculated for the spill and flow analyses conducted for this study.

The updated parameter values suggest the use of a higher heat flux, lower flame height, and the same pool diameters previously used, which result in about a two percent decrease in the thermal hazard distances relative to those predicted in the 2004 Sandia report for spills from smaller LNG vessels. Using the same approach, the hazard distances are reduced by about 7 to 8 percent relative to the 2008 Sandia report for larger vessels and larger spills.

From a cascading damage viewpoint, the analyses presented suggest that significant LNG vessel damage is likely from a large spill, but the major damage occurs about 15-30 minutes after an initial breach and spill. This is about the same time that a fire from an initial breach will begin to die out from a large spill. Therefore, it is expected that if cascading damage occurs, it will likely be a sequential, but not simultaneous, breach of other LNG cargo tanks, and suggests that evaluating hazard distances based on a nominal one-tank spill, with a maximum of a three-tank spill, as has been recommended in the 2004 Sandia report, is still appropriate for estimating hazard distances.

Table 6: Thermal hazard distances using parameters from the 2009 large pool fire test data

HOLE SIZE (m^2)	TANKS BREACHED	DISCHARGE COEFFICIENT	BURN RATE (m/s)	SURFACE EMISSIVE POWER (kW/m^2)	τ	POOL DIAMETER (m)	BURN TIME (min)	DISTANCE TO	
								37.5 kW/m^2 (m)	5 kW/m^2 (m)
INTENTIONAL EVENTS									
2	3	0.6	3.3×10^{-4}	286	nom	199	20	299	895
5	3	0.6	3.3×10^{-4}	286	nom	546	8.1	697	1894
5*	1	0.6	3.3×10^{-4}	286	nom	315	8.1	433	1266
5	1	0.3	3.3×10^{-4}	286	nom	223	16	329	974
5	1	0.6	1.9×10^{-4}	286	nom	415	8.1	471	1180
5	1	0.6	5.1×10^{-4}	286	nom	253	8.1	393	1252
5	1	0.6	3.3×10^{-4}	286	low	315	8.1	320	922
5	1	0.6	3.3×10^{-4}	248	nom	315	8.1	404	1183
5	1	0.6	3.3×10^{-4}	326	nom	315	8.1	479	1347
12	1	0.6	3.3×10^{-4}	286	nom	488	3.4	636	1748

*nominal case

Table 7: Thermal hazard distances in the 2004 Sandia LNG report

HOLE SIZE (m^2)	TANKS BREACHED	DISCHARGE COEFFICIENT	BURN RATE (m/s)	SURFACE EMISSIVE POWER (kW/m^2)	τ	POOL DIAMETER (m)	BURN TIME (min)	DISTANCE TO	
								37.5 kW/m^2 (m)	5 kW/m^2 (m)
INTENTIONAL EVENTS									
2	3	.6	3×10^{-4}	220	.8	209	20	250	784
5	3	.6	3×10^{-4}	220	.8	572	8.1	630	2118
5*	1	.6	3×10^{-4}	220	.8	330	8.1	391	1305
5	1	.3	3×10^{-4}	220	.8	233	16	263	911
5	1	.6	2×10^{-4}	220	.8	395	8.1	454	1438
5	1	.6	8×10^{-4}	220	.8	202	8.1	253	810
5	1	.6	3×10^{-4}	220	.5	330	8.1	297	958
5	1	.6	3×10^{-4}	175	.8	330	8.1	314	1156
5	1	.6	3×10^{-4}	350	.8	330	8.1	529	1652
12	1	.6	3×10^{-4}	220	.8	512	3.4	602	1920

*nominal case

VIII. LNG Spill Prevention and Risk Management

As noted in both the 2004 and 2008 Sandia LNG reports, risk prevention and mitigation techniques can be important tools in reducing both the potential for a spill and the hazards from a spill, especially in locations where the potential impact on public safety and property can be high. However, what might be applicable for cost-effective risk reduction in one location might not be appropriate at another location. Therefore, coordination of risk prevention and management approaches with local and regional emergency response and public safety officials is important in providing a comprehensive, efficient, and cost-effective approach to protect the public and property at a given LNG import or export location.

From an LNG vessel damage viewpoint, the analyses conducted and presented in this report suggest that significant damage is likely to LNG vessels from medium and large breach events and spills. Therefore, a large breach and spill could have both short-term and long-term impacts on public safety, energy security and reliability, and harbor and waterway commerce at some sites. For this reason, significantly more attention and proactive measures should be considered for preventing the possibility of larger breach and spill events or for mitigating the cryogenic and fire impacts of larger spills on LNG vessels.

Risk management options should be focused on approaches that can be used to actively prevent or mitigate larger spills. Some risk management approaches that can be considered to help reduce the possibility of an event occurring, or reduce the hazards to the vessel and the public should an event occur include:

- Implementation of enhanced operational security measures, to include:
    - Positive control of other vessel movements during LNG vessel transits and operations;
    - Review of LNG vessel escort protocols and operations to improve the ability to enforce exclusion zones through enhanced standoff and active interdiction approaches;
- Review of port operational contingency plans to ensure procedures are in place to address larger spills, to include options for moving the vessel to a safe anchorage to monitor, inspect, and assess damage, and for longer-term response options, including vessel lightering;
- Review of emergency response coordination and procedures for the LNG vessel, terminal or port, port authority, and emergency response groups to reduce the overall impacts and consequences of larger spills; and
- Review LNG vessel design, equipment, and operational protocols for improved fire protection to the LNG vessel, terminals, and vessel personnel from a large LNG fire.

IX. Conclusions

The major findings for smaller breach events include:

- For the very small breach events, which could occur from a number of credible accidental or intentional events, the spill rates are more than a 1,000 times less than that of potential larger breach events.
- This puts smaller spills into a regime that would typically fall within current spill detection and safety systems on LNG vessels such that it is extremely likely there would be sufficient time to move the vessel to a safe anchorage to monitor, inspect, and assess damage and long-term response options.

The major findings for medium and larger breach events:

- Large-scale fracture testing, cryogenic flow analyses, and fire modeling indicated that LNG vessels would be disabled, severely damaged, and at risk of sinking.
- For these events, LNG vessels would not be capable of movement to a safe anchorage, and would require longer periods to monitor, inspect, assess, and establish long-term response and remediation measures.

The major findings for Cascading Damage Hazards:

- Current LNG vessel and cargo tank design, materials, and construction practices are such that simultaneous multi-cargo tank cascading damage spill scenarios are extremely unlikely, though sequential multi-cargo tank cascading damage spill scenarios are possible.

- Should sequential cargo tank spills occur, they are not expected to increase hazard distances resulting from an initial spill and pool fire, but could increase the duration of the fire hazards.
- Based on the data collected from the large-scale LNG pool fire tests conducted, thermal (fire) hazard distances to the public from a large LNG pool fire will decrease by at least 2 to 7 percent compared to results obtained from previous studies.
- Risk management strategies to reduce potential LNG vessel vulnerability and damage from breach events which can result in large spills and fires should be considered for implementation as a means to eliminate or reduce both short-term and long-term impacts on public safety, energy security and reliability, and harbor and waterways commerce.

References

Adaptive Research, (2008). CFD2000 - A general-purpose CFD program intended for complex scientific and engineering flow calculations), Keith Kevin O'Rourke.

Blanchat, T., Helmick, P., Jensen, R., Luketa, A., Deola, R., Suo-Anttila, S., Mercier, J., Miller, T., Ricks, A., Simpson, R., Demosthenous, B., Tieszen, S., and Hightower, M., (2010). *The Phoenix Series Large Scale LNG Pool Fire Experiments*, SAND2010-8676, Sandia National Laboratories, Albuquerque, NM.

Blanchat, T. (2011). *LNG Carrier Tank Insulation Decomposition Experiments with Large Scale Pool Fire Boundary Conditions*, SAND2011-1880, Sandia National Laboratories, Albuquerque, NM.

Figueroa, V.G., Lopez, C., O'Rourke, K.K.,(2011). *LNG Cascading Damage Study Volume II: Flow Analysis for Spills from MOSS and Membrane LNG Cargo Tanks*, SAND2011-9464. Sandia National Laboratories, Albuquerque, NM.

GAO (2007). "Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification," Government Accountability Office report, GAO -07-316, February 2007.

Hightower, M., et al. (2004). *Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural (LNG) Spill Over Water*, SAND2004-6258. Albuquerque, NM: Sandia National Laboratories.

Hightower, M., Luketa-Hanlin, A., Gritzo, L.A., Covan, J.M. (2006). *Review of Independent Risk Assessment of the Proposed Cabrillo Liquefied Natural Gas Deepwater Port Project*, SAND2005-7339, Sandia National Laboratories, Albuquerque, NM.

Kalan, R. J., Petti, J. P.(2010). *LNG Cascading Damage Study Volume I: Fracture Testing Report*, SAND2011-3342, Sandia National laboratories, Albuquerque, NM.

Luketa, A.J., (2005). *A Review of Large-Scale LNG Spills: Experiment and Modeling*, SAND2005-2452J, Sandia National Laboratories, Albuquerque, NM.

Luketa, A.J., M.M. Hightower, S. Attaway, (2008). *Breach and Safety Analysis of Spills over Water from Large Liquefied Natural Gas Carriers*, SAND2008-3153, Sandia National Laboratories, Albuquerque, NM.

Luketa, A. J. (2011), *Recommendations on the Prediction of Thermal Hazard Distances from Large Liquefied Natural Gas Pool Fires on Water for Solid Flame Models*, SAND2011-9415, Sandia National Laboratories, Albuquerque, NM.

Morrow, C., *Cascading Damage from LNG Pool Fire – Potential for Overpressure or Thermal Damage to Adjacent Cargo Tanks*, SAND2011-9414, Sandia National Laboratories, Albuquerque, NM.

Petti, J.P., Wellman, G.W., Villa, D., Lopex, C., Figueroa, V.G., Heinstein, M. (2011), *LNG Cascading Damage Study Volume III: Vessel Structural and Thermal Analysis Report*, SAND2011-6226, Sandia National Laboratories, Albuquerque, NM.

SIGTTO (2009). Report on the Effects of Fire On LNG Carrier Containment Systems, Society of International Gas Tanker & Terminal Operators, March 19, 2009, Witherby Seamanvessel International Ltd, Scotland, UK.

Exhibit 7

SANDIA REPORT

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

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Abstract

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

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

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Eric Linsner – PRONAV Ship Management
Mike Edens – Office of Naval Intelligence
Richard Hoffmann – Federal Energy Regulatory Commission
Chris Zerby – Federal Energy Regulatory Commission

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

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Dr. Carlos Fernandez-Pello – Professor of Fire Sciences, University of California Berkeley
Dr. Ron Koopman – Consultant on LNG spills and modeling
Dr. Fred Mowrer – Associate Professor of Fire Protection Engineering, University of Maryland

CONTENTS

APPENDICES

APPENDIX A RECENT LNG SPILL MODELING REVIEW

APPENDIX B THREAT ANALYSIS AND SPILL PROBABILITY

APPENDIX C LNG SPILL AND DISPERSION ANALYSIS

APPENDIX D SPILL CONSEQUENCE ANALYSIS

FIGURES

TABLES

SYMBOLS AND ACRONYMS

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

FOREWORD

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

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

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

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

1 EXECUTIVE SUMMARY

The increasing demand for natural gas in the U.S. could significantly increase the number and frequency of marine LNG imports. While many studies have been conducted to assess the consequences and risks of potential LNG spills, the increasing importance of LNG imports suggests that consistent methods and approaches be identified and implemented to help ensure protection of public safety and property from a potential LNG spill.

For that reason, the U.S. Department of Energy (DOE), Office of Fossil Energy, requested that Sandia National Laboratories (Sandia) develop guidance on a risk-based analysis approach to assess and quantify potential threats to an LNG ship, the potential hazards and consequences of a large spill from an LNG ship, and review prevention and mitigation strategies that could be implemented to reduce both the potential for and the risks of an LNG spill over water. Specifically, DOE requested:

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

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

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

Key Conclusions

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

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

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

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

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

1.1.1 LNG Spill Prevention and Mitigation

Risks from a potential LNG spill over water could be reduced through a combination of approaches, including 1) reducing the potential for a spill, 2) reducing the consequences of a spill, or 3) improving LNG transportation safety equipment, security, or operations to prevent or mitigate a spill.

For example, a number of international and U.S. safety and design standards have been developed for LNG ships to prevent or mitigate an accidental LNG spill over water. These standards are designed to prevent groundings, collisions, and steering or propulsion failures. They include traffic control, safety zones around the vessel while in transit within a port, escort by Coast Guard vessels, and coordination with local law enforcement and public safety agencies. In addition, since September 11, 2001, further security measures have been implemented to reduce the potential for intentional LNG spills over water. They include earlier notice of a ship's arrival (from 24 hours to 96 hours), investigation of crew backgrounds, at-sea boardings of LNG ships and special security sweeps, and positive control of an LNG ship during port transit.

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

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

Risk prevention and mitigation techniques can be important tools in reducing both the potential for and the hazards of a spill, especially in zones where the potential impact on public safety and property can be high. However, what might be applicable for effective risk reduction in one location might not be appropriate at another. The options identified in Table 1 provide examples of how implementation of different strategies, alone or in combination, can be used to reduce certain threats, mitigate consequences of a spill, or reduce hazard analysis uncertainties.

Table 1: Representative Options for LNG Spill Risk Reduction

IMPACT ON PUBLIC SAFETY	REDUCTION IN EVENT POTENTIAL (Prevention)	IMPROVE SYSTEM SECURITY AND SAFETY (Mitigation)	IMPROVED HAZARD ANALYSIS (Reduce Analytical Uncertainties)	RESULTANT RISK REDUCTION
High and Medium	▪ Early off-shore interdiction ▪ Ship inspection ▪ Control of ship, tug and other vessel escorts ▪ Vessel movement control zones (safety/security zones) ▪ One-way traffic ▪ LNG offloading system security interlocks	▪ Harbor pilots ▪ Ship and terminal safety and security upgrades ▪ Expanded emergency response and fire fighting to address fires, vapor clouds, and damaged vessels	▪ Use of validated CFD models for LNG spill and thermal consequence analysis for site specific conditions ▪ Use of CFD and structural dynamic models for spill/structure interactions	Combination of approaches to reduce risks to acceptable levels
Low	Use of existing best risk management practices on traffic control, monitoring & safety zones	Use of existing best risk mitigation practices to ensure risks remain low	Use of appropriate models to ensure hazards are low for site-specific conditions	Combination of approaches to ensure risks are maintained at acceptable levels

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

1.1.2 LNG Breach, Spill, and Hazard Analyses

Currently, the potential for an LNG cargo tank breach, whether accidental or intentional, the dynamics and dispersion of a large spill, and the hazards of such a spill, are not fully understood, for two primary reasons. First, the combination of current LNG ship designs and safety management practices for LNG transportation have reduced LNG accidents to the extent that there is little historical or empirical information on the consequences of breaches or large spills. Second, existing experimental data on LNG spill dynamics and its dispersion over water address spill sizes that are more than a factor of one hundred smaller than spill sizes currently being postulated for some intentional events. Variations in site conditions, LNG ship designs, and environmental conditions further complicate hazard predictions.

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

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

LNG Cargo Tank Breach Analysis

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

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

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

Spill and Dispersion Analysis

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

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

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

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

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

Hazards Analysis and Public Safety Impacts

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

To assess the general magnitude of expected hazard levels, a limited sensitivity analysis was performed using simplified models for a range of spill volumes. The spill volumes were based on potential breaches from credible accidental and intentional threats. These analyses are summarized in Sections 4 and 5 of this report. While not conducted for a specific site, the analyses provide examples of general considerations for hazards and risks. From the assessment conducted, thermal hazards will occur predominantly within 1600 m of an LNG ship spill, with the highest hazards generally in the near field (approximately 250 - 500 m of a spill). While thermal hazards can exist beyond 1600 m, they are generally lower in most cases.

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

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

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

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

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

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

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

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

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

1.2 Safety Analysis Conclusions

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

1.2.1 General Conclusions

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

1.2.2 Accidental Breach Scenario Conclusions

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

1.2.3 Intentional Breach Scenario Conclusions

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

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

1.3 Guidance on Risk Management for LNG Operations over Water

Risk identification and risk management processes should be conducted in cooperation with appropriate stakeholders, including public safety officials and elected public officials. Considerations should include site-specific conditions, available intelligence, threat assessments, safety and security operations, and available resources. This approach should be performance-based and include identification of hazards and risks, protection required for public safety and property, and risk prevention and mitigation strategies.

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

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

1.3.1 Guidance on Risk Management for Accidental LNG Spills

Zone 1

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

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

Zone 2

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

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

Zone 3

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

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

1.3.2 Guidance on Risk Management for Intentional LNG Spills

Zone 1

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

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

Zone 2

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

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

Zone 3

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

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

2 BACKGROUND

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

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

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

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

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

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

2.1 History and Description of LNG

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

2.1.1 Growth of International LNG Transportation

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

A fleet of about 150 specially designed LNG ships is currently being used to transport natural gas around the globe. Worldwide, there are 17 LNG export (liquefaction) terminals and 40 import (re-gasification) terminals. This commercial network handles approximately 120 million tons of LNG every year. LNG carriers often travel through areas of dense traffic. In 2000, for example, Tokyo Bay averaged one LNG cargo every 20 hours and one cargo per week entered Boston harbor. Estimates are that world wide LNG trade will increase 35% by 2020. The major areas for increased LNG imports are Europe, North America, and Asia [Kaplan and Marshal 2003] [DOE 2003].

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

Import of natural gas into the U.S. is expected to double over the next 20 years [DOE 2003]. Four to eight new LNG terminals are expected to be constructed in the next four to five years and more than 40 new terminal sites are under consideration and investigation. A factor in the siting of LNG receiving terminals is the proximity to market. Therefore, terminals are being considered in areas with high natural gas demands, which includes locations on all three U.S. coasts. Most are being planned to handle one to two LNG tanker shipments per week.

2.1.2 LNG Transportation by Ship

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

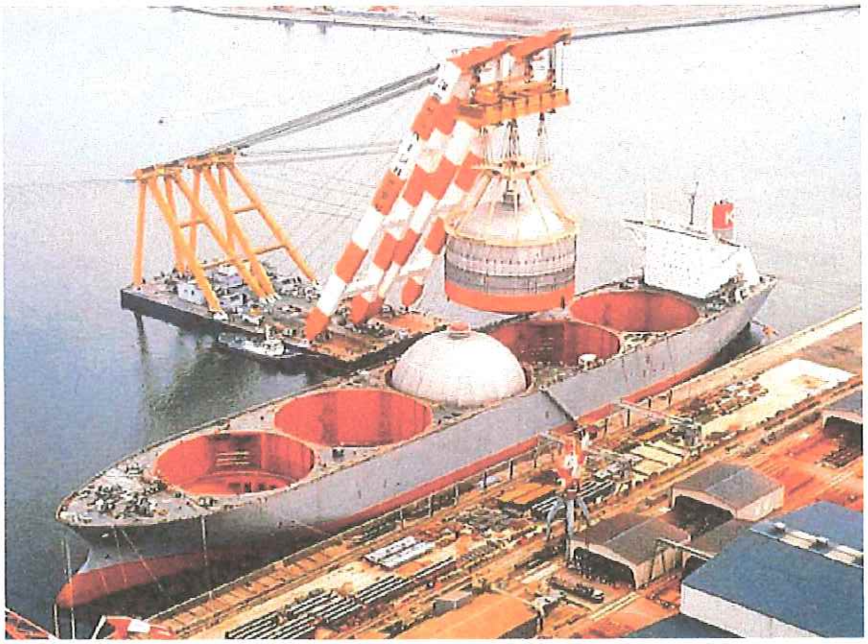


Figure 1. Moss-Spherical LNG Tanker Ship

Figure 2. Prismatic Tanker Ship

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

Some of the special features of LNG ships include:

- Construction of specialized materials and equipped with systems designed to safely store LNG at temperatures of -260 °F (-162.2°C).
- All LNG ships are constructed with double hulls. This construction method not only increases the integrity of the hull system but also provides additional protection for the cargo tanks in the event of an accidental collision.
- Coast Guard regulations and the "International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk" (International Gas Carrier Code) require that LNG ships meet a Type IIG standard, which is an intermediate-level safety design standard for hazardous cargoes that includes direction on double-hull designs and materials, subdivision, damage stability, and cargo tank location.

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

2.1.3 LNG Properties

Typical properties of LNG:

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

Table 4 lists the flammability limits for several compounds.

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

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

2.2 Growing Interest in LNG Safety and Security

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

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

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

3 RISK ASSESSMENT OF LNG SPILLS OVER WATER

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

Risk = $\mathbf{P_t}$ (threat occurring) x $\mathbf{P_s}$ (system failure/threat) x **Consequences**;

Where: $\mathbf{P_t}$ = the probability of an accidental or intentional threat,

$\mathbf{P_s}$ = the probability that preventive or mitigating measures fail, and

Consequences = usually expressed in fatalities or costs.

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

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

3.1 Risk Analysis Elements of a Potential LNG Spill

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

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

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

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

3.2 LNG Spill Risk Assessment and Management Process

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

- Evaluating the potential for an event that could cause a breach or loss of LNG from a ship;
- Establishing the potential damage to a cargo tank or other system from these events and the potential spills that could occur;
- Estimating the volume and rate of a potential LNG spill based on the dimensions and location of the breach, properties and characteristics of the LNG, ship construction and design, and environmental conditions (e.g., wind, waves, currents, etc.);
- Estimating the dispersion, volatilization, and potential hazards of a spill based on physical and environmental conditions; and
- When necessary, identifying prevention and mitigation approaches and strategies to meet risk management goals.

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

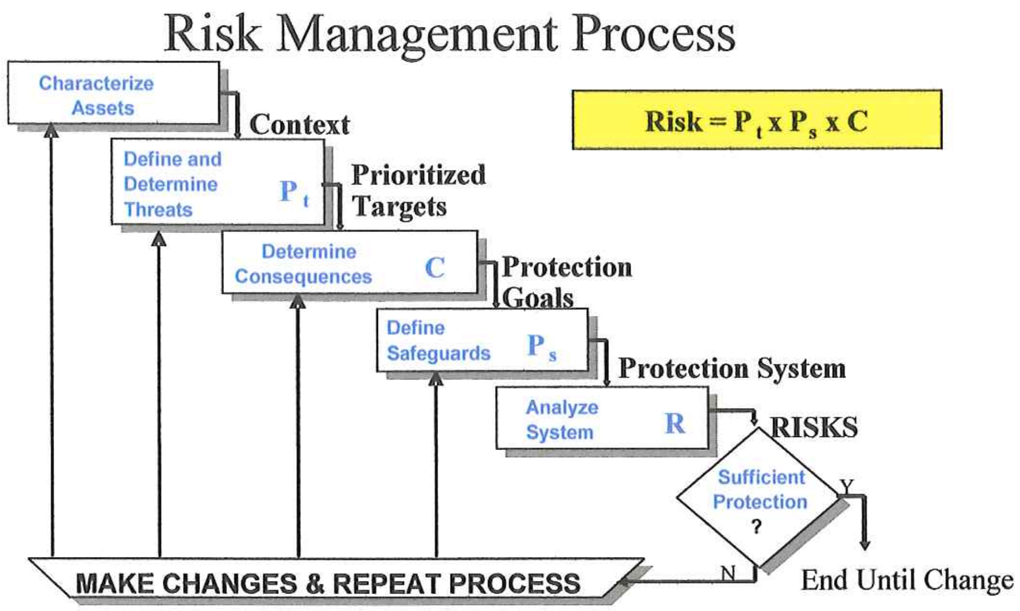


Figure 3. Risk Assessment and Risk Management Approach

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

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

Table 5: Examples of Potential LNG Transportation Safeguards and Impacts

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

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

3.3 The Elements of an LNG Spill over Water

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

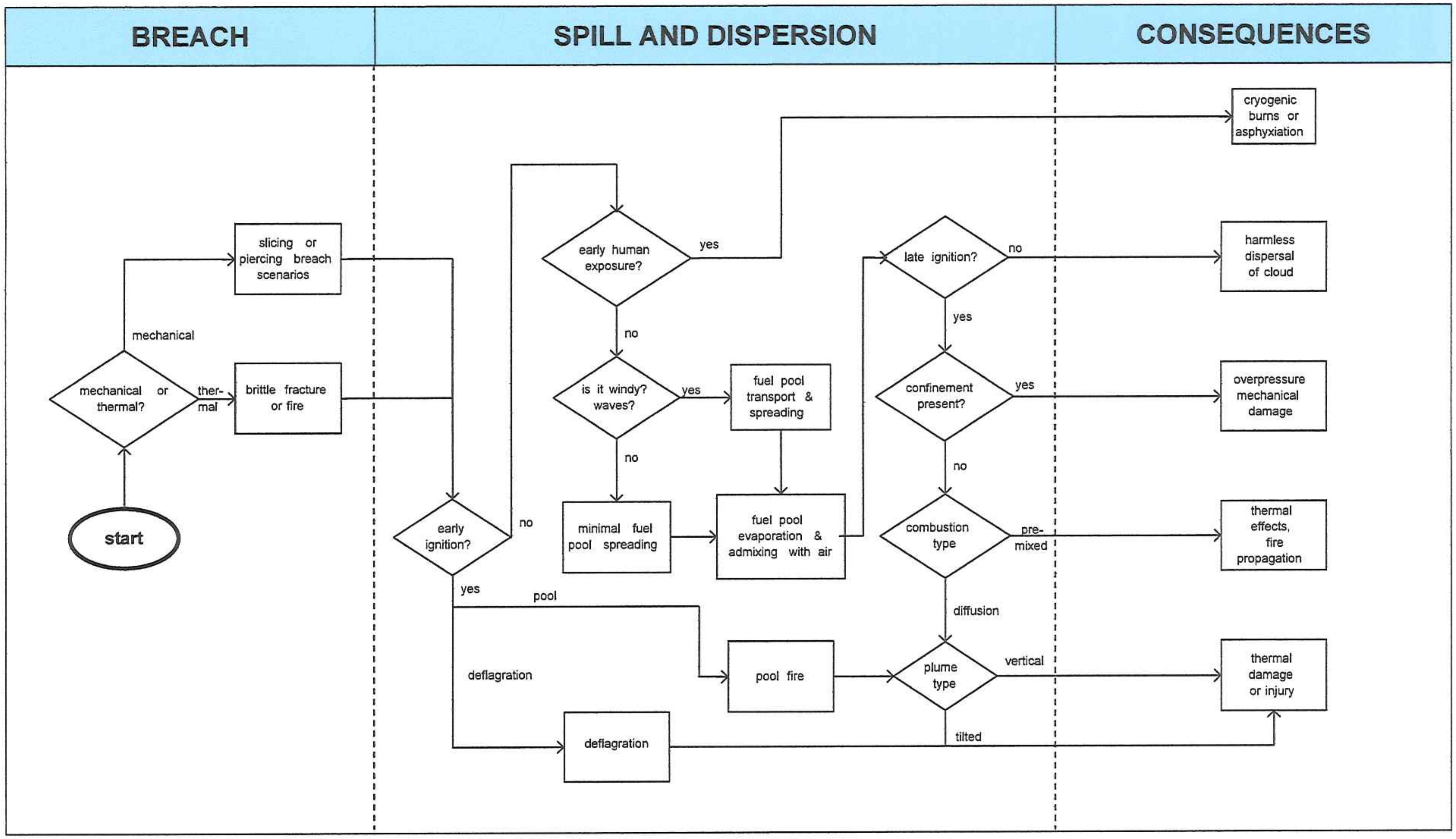


Figure 4. Potential Sequences of Events Following a Breach of an LNG cargo tank

3.3.1 LNG Cargo Tank Breaches

The variables that influence an LNG cargo tank breach include:

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

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

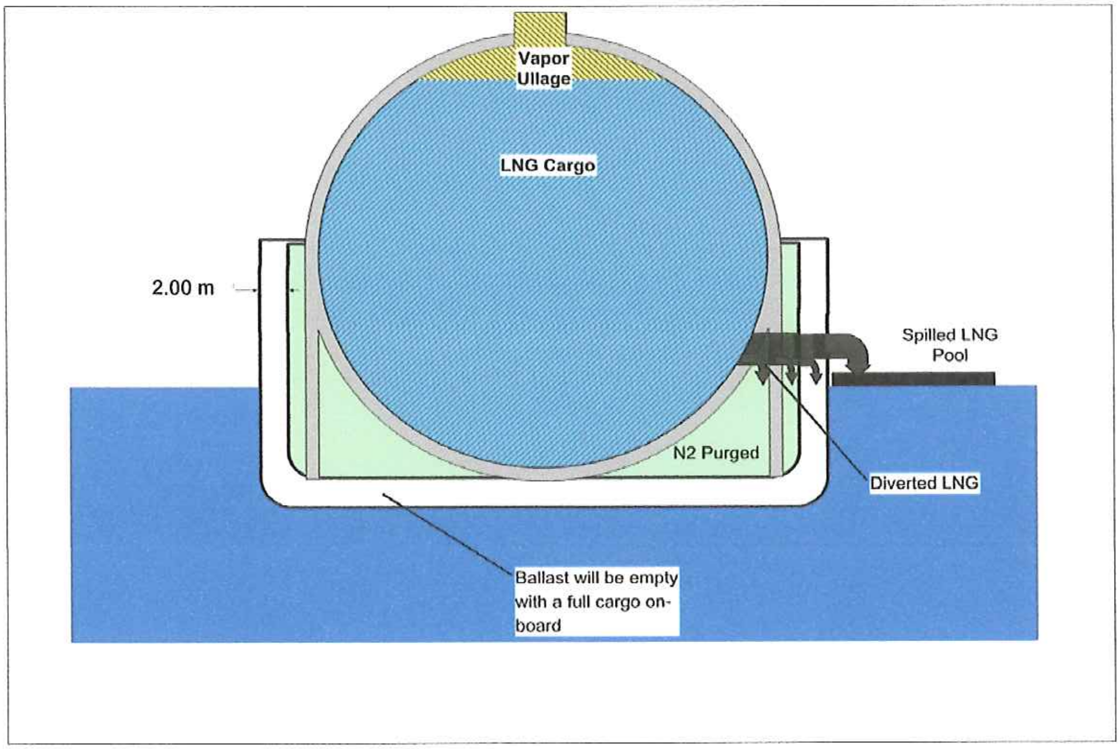


Figure 5. Anatomy of an LNG Spill on Water

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

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

3.3.2 LNG Spill Dispersion after a Breach

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

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

3.3.3 Potential Consequences from an LNG Spill over Water

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

Asphyxiation

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

Cryogenic Burns and Structural Damage

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

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

Combustion and Thermal Damage

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

Table 6: Common, Approximate Thermal Radiation Damage Levels

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

*Based on an average 10 minute exposure time

[Barry 2002]

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

Generally, combustion of LNG vapor is controlled by two limiting factors: 1) whether the LNG vapor does not have enough time to mix with the air (called non-pre-mixed combustion), and 2) whether the ignition occurs after the fuel has time to mix with the surrounding air (appropriately called 'pre-mixed combustion'). Therefore, ignition time is important in spill scenarios to assess appropriately the type and extent of thermal radiation from an LNG spill and fire. As noted in Table 6, combustion and thermal damage from a fire can have severe consequences and should be carefully and thoroughly analyzed.

LNG/Fireballs

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

LNG/Air Explosions

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

Rapid Phase Transitions (RPT)

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

3.4 Evaluation of Four Recent LNG Spill Modeling Studies

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

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

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

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

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

Table 7: Summary of Assumptions in the Four Studies Analyzed

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

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

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

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

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

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

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

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

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

4 ACCIDENTAL LNG BREACH, SPILL, AND HAZARD ANALYSES

Currently, the potential for an accidental LNG cargo tank breach, the dynamics and dispersion of a spill, and the hazards of such a spill, are only generally understood because the combination of LNG ship designs and current safety management practices for LNG transportation have reduced LNG accidents to a level such that there is little historical or empirical information on breaches or spills.

This lack of information forces analysts to make many assumptions and simplifications when calculating the size, dispersion, and thermal hazards of a spill, as discussed in Section 3 and detailed in Appendix A for four recent LNG spill studies. Therefore, it should be understood that while many existing models and techniques can be used to provide adequate guidance on the hazards of an LNG spill, a level of variability can exist in estimating the potentiality and size of a breach and the extent of the hazards from an associated spill.

This section summarizes the modeling and analyses conducted to assess the potential for an accidental breach of an LNG cargo tank, the probable size of a potential accidental breach, and the associated spill size and hazards to people and property from a resulting spill. The detailed results of these analyses are presented in Appendices B – D.

4.1 Analysis of Accidental Breach Scenarios of an LNG Cargo Tank

As noted in Section 2 of this report, the LNG industry has an exemplary safety record, with only eight accidents over the past 40 years. None of these accidents led to a loss of life. Even with this excellent safety record, consideration should be given to what might be a likely LNG cargo tank breach based on a potential accidental collision with another ship, grounding, or ramming. The severity of a breach based on these events depends on the location, vessel design, relative vessel speeds and collision alignment, and mitigation or prevention systems in place to limit potential damage.

Using previously conducted finite element modeling of collisions of a series of ships with a double-hulled oil tanker similar in overall size, mass, and design to an LNG vessel, we were able to estimate the level of damage and hole sizes expected for several different accident scenarios [Ammerman 2002]. These analyses were conducted using PRONTO-3D, a transient dynamic, explicitly integrated, Eulerian finite volume code. The analysis tracked the progressive failure of the struck ship as the striking ship penetrated and the results are discussed and presented in detail in Appendix B. The results show that breaching of the inner hull does not occur until impact velocities exceed approximately 5 – 6 knots for large vessels. For small vessels, such as pleasure craft, the kinetic energy is generally insufficient to penetrate the inner hull of a double-hulled vessel such as an LNG ship. This analysis also calculated that penetration into a double-hulled tanker must be approximately three meters before a hole occurs in the inner hull, which can be used to estimate the minimum size of a penetration to cause a spill in a grounding event.

Because of the additional insulation and third level of containment in many LNG vessels, it is expected that a deeper penetration would be required to rupture the primary LNG cargo tank. Therefore, because of its general design and construction, collision velocities for equivalent hole sizes could be expected to be one to two knots higher for an LNG vessel. This would suggest that the required velocity to cause a breach of an LNG cargo tank during a 90 deg collision with a large vessel could be six to seven knots.

After a collision with an LNG tanker in which LNG is pouring out, the striking ship would probably back out, unless it could not move. In many collisions between two ships, the ships can remain joined for several hours, if significant penetration of one ship occurs. The analysis by Ammerman discussed in Appendix B suggests that as little as 5% – 10% of the generated breach size would be available for the release of LNG. Therefore, the collision of a large ship with an LNG carrier at even 10 knots is expected to produce an effective hole size of no more than approximately one square meter for an LNG spill.

The size and location of potential breaches were used as a basis for analysis of the potential for cryogenic damage to the structural steel of an LNG ship from a spill. Contact of steel with cryogenic fluids is known to cause embrittlement, which can significantly reduce the strength of steel [Vaudolon 2000]. A detailed structural analysis was beyond the scope of this review; but structural integrity embrittlement scoping analyses were conducted to assess the potential damage to an LNG ship from small and large LNG spills based on available fracture mechanics data and models. These analyses were guided by available information on LNG ship and tank designs, construction, and structural steel material property data [Linsner 2004] [Shell 2002] [Wellman 1983] and are discussed in detail in Appendix D.

In general, the results suggest that the critical flaw size for cryogenic damage of common LNG ship steels is less than one-tenth of an inch. It is common to see flaws of this size in typical, welded construction or around corrosion areas. Therefore, it is expected that some cryogenic damage of the LNG vessel, even for some accidental spills, would be likely. The extent and impact of the damage will depend on the breach and spill size and location and effectiveness of risk prevention and mitigation strategies and should be considered relative to overall ship integrity and LNG cargo tank support integrity.

A summary of the potential breach size and potential ship damage from several different accident scenarios is presented in Table 9, based on the detailed analyses presented in Appendices B and D.

Table 9: Estimated LNG Cargo Tank Breach Sizes for Accidental Scenarios

ACCIDENTAL BREACHES			
Type	**Breach Size**	**Tanks Breached**	**Ship Damage**
Accidental collision with small vessel	None	None	Minor[b]
Accidental collision with large vessel	5 - 10m^2 (Spill area 0.5 – 1m^2)[a]	1	Moderate[c]
Accidental Grounding	None	None	Minor

Notes:
a - Assumes vessels remain joined during spill event and breach is mostly plugged
b - Minor suggests ship can be moved and unloaded safely
c – Moderate suggests damage that might impact vessel and cargo integrity

The potential breaching of an LNG cargo tank due to an accident, such as a collision or grounding, appears to be minimal. Such a breach can be easily reduced through a number of operational mechanisms, including managing ship traffic, coordinating ship speeds, and by active ship control in inner and outer harbors where the consequences of a potential LNG spill might be most severe. These methods are all currently used by the Coast Guard. Therefore, the safety and hazard issues that can lead to an accidental breach appear manageable with current safety policies and practices.

4.2 Spill and Hazard Analysis of an Accidental Breach of a Cargo Tank

After developing an assessment of the potential sizes of LNG cargo tank breaches, the relative size of various spills and potential hazards and impacts on public safety and property were assessed. These results are discussed in detail in Appendix C for evaluation of spill dispersion and volatilization and thermal impacts; and in Appendix D for evaluation of asphyxiation, LNG ship structural damage, and structural damage to critical infrastructure elements.

4.2.1 Fire Hazard Evaluation of an Accidental LNG Spill

In most of the scenarios identified, the thermal hazards from an accidental spill are expected to manifest as a pool fire, based on the high probability that an ignition source will be available from most of the events identified. Based on a detailed review of the existing experimental literature presented in Appendix C, nominal fire modeling parameters were used to calculate the expected thermal hazards from a fire for the accidental breach scenarios developed.

For example, a solid flame model that accounts for view factors and transmissivity and the Moorhouse correlation for flame height to diameter was used. A low wind condition was assumed; therefore, flame tilt and drag were not required. A surface emissive power of 220 kW/m^2, a transmissivity value of 0.8, and a burn rate of 3×10^{-4} were also used. The volume of the spill assumed for each breached LNG cargo tanks was approximately 12, 500 m^3 or about half the contents of the average LNG cargo tank. The fire duration was based on the hole size, associated spill rate and the assumed burn rate.

Several significant fire parameters have a range of values, thus a parameter variation was performed to ascertain the result on thermal hazard distance. By grouping these parameters to result in extremes of hazard distances, it can be shown that the ranges can vary by factors of five to ten. Such groupings are not probable; therefore, it is more reasonable to choose a nominal case and conservatively vary different factors individually to bounding values to obtain hazard distances. This general approach is presented in Appendix D and a summary of the results calculated using that approach for potential accidental spills is shown in Table 10, where the distance to 37.5 kW/m^2 and 5 kW/m^2 is from the center of the pool.

Table 10: Effect of Parameter Combinations on Pool Diameter in an Accidental Breach

HOLE SIZE (m^2)	TANKS BREACHED	DISCHARGE COEFFICIENT	BURN RATE (m/s)	SURFACE EMISSIVE POWER (kW/m^2)	POOL DIAMETER (m)	BURN TIME (min)	DISTANCE TO 37.5 kW/m^2 (m)	DISTANCE TO 5 kW/m^2 (m)
1	1	.6	$3X10^{-4}$	220	148	40	177	554
2	1	.6	$3X10^{-4}$	220	209	20	250	784
2	3	.6	$3X10^{-4}$	220	362	20	398	1358

The results presented in Table 10 show that thermal hazards of 37.5 kW/m^2 from a potential accidental breach of an LNG cargo tank and potential fire are expected to exist within approximately 150 - 250 m of the spill, depending on site-specific conditions. Thermal hazards of 5 kW/m^2 are expected to exist out to 500 and 750 m from the spill.

The multi-hole spill scenario presented considers the potential for a failure of three cargo tanks due to a long-duration fire that might occur in a smaller accidental spill. The impact of a fire on adjacent LNG cargo tanks is discussed in detail in Appendix D. Based on this analysis, depending on cargo tank design and fire duration, the potential for cascading damage to additional LNG tanks cannot be ruled out. A conservative estimate of the size of such a cascading fire and the thermal hazard distances from the fire were calculated assuming three simultaneous ruptures. In reality, the tank ruptures would more likely be sequential and, therefore, the hazard distances presented should be considered as conservative estimates.

4.2.2 Evaluation of Vapor Dispersion Hazard of Accidental LNG Spills

In most of the scenarios identified, the thermal hazards from an accidental spill are expected to manifest as a pool fire, based on the high probability that an ignition source will be available from most of the events identified. In some instances, an immediate ignition source might not be available and the spilled LNG could, therefore, disperse as a vapor cloud. Based on Sandia's review of data discussed in Appendix C, the vapor cloud for large spills could extend to beyond 1600 m, depending on spill location and site atmospheric conditions. In congested or highly populated areas, an ignition source would be likely; as opposed to remote areas, in which an ignition source might be less likely.

This suggests that LNG vapor dispersion analysis should be conducted using site-specific atmospheric conditions, location topography, and ship operations to assess adequately the potential areas and levels of hazards to public safety and property. Risk mitigation measures, such as development of procedures to quickly ignite a dispersion cloud and stem the leak, should be considered if conditions exist that the cloud would impact critical areas.

If ignited close to the spill, and early in the spill, the thermal loading from the vapor cloud ignition might not be significantly different from a pool fire, because the ignited vapor cloud would burn back to the source of liquid LNG and transition into a pool fire. If a large vapor cloud formed, the flame could propagate downwind, as well as back to the source. If the cloud is ignited at a significant distance from the spill, the thermal hazard zones can be extended significantly. The thermal radiation from the ignition of a vapor cloud can be very high within the ignited cloud and, therefore, particularly hazardous to people.

In order to obtain LNG dispersion distances to the lower flammability level (LFL) for accidental events, calculations were performed using VULCAN, a CFD code capable of simulating fire and non-fire conditions. The details of this modeling approach are discussed in detail in Appendix D. A low wind speed and highly stable atmospheric condition were chosen because this has shown to result in the greatest distances to LFL from experiment, and thus should be most conservative. A wind speed of 2.33 m/s at 10 m above ground and an F stability class were used for these simulations. The time it took for the LFL to be reached was approximately 20 minutes. As indicated in Table 11, dispersion distances to LFL for LNG spill vapor dispersion from an accidental spill might conservatively be approximately 1500 to 1700 m.

Table 11: Dispersion Distances to LFL for Accidental Spills

HOLE SIZE (m^2)	TANKS BREACHED	POOL DIAMETER (m)	SPILL DURATION (min)	DISTANCE TO LFL (m)
1	1	148	40	1536
2	1	209	20	1710

The results from the fire and vapor dispersion calculations suggest that high thermal hazards for accidental spills do not extend significantly from the spill location, but that some thermal hazards are possible to significant distances, especially if a vapor cloud occurs without early ignition and drifts into a critical area of facility. Table 12 summarizes the estimated results of the impact on public safety and property for an accidental LNG cargo tank breach and spill. In this table, high impact would include a thermal intensity in the range of 37.5 kW/m^2 and low values would correspond to thermal intensities in the range of 5 kW/m^2.

Table 12: Estimated Impact of Accidental LNG Breaches & Spills on Public Safety & Property

EVENT	POTENTIAL SHIP DAMAGE AND SPILL	POTENTIAL HAZARD	POTENTIAL IMPACT ON PUBLIC SAFETY*		
			~250 m	~250 – 750 m	>750 m
Collisions: Low speed	Minor ship damage, no breach	Minor ship damage	Low	Very Low	Very Low
Collisions: High Speed	LNG cargo tank breach from 0.5 to 1.5 m^2 spill area	▪ Small fire ▪ Damage to ship ▪ Vapor Cloud	High Medium High	Medium Low High - Medium	Low Very Low Medium
Grounding: <3 m high object	Minor ship damage, no breach	Minor ship damage	Low	Very Low	Very Low

*Distance to spill origin, varies according to site

Very low – little or no property damage or injuries
Low – minor property damage and minor injuries
Medium –potential for injuries and property damage
High – major injuries and significant damage to structures

5 INTENTIONAL LNG BREACH, SPILL, AND HAZARD ANALYSES

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

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

5.1 Analysis of Intentional Breach Scenarios of an LNG Cargo Tank

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

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

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

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

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

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

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

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

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

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

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

5.1.1 Evaluation of the Fire Hazard of an Intentional LNG Spill

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

As stated in Section 4, in most of the scenarios identified, the thermal hazards from an intentional spill are expected to manifest as a pool fire, based on the high probability that an ignition source will be available from most of the events identified. Based on a detailed review of the existing experimental literature presented in Appendix C, nominal fire modeling parameters were used to calculate the expected thermal hazards from a fire for the intentional breach scenarios developed. The same modeling approach and assumptions as discussed in Section 4 were used for these analyses. While the details of the analyses are presented in Appendix D, a summary of these results is shown in Table 14, where the distances to 37.5 kW/m^2 and 5 kW/m^2 are from the center of the pool.

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

HOLE SIZE (m^2)	TANKS BREACHED	DISCHARGE COEFFICIENT	BURN RATE (m/s)	SURFACE EMISSIVE POWER (kW/m^2)	POOL DIAMETER (m)	BURN TIME (min)	DISTANCE TO 37.5 kW/m^2 (m)	DISTANCE TO 5 kW/m^2 (m)
2	3	.6	3×10^{-4}	220	209	20	250	784
5	3	.6	3×10^{-4}	220	572	8.1	630	2118
5*	1	.6	3×10^{-4}	220	330	8.1	391	1305
5	1	.9	3×10^{-4}	220	405	5.4	478	1579
5	1	.6	2×10^{-4}	220	395	8.1	454	1538
5	1	.6	3×10^{-4}	350	330	8.1	529	1652
12	1	.6	3×10^{-4}	220	512	3.4	602	1920

*nominal case

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

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

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

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

5.1.2 Evaluation of Vapor Dispersion Hazard of Intentional LNG Spills

In most of the scenarios identified, the thermal hazards from a spill are expected to manifest as a pool fire, based on the high probability that an ignition source will be available from most of the events identified. In some instances, such as an intentional spill without a tank breach, an immediate ignition source might not be available and the spilled LNG could, therefore, disperse as a vapor cloud. For large spills, the vapor cloud could extend to more than 1600 m, depending on spill location and site atmospheric conditions. In congested or highly populated areas, an ignition source would be likely, as opposed to remote areas, in which an ignition source might be less likely.

As mentioned in Section 4, the impact from a vapor cloud dispersion and ignition from a large spill can extend beyond 1600 meters, based on our review of external data discussed in Appendix C. This suggests that LNG vapor dispersion analysis should be conducted using site-specific atmospheric conditions, location topography, and ship operations to assess adequately the potential areas and levels of hazards to public safety and property. Consideration of risk mitigation measures, such as development of procedures to quickly ignite a dispersion cloud and stem the leak, if conditions exist that the cloud would impact critical areas.

If ignited close to the spill, and early in the spill, the thermal loading from the vapor cloud ignition might not be significantly different from a pool fire, because the ignited vapor cloud would burn back to the source of liquid LNG and transition into a pool fire. If a large vapor cloud formed, the flame could propagate downwind, as well as back to the source. If the cloud is ignited at a significant distance from the spill, the thermal hazard zones can be extended significantly. The thermal radiation from the ignition of a vapor cloud can be very high within the ignited cloud and, therefore, particularly hazardous to people.

In order to obtain LNG dispersion distances to LFL for intentional events, calculations were performed using VULCAN, as discussed in Section 4. A low wind speed and highly stable atmospheric condition were chosen because this state has shown to result in the greatest distances to LFL from experiment, and thus should be the most conservative. A wind speed of 2.33 m/s at 10 m above ground and an F stability class were used for these simulations. For intentional events, two cases were run, one for the nominal case of a 5-m^2 hole and one tank breach, and the other for a 5-m^2 hole and three tanks breached. This case is the largest spill; hence, it should give the greatest LFL for intentional events. As indicated in Table 15, the dispersion distance to LFL for intentional events might extend from nominally 2500 m to a conservative maximum distance of 3500 m for this unlikely event.

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

Table 15: Dispersion Distances to LFL for Intentional Spills

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

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

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

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

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

[a] Distance to spill origin, varies according to site

Very low – little or no property damage or injuries
Low – minor property damage and minor injuries
Medium –potential for injuries and property damage
High – major injuries and significant damage to structures

6 RISK REDUCTION STRATEGIES

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

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

6.1 Target – Mechanism – Consequence Model

Target

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

Table 17: Targets Table

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

Mechanism

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

Table 18: Mechanisms Table

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

Consequence

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

Table 19: Consequences Table

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

6.2 Risk Management Strategies: Prevention and Mitigation

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

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

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

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

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

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

Table 20: Prevention and Mitigation Strategies

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

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

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

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

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

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

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

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

New maritime security regulations have been recently developed for terminal facilities. These regulations require the LNG terminal operator to conduct a facility security assessment and develop a threat-scalable security plan that addresses the risks identified in the assessment. Much like the requirements prescribed for vessels, the facility security plan establishes access control measures, security measures for cargo handling and delivery of supplies, surveillance and monitoring, security communications, security incident procedures, and training and drill requirements.

6.3 Risk Reduction Examples

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

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

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

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

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

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

Ramming

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

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

Triggered Explosion

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

Insider Takeover or Hijacking

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

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

External Terrorist Actions

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

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

6.4 Recommended Focus for Risk Prevention

The threats considered and the safety and security measures employed to address them must be based on site-specific and location-specific conditions. The level of risk prevention or mitigation required will depend on the site and its location relative to major population areas and critical infrastructures. In all cases, the risk reduction strategies identified should be considered from a cost-effectiveness viewpoint; i.e. reducing risks to acceptable levels in the most cost-effective manner possible for a given site and location.

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

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

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

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

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

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

Before implementation of specific safety or security measures is contemplated at a site, a baseline risk analysis should be conducted, a minimum acceptable risk estimated, and vulnerabilities and hazards evaluated. After the initial risk analysis has been completed, prevention and mitigation measures or strategies can then be considered and evaluated. These can then be compared to assess if they provide the enhancements required to reduce the risks of an LNG spill to acceptable levels for a site.

6.5 Application of the Risk Management Process

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

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

Applying the Risk Management Process to LNG Imports

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

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

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

If the initial risk assessment determines that the identified risk management goals are not being met, then potential modifications in location and site conditions, import operations, safety and security measures, emergency response and early warning measures should be assessed to determine effective improvements in the overall risk management system Below, we provide a summary of the elements that should be considered for LNG import facility applications for each step of the risk management process identified in Figure 3 of this report. These steps provide a context of how the safety analysis and risk guidance provided in this report can be used to evaluate options to protect property and public health and safety associated with LNG import terminals and operations.

<u>Step One</u> - Characterize Assets

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

- **Type and Proximity of Neighbors (Sections 3.3, 4.2, and 5.1)**

  -Distance to residential, commercial, and industrial facilities or other critical infrastructures such as bridges or tunnels, and

  -Transit – Near or in major ship channel or remote from channel

- **Environmental Conditions (Sections 3.2 and 3.3)**

  -Wind-driven Spill Movement & Dispersion – prevailing wind direction, speed, and variability,

  -Severe Weather Considerations – hurricanes, storm surges,

  -Tidal-driven Spill Movement & Dispersion – height, current, and influence on spill movement and dispersion,

  -Seismic issues - ground displacement, soil liquefaction, and

  -Temperature issues – ice, thermal impediment to operations

- **Nominal Operational Conditions (Sections 2.1, 2.2, and 3.3)**

  -LNG tanker size and design,

  -Expected frequency of shipments,

  -Importance of LNG Shipments – Available storage, seasonal demands, percentage of regional or local supply, and

  -Transit – additional traffic (near other large ships, pleasure boats) and distance to it; transit near critical infrastructures, such as other terminals, commercial areas, or residential areas; number of critical facilities along transit; distance to critical facilities along transit.

<u>Step Two</u> – Identify Potential Threats (Sections 4.1 and 5.1)

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

- **Accidental Event Considerations** – shipping patterns, frequency of other large ships, major objects or abutments to be avoided, warning systems, weather impacts on waterways or operations,

- **Intentional Event Considerations** – threat levels identified by Homeland Security, identified threats, past threats and shipping attacks, difficulty of attack scenarios for a given site, and

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

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

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

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

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

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

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

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

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

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

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

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

7 GUIDANCE: SAFETY AND RISK ANALYSIS AND RECOMMENDATIONS

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

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

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

7.1 Guidance: Using Models for Spill and Hazard Evaluations

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

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

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

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

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

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

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

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

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

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

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

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

Development of validated CFD models will require implementation of equations to represent phenomena, including: 1) the dynamics of cryogenic liquids, including evaporation and spread on water, and 2) the mixing and burning of low temperature natural gas vapor in very large plumes. These models must be verified (i.e. ensure that the equations are being solved correctly) and validated (i.e. ensure that the right equations are being solved for the application of interest) through analysis efforts and comparisons with high quality data.

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

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

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

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

7.2 Safety Analysis Guidance and Recommendations

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

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

These efforts have all significantly prevented or mitigated the potential for an accidental LNG cargo tank breach. While existing safety measures have been very effective, intentional attempts to breach an LNG cargo tank are now being considered as potential spill scenarios. Many recent studies have begun to consider both types of events and assess the safety and hazard issues of a subsequent fire or explosion of the spilled LNG. To date, most of these studies usually concentrate on postulating a spill scenario and calculating potential hazards and consequences without considering the likelihood of such an event. In addition, they often do not include experimental validation of the assumptions or analyses for the conditions postulated, nor do they consider prevention or mitigation strategies that could reduce the impact or hazards of the postulated events.

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

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

7.2.1 Accidental Breach Scenario Conclusions

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

7.2.2 Intentional Breach Scenario Conclusions

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

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

7.3 Risk Management Guidance for LNG Spills over Water

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

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

7.3.1 General Risk Management Guidance

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

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

7.3.2 Guidance on Risk Management for Accidental Spills

Zone 1

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

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

Zone 2

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

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

Zone 3

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

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

7.3.3 Guidance on Risk Management for Intentional LNG Spills

Zone 1

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

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

Zone 2

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

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

Zone 3

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

7.4 Key Conclusions: Safety Analysis and Risk Management

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

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

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

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

APPENDIX A
RECENT LNG SPILL MODELING REVIEW

1 INTRODUCTION

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

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

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

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

2 ASSUMPTIONS, MODELS, AND RESULTS FOR EACH STUDY

2.1 Lehr Study

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

2.1.1 Breach Scenario Assumptions

No assumptions were made regarding how a spill might occur.

2.1.2 Spreading Model

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

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

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

Viscosity and surface tension of the LNG are neglected.

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

2.1.3 Dispersion Model

Dispersion is not considered.

2.1.4 Flame model

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

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

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

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

2.1.5 Results

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

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

The maximum burn time is approximately two – three minutes.

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

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

The pool radius calculated was not stated.

2.2 Fay Study

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

2.2.1 Breach Scenario Assumptions

No assumptions were made regarding how a spill might occur.

2.2.2 Spreading Model

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

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

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

Viscosity and surface tension of the LNG are neglected.

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

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

2.2.3 Dispersion Model

Dispersion is not considered.

2.2.4 Flame model

The flame is not modeled.

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

2.2.5 Results

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

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

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

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

2.3 Quest Study

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

2.3.1 Breach Scenario Assumptions

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

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

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

No explosions occur.

2.3.2 Spreading Model

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

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

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

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

Viscosity and surface tension of the LNG are neglected.

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

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

2.3.3 Dispersion Model

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

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

2.3.4 Flame model

The fuel is assumed to ignite because of the collision.

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

2.3.5 Results

Quest concluded the following values from its analyses:

Table 24: Model Results (Quest Study)

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

At these radiant flux levels, the following occur:

Table 25: Impact of Radiation (Quest Study)

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

For the dispersion calculations of the vapor cloud:

Table 26: Dispersion Calculations (Quest Study)

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

2.4 Vallejo Study

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

2.4.1 Breach Scenario Assumptions

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

2.4.2 Spreading Model

Both one-meter and five-meter diameter holes in one 25,000 m^3 LNG ship tank were analyzed. The National Ocean Atmospheric Administration's code, ALOHA (Aerial Locations of Hazardous Atmospheres), was used to calculate the spill from the ship tank. In 6 min., 14,300 m^3 were spilled from the five-meter diameter hole and in 35 min from the one-meter diameter hole. The five-meter diameter hole resulted in a pool with a maximum area of 110,000-130,000 m^2. Vaporization rates of 5×10^{-4} m/s were used for evaporation from the water alone, and 8×10^{-4} m/s when fire was present.

2.4.3 Dispersion Model

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

2.4.4 Flame Model

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

2.4.5 Results:

Pool fire heat radiation results:

Table 27: Fire Heat Radiation Results (Vallejo Study)

HOLE SIZE (m)	DISTANCE TO RADIANCE FLUX LEVEL OF:		
	30 kW/m²	17 kW/m²	5 kW/m²
5 (16.4 ft)	0.35 miles (563 m)	.5 miles (804 m)	0.8 miles (1287 m)

Dispersion calculations of the vapor cloud results:

Table 28: Vapor Cloud Dispersion Calculations (Vallejo Study)

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

*Does not consider the limiting effect of topography

3 SUMMARY OF LNG SPILL ASSUMPTIONS AND RESULTS FROM EACH STUDY

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

Table 29: Summary of Study Assumptions

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

Table 30: Summary of Study Results

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

[a] A thirty-second exposure to heat levels of 5 kW/m^2 causes second-degree skin burns(blisters) at this distance.

[b] A seventeen-second exposure to heat levels of 22 kW/m^2 causes newspaper to ignite at this distance. (Ref.: SFPE Handbook of Fire Protection Engineering, 2nd ed., National Fire Protection Association, (1995).

[c] Distance from edge of spill

[d] Assuming a wind speed of 9 m/s (20 mph).

[e] Considers a range of hole sizes. This size chosen for comparison.

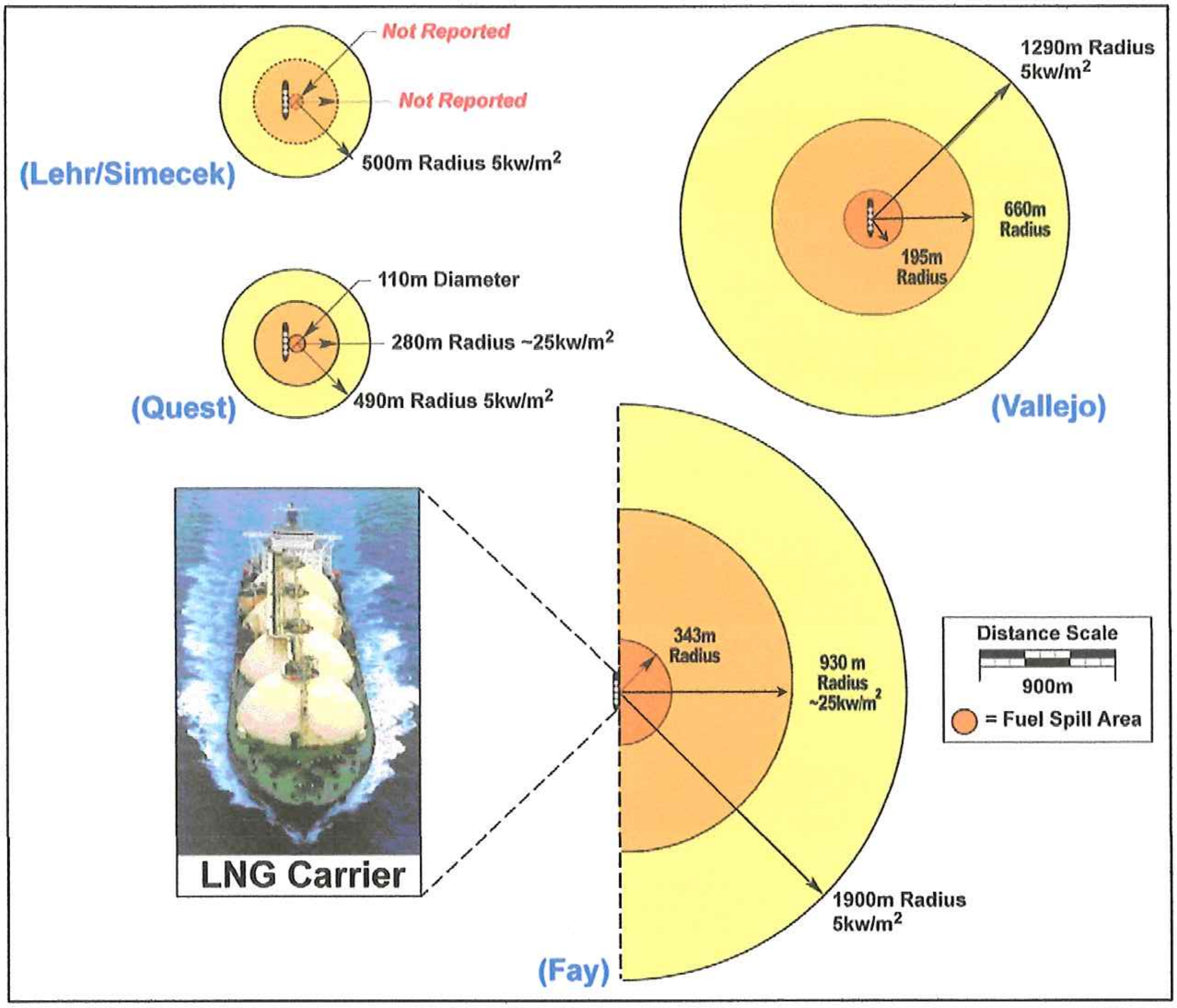


Figure 6. Graphical Summary of the Results of the *Lehr, Fay, Quest & Vallejo* Studies
(Yellow = 5kW/m^2; lt. Orange = 25 kW/m^2; dk. Orange = fuel spill radius)

4 WHY THE STUDIES DIFFER

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

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

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

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

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

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

The value reported by *Quest* and *Fay* for the distance required for an object to receive a radiant flux of approximately 5 kW/m^2 is significantly different: 493 m versus 1900 m, respectively. One obvious reason for this difference is that *Fay's* analysis predicts a much larger pool fire. For instance, by using the relation that *Fay* used to determine the radiant flux at the distance and pool area given by *Quest*, the distance is 353 m at which the radiant flux is 5 kW/m^2. Thus, pool area will make a significant difference.

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

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

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

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

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

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

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

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

5 IDENTIFICATION OF GAPS AND LIMITATIONS IN THE STUDIES

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

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

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

5.1 LNG Cargo Tank Breach Modeling

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

5.2 LNG Liquid Transport Modeling

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

5.3 LNG Combustion Modeling

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

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

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

5.4 LNG Plume Modeling

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

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

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

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

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

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

5.5 LNG Spill Overpressure Considerations

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

6 RECOMMENDATIONS BASED ON REVIEW OF THE FOUR STUDIES

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

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

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

APPENDIX B
THREAT ANALYSIS AND SPILL PROBABILITY

1 INTRODUCTION

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

2 ASSUMPTIONS, MODELS, AND THREAT ANALYSIS

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

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

2.1 Accidental Breaching Evaluations

As noted in Section 2 of this report, the LNG industry has an exemplary safety record with only eight marine accidents over the past 40 years in which LNG was spilled, but without resultant fires. None of these accidents led to a loss of life. Even with this excellent safety record, consideration should be given to what might be a likely LNG cargo tank breach based on a potential accidental collision with another ship, grounding, or ramming. The severity of a breach based on these events depends on the location, vessel design, relative vessel speeds and collision alignment, and mitigation or prevention systems in place to limit potential damage.

Sandia had previously conducted sophisticated finite element modeling of collisions of a series of ships with a double-hulled oil tanker similar in overall size, mass, and design to an LNG vessel. A summary of the analysis of a 90-degree collision of a large container ship (50,000 metric ton class ship) and a double-hull tanker (80,000 metric ton class) is shown in Figure 7 and collisions with smaller ships are shown in Figure 8 [Ammerman 2002]. The analysis tool included an approximately 250,000 finite element model of both the impacting vessel and the double-hulled tanker using PRONTO-3D run on a massively parallel computer with 256 processors. This is a transient dynamic, explicitly integrated, Lagrangian solver of the equations of motion. The analysis tracked the progressive failure of the struck ship as the striking ship penetrated. As noted in these figures, breaching of the inner hull does not occur until impact velocities exceed approximately 5 – 6 knots for large vessels. For small vessels, such as pleasure craft, kinetic energy is approximately one to two million N·m. Figure 8 shows that this level of kinetic energy is generally insufficient to penetrate the inner hull of a double-hulled vessel such as an LNG ship.

This analysis also calculated that penetration into a double-hulled tanker must be approximately three meters before a hole occurs in the inner hull. This, therefore, can be used to estimate the minimum size of a penetration to cause a penetration and spill in a grounding event. Because of the design of LNG ships, the penetration could be even greater in many cases. The results for this analysis were compared with initial collision information from the recent Baltic Carrier collision at approximately 12 knots. The results of these analyses over-predict, by about 15%, the external hole size measured for that collision

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

An additional element to consider in the accident scenario is that the hole size developed probably is not the size of the spill orifice. In many collisions between two ships, the ships can remain joined for several hours if significant penetration of one ship occurs. The analysis by Ammerman suggests that as little as 5 – 10% of the generated breach size would be available for the release of LNG. Therefore, the collision of a large ship with an LNG carrier at even 12knots is expected to produce an effective hole area of no more than approximately one square meter for an LNG spill. If larger spills do occur, hole sizes could approach those calculated for intentional breaches.

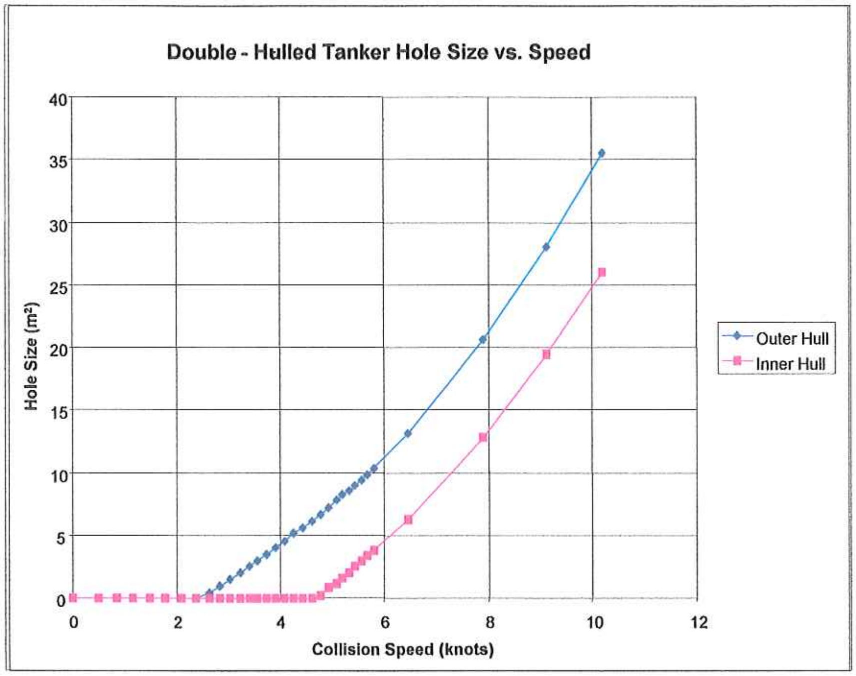


Figure 7. Study Estimate of Speed Required to Create a Given Hole Size

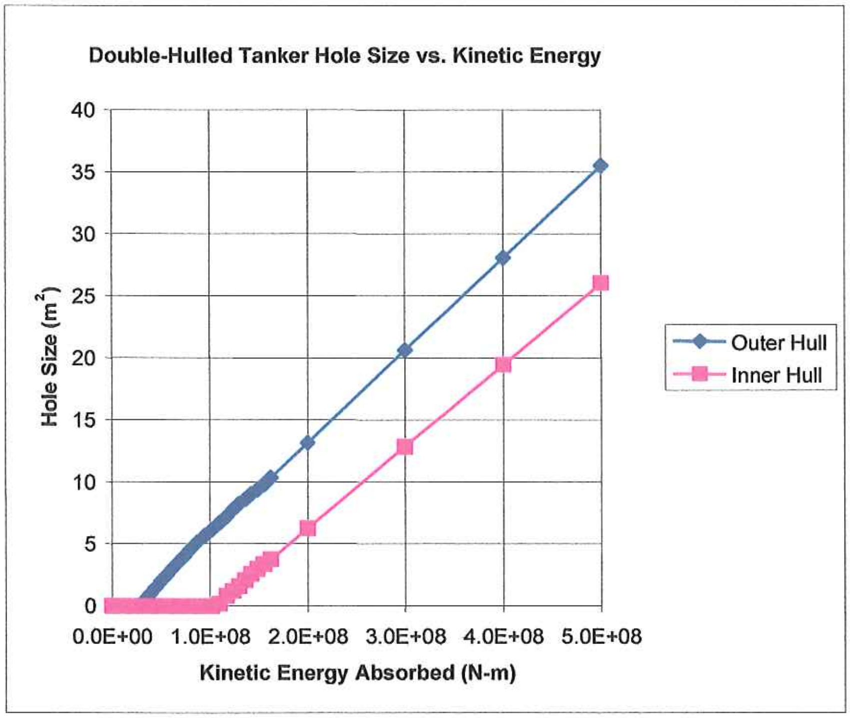


Figure 8. Double-Hull Tanker Study of Energy Required to Create a Given Hole Size

2.2 Intentional Breaching Evaluations

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

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

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

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

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

3 LNG BREACH SUMMARY

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

As shown conceptually in Figure 5, based on the evaluation of the available void space between the hulls, in some cases almost all of the LNG spilled in a breach might be captured within the LNG vessel. While this will reduce the volume of LNG spilled onto the water and the potential spill surface size, it could negatively impact the structural integrity of the LNG vessel. This has been evaluated and is discussed in Appendix D.

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

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

The risk of a breach of an LNG cargo tank due to an accident, such as a collision or grounding, appears to be minimal. The risk of such a breach can be easily reduced through a number of operational mechanisms that includes managing ship traffic, coordinating ship speeds, and by active ship control in inner and outer harbors where the consequences of a potential LNG spill might be most severe. The Coast Guard currently uses all these methods. The safety and hazard issues from an accidental breach appear manageable and adequate with current safety policies and practices based on the safety records of LNG vessels in port.

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

APPENDIX C
LNG SPILL AND DISPERSION ANALYSIS

1 INTRODUCTION

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

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

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

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

2 LIQUID POOL

2.1 Spreading

2.1.1 Experiments

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

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

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

2.1.2 Models

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

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

Opschoor developed a model for the spread and evaporation of LNG on open and confined quiescent water surfaces [Opschoor 1980]. For unconfined water surfaces, the model assumes that boiling occurs in the film-boiling mode and that no ice formation occurs. For confined water surfaces, the model assumes that, during the spreading phase, no ice formation occurs due to film boiling and that, after spreading, an ice layer forms due to a decrease in the temperature difference between LNG and water such that film boiling cannot be maintained, resulting in contact between the LNG and water. The results were compared with experiments by Shell for spills of 38kg (.09 m3) [Boyler and Kneebone 1973]. There was agreement with evaporation rate for confined water surfaces for the ice formation period, and fair agreement for confined water surfaces for pool radius. When compared to experiments by the U.S. Bureau of Mines (163 kg), the model under-predicts the pool radius over time [Burgess et al. 1970].

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

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

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

2.2 Pool Boiling

2.2.1 Experiments

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

Results by Drake on laboratory scale experiments showed that LNG had a higher boiling rate than pure methane on a bound-free surface [Drake et al. 1975]. The rate of boiling increased with time and foaming of the LNG occurred on the water surface. These results agree with Valencia-Chavez and Reid on laboratory scale confined spills [Valencia-Chavez and Reid 1979].

2.2.2 Models

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

2.3 Rapid Phase Transition (RPT) Explosions

2.3.1 Experiments

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

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

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

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

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

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

2.3.2 Models

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

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

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

Napier and Roochland raise the issue of rapid phase transitions causing ignition by either electrostatic discharge or frictional sparks created near the explosion, or by shock heating of the methane-air mixture [Napier and Roochland 1984]. Based on using shock tube analysis, they concluded that shock heating of unconfined flammable mixtures of methane to the auto ignition temperature (813°K) is not possible. The experimentally determined temperature available is 450°K; the theoretical is 500°K. They state that ignition is possible via an electrostatic discharge or frictional sparks; but that these ignition modes are difficult to quantify. The ignition source would have to be located on the boundary of the RPT, where the fuel concentration is between the flammability limits.

3 DISPERSION

3.1 Experiments

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

Shell Jettison Tests – 1973 [Kneebone and Prew 1974]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Falcon Tests – 1987 [Wiersma and Williams 1989]

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

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

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

Tests were performed with and without the vapor fence. With the fence in place, the downwind distance to the 2.5% concentration on the ground was reduced from approximately 380 m to 235 m and a substantial reduction in the hazardous areas was achieved. The persistence of the cloud at a 2.5% concentration near the center of the spill was 530 s with the fence versus 330 s without the fence. Although the fence reduced the downwind distance of the hazardous area and delayed cloud arrival time, it prolonged the cloud persistence time within the fence, thereby prolonging the potential for ignition.

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

3.1.1 Models

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

Navier-Stokes Based Models

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

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

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

Lagrangian Nonlinear Puff Models

Gaussian puff models are typically for buoyant or neutrally buoyant releases, such as from an elevated stack source. Recently, the code called SCIPUFF (Second-order Closure Integrated Puff), developed by Titan Research and Technology, includes a dense gas release model [Sykes et al. 1999]. SCIPUFF uses a Lagrangian puff dispersion model that captures nonlinear interaction among a collection of Gaussian puffs to represent a three-dimensional, time-dependent concentration field. Dense gas effects are captured by using the conservation of vorticity moment equation. Turbulent diffusion is based on a second-order closure model. Finite duration, unsteady, and multiple sources can be modeled, as well as flow over flat or complex terrain. Comparisons to dense gas field data on maximum concentration over all sampling locations at a given distance and over the sampling period from Maplin, Burro, and Coyote tests show the model predicting concentration values within a factor of two.

Shallow-Layer Models

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

One-Dimensional Integral Models

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

Empirical Models

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

3.1.2 Model Evaluation Studies

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

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

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

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

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

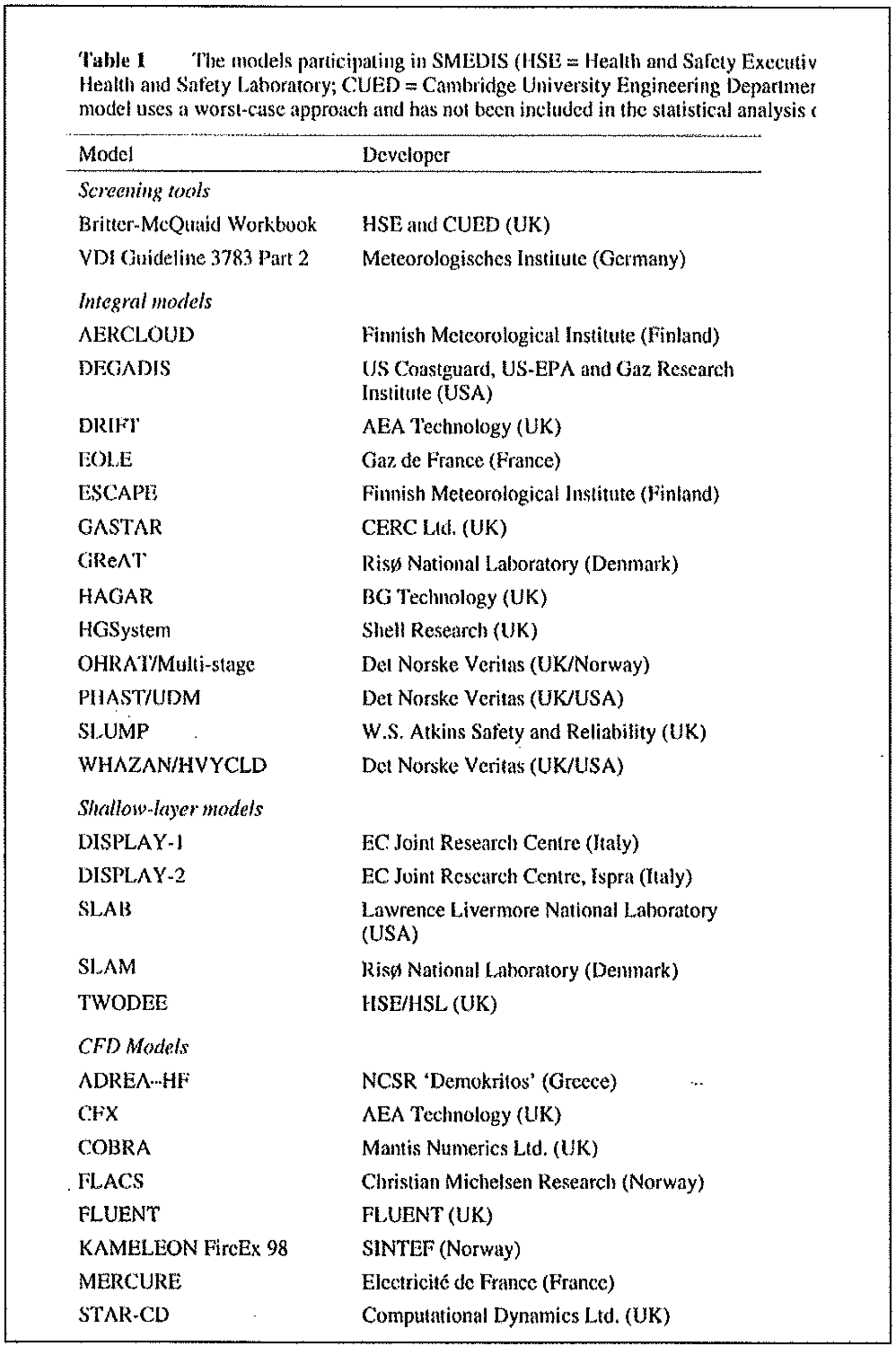


Table 1 The models participating in SMEDIS (HSE = Health and Safety Executiv
Health and Safety Laboratory; CUED = Cambridge University Engineering Departmer
model uses a worst-case approach and has not been included in the statistical analysis (

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

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

[Carissimo, et al. 2001]

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

[Carissimo, et al. 2001]

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

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

[Carissimo, et al. (2001)]

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

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

[Carissimo, et al. 2001]

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

3.1.3 Model Directory

The Office of the Federal Coordinator for Meteorology (OFCM) has published a directory of a number of transport and dispersion models for the release of hazardous materials into the atmosphere [http://www.ofcm.noaa.gov/atd_dir/pdf/frontpage.htm]. An in-depth compilation and description of the models are provided, as well as model validation and verification information. No assessment or comparison of model performance is provided.

4 POOL FIRE AND VAPOR CLOUD STUDIES

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

Table 38: Large Scale LNG Fire Studies

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

4.1 LNG Fire Experiments over Water

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

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

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

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

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

The measured regression rates varied from $4\text{x}10^{-4}$ to $11\text{x}10^{-4}$ m/s. For higher spill rates, it was observed that the regression rates were higher, speculated as possibly due to the interaction between the jet and water effectively increasing the heat transfer area.

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

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

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

In all of these tests a vapor cloud fire developed, and for one test the vapor cloud fire propagated back to the spill point for a pool fire to form. This pool fire lasted only for a few seconds before the fuel ran out and did not have time to develop completely. As noted by the authors incomplete photographic records also made the analysis of this test difficult. In order to determine surface emissive power the pool fire was modeled as a tilted cylinder. An effective pool diameter was calculated by approximating the actual flame base area as an ellipse. An effective pool diameter of 30m (crosswind) was calculated for the LNG pool fire. From this test, an approximate fuel regression rate of 2.1×10^{-4} m/s was calculated. For the LNG pool fire, an average surface emissive power of 203 kW/m^2 with a range of 178-248 kW/m^2 was measured.

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

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

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

Coyote Tests – 1981 [Rodean et al. 1984]

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

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

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

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

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

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

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

4.2 LNG Fire Experiments Over Land

Maplin Sands Tests – 1982 [Mizner and Eyre 1982]

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

The flame appeared roughly cylindrical in shape and tilted due to a 6.15 m/s wind. For the LNG fire the production of black soot appeared much higher in the flame and was significantly less than that produced by LPG or kerosene. The measured mean flame length using video recordings for the LNG fire was 43 m with a flame length-to-diameter ratio of 2.15. The Thomas correlation for flame length-to-diameter ratio predicts a value of 1.88, if the measured burning rate is used, underestimating the observed mean flame length by 12.6%. The measured burning rate was 0.106 kg/m^{2}s (2.37 x10^{-4} m/s) for LNG, versus 0.13 kg/m^{2}s (2.17 x10^{-4} m/s) for LPG.

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

Montoir Tests – 1989 [Nedelka et al. 1989]

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

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

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

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

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

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

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

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

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

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

4.2.1 Models

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

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

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

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

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

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

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

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

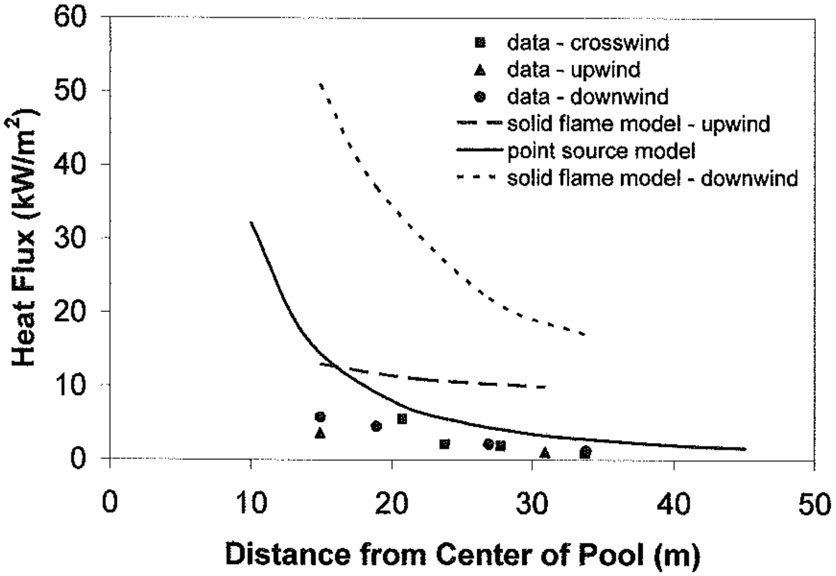


Figure 10. Flame Model Comparison with Trench Fire Data

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

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

4.3 Detonation Studies

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

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

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

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

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

4.3.1 Reviews

There have been several reviews on detonations of hydrocarbon/air mixtures [Lee and Moen 1980] [Moen 1993] [Nettleton 2002]. It was pointed out by Moen that weak ignition of vapor clouds in an unconfined and unobstructed environment is unlikely to result in a deflagration to detonation (DDT), even for more sensitive fuel/air mixtures; but it is likely with confinement and the presence of obstacles [Moen et al. 1980]. The occurrence of DDT depends upon the degree of confinement, obstacles configuration, ignition source, initial turbulence, and the fuel-air mixture. Nettleton indicates that the understanding of how confinement, temperature, pressure, and mixture composition influence the initiation source and distance to DDT is not complete. Further work must be done before prediction can be made whether DDT will occur for any given spill scenario.

4.3.2 Flame Acceleration Studies

Moen et al. – 1980 [Moen et al. 1980]

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

Urtiew – 1982 [Urtiew 1982]

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

Harrison and Eyre – 1987 [Harrison and Eyre 1987]

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

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

Grids with low blockage ratios or low height produced overpressures of 29 – 63 mbars decaying as 1/r and flames speeds of 37 – 51 m/s, not sufficient to cause severe structural damage. The test with the great congestion obtained a maximum flame speed of 119 m/s and overpressure of 208 mbars decaying as 1/r, which can be sufficient to cause structural damage to buildings in the immediate vicinity of the cloud. In all tests, flame speed and overpressures decayed rapidly after the flame emerged from the grid of obstacles, typically within 5m of the last grid. Thus, the size of the obstacle array, not the size of the gas cloud, defined the size of the pressure source.

Shell – 2001 [Bradley et al. 2001]

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

5 DISCUSSION

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

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

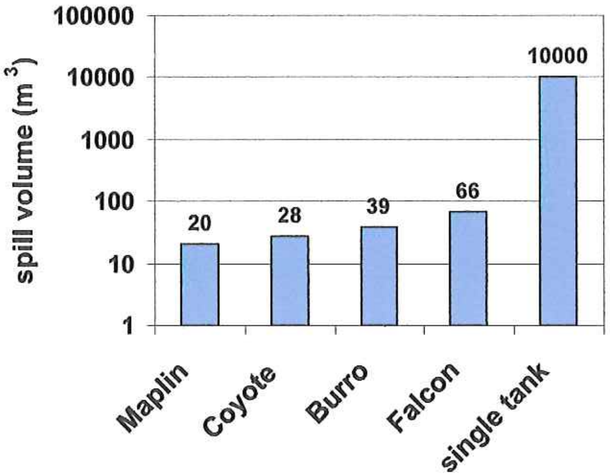


Figure 11. Log Scale Comparison of Experimental Spills vs. Possible Cargo Tank Spills

- Of the larger spill tests performed, there have been only a few LNG pool fires on water tests where measurements were taken. This was for a spill size of 10.35 m^3, which is far below the spill volume that could occur for a 2 or 12m^2 hole in one tank of a vessel. This pool fire lasted only for a few seconds before the fuel ran out and did not have time to fully develop. It was also noted that photographic records necessary for analysis were incomplete. In order to determine the thermal radiation hazard from a pool fire, the surface emissive power needs to be determined. The pool fire tests on land indicate that the surface emissive power increases for pool diameters up to 35 m. Whether the maximum surface emissive power was obtained is uncertain, though most likely it isn't much higher than that measured for 35 m. It is difficult to determine whether the surface emissive power and the pool mass flux has leveled off for pool fires on water since only one test of a larger scale has been performed. Thus, more data on large-scale LNG pool fires on water is needed. More tests on the order of spill volumes of 10 m^3 should be performed, and ideally on the order of 100 m^3, so that maximum surface emissive powers and pool mass fluxes are reached. Also, at these larger scales, a regime may be revealed at which a single coherent pool fire cannot be maintained, but rather a break up into multiple pool fires occurs.

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

APPENDIX D
SPILL CONSEQUENCE ANALYSIS

1 INTRODUCTION

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

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

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

2 ASPHYXIATION POTENTIAL AND IMPACTS

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

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

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

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

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

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

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

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

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

3 CRYOGENIC SHIP DAMAGE: POTENTIAL AND IMPACTS

As noted in Appendix B, a range of LNG cargo tank breaches were calculated from the analysis of credible accidental and intentional breaching events. The size and location of potential breaches were used as a basis for the analysis of the potential for cryogenic damage to the structural steel of an LNG ship from a spill in the absence of a fire. Contact of steel with cryogenic fluids is known to cause embrittlement, which can significantly reduce the strength of steel [Vaudolon 2000]. A detailed structural analysis was beyond the scope of this review; but structural integrity embrittlement scoping analyses were conducted to assess the potential damage to an LNG ship from small and large LNG spills based on available fracture mechanics data and models. These analyses were guided by available information on LNG ship and tank designs, construction, and structural steel material property data [Linsner 2004] [Shell 2002] [Wellman 1983].

A review of the structural steel used in LNG ship fabrication shows extensive use of ABS-Class A, B, and C structural ship steel [Linsner 2004]. In discussions with the U.S. Coast Guard, ABS Class E and F structural steels are also being used in some newer LNG ships. Selected material properties for ABS Class B steel include [Wellman 1983] room temperature yield strength equal to $37\text{x}10^3$ psi., coefficient of thermal expansion equal to $8.3\text{x}10^{-6}$ in/in °F, Young's modulus (E) equal to $30\text{x}10^6$ psi. As with all low alloy carbon steels, A131 class B and C transition from ductile to brittle behavior with decreasing temperature. Lower shelf (brittle) behavior starts at about 32°F. For these steels, the fracture toughness (Kc) decreases approximately linearly from $90\text{x}10^3$ psi√in at -60°F to $20\text{x}10^3$psi√in at –260°F.

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

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

An alternate approach to estimation of fracture toughness can be appropriated from the nuclear pressure vessel industry [Barsom and Rolfe 1987]. Here, a reference curve (K_{IR}) has been constructed from an extensive database of fracture testing on low alloy carbon steels with yield strength of less than 50 ksi. Fracture toughness as a function of temperature for steels typical of this class of materials is shown in Figure 12.

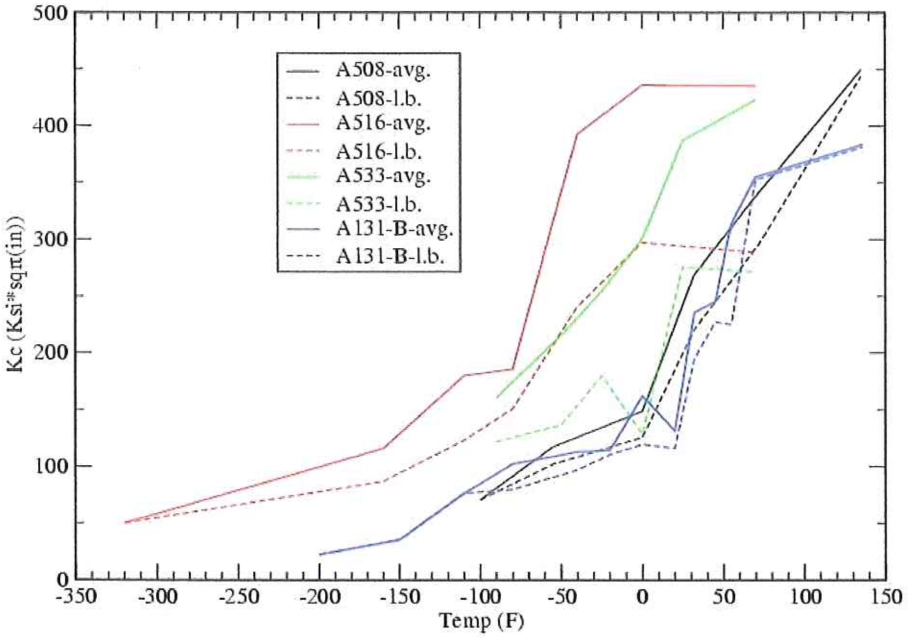


Figure 12. Fracture Toughness of Low Alloy Carbon Steels

This curve is represented by the following equation:

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

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

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

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

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

Scenario 1 (Small Spill)

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

$$\sigma = 0.5 \bullet \alpha \bullet \Delta T \bullet E$$

where σ = stress
α= coefficient of thermal expansion
ΔT= change in temperature
E= modulus of elasticity

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

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

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

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

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

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

Scenario 2 (Large, Internal Spill)

The second case considered is that of an entire structure at a low temperature supported by a structure of similar stiffness at a higher temperature. A penetration in the cryogenic LNG cargo tank, with the inner hull intact, could lead to the filling of the inner hull with the cryogenic liquid. If the ship is not ballasted, the space between the inner and outer hull would be filled with air or nitrogen, essentially an insulator. Thus, the inner hull would be at the cryogenic temperature, while the outer hull is at sea temperature. The inner and outer hulls are of comparable stiffness. The equation for computing stress in this case is identical to that for the cold spot discussed above. The thermal stresses, fracture toughness, critical flaw size, etc. are nearly identical to the case of the cold spot. The conclusion here is that a flaw could propagate through the entire inner hull, either from side-to-side or axially, from front containment bulkhead to aft containment bulkhead of the compromised compartment.

Scenario 3 (Spill Between Ship Hulls)

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

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

This equation results in an elastically computed stress significantly in excess of the room temperature yield stress ($100\text{x}10^3$ psi). No attempt was made to include nonlinear material properties (plasticity). However, due to plastic deformation, the actual stresses resulting from this case will be significantly less than the elastically computed $100\text{x}10^3$ psi., but still greater than the stresses resulting from the prior two cases. The potential for cracking is similar to the prior two cases.

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

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

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

Notes: a - Assumes vessels remain joined during spill event and breach is mostly plugged
b - Minor suggests ship can be moved and unloaded safely
c – Moderate suggests damage that might impact vessel and cargo integrity
d – Severe suggests significant structural damage. Ship might not be able to be moved without significant difficulty and includes potential for cascading damage to other tanks

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

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

4 LNG SPILL DISPERSION AND THERMAL HAZARDS

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

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

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

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

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

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

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

Nomenclature:

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

Basic Equations:
First apply continuity equation where:

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

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

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

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

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

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

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

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

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

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

$$v_o = C_d \sqrt{2 g h_t} \qquad (3)$$

Total time of discharge:

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

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

Total time to drain is:

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

Average flow rate:

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

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

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

Condition 2: Spreading Equation

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

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

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

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

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

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

Nomenclature:

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

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

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

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

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

$$q'' = E_p \tau F \tag{7}$$

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

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

Table 41: Sensitivity Analysis of Thermal Intensity Level Distances

HOLE SIZE (m^2)	TANKS BREACHED	DISCHARGE COEFFICIENT	BURN RATE (m/s)	SURFACE EMISSIVE POWER (kW/m^2)	POOL DIAMETER (m)	BURN TIME (min)	DISTANCE TO 37.5 kW/m^2 (m)	DISTANCE TO 5 kW/m^2 (m
ACCIDENTAL EVENTS								
1	1	.6	3X10^{-4}	220	148	40	177	554
2	1	.6	3X10^{-4}	220	209	20	250	784
INTENTIONAL EVENTS								
2	3	.6	3 x 10^{-4}	220	209	20	250	784
5	3	.6	3 x 10^{-4}	220	572	8.1	630	2118
5*	1	.6	3 x 10^{-4}	220	330	8.1	391	1305
5	1	.9	3 x 10^{-4}	220	405	5.4	478	1579
5	1	.6	2 x 10^{-4}	220	395	8.1	454	1538
5	1	.6	3 x 10^{-4}	350	330	8.1	529	1652
10	1	.6	3 x 10^{-4}	220	467	4.1	549	1823

*nominal case

The results in Table 41 suggest that, for most of the credible accidental breach and spill scenarios, the general distance for major structural damage (high hazards where the thermal intensity is about 37.5 kW/m^2) can occur, on average, up to 250 m from a spill. The results also suggest that, for most of the credible intentional breach and spill scenarios, the general distance for major structural damage (high hazards) can occur, on average, up to 500 m from a spill. In general, the distance to low thermal hazard levels, about 5 kW/m^2 is about 600-750 m for accidental spills and approximately 1600 m for intentional spills. For a very large, cascading spill, high hazard zones could approach 2000 m. These results were used to help quantify the hazard zone identification and hazard level identification for various breach and spill events.

Consideration of Mass Fires and Pool Fires

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

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

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

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

The pool diameter and flame height suggested are speculative because experiments for large pool fires have yet to be performed. Many researchers have provided flame height correlations based on pool fires much smaller than those presently being considered [Heskestad 1998]. These results suggest LNG pool fires of as much as 8900 m in diameter before breakup, based on results of laboratory testing on approximately 7 m by 7m wood fiberboards. Whether their results can be extrapolated to very large pool fires remains to be determined.

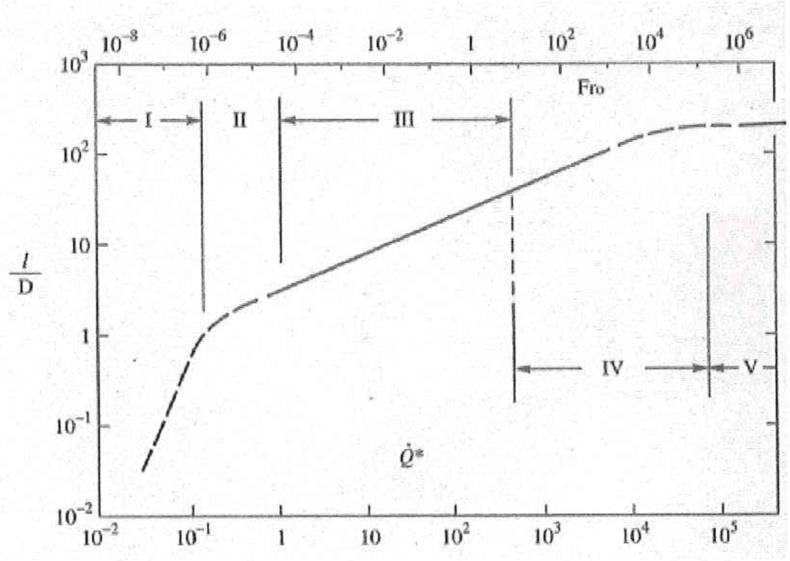


Figure 13. Flame Height/Diameter Ratio vs. Dimensionless Heat Release Rate

Taken from: [Zukoski, 1995]

The following calculations in Table 42 show the differences in the thermal hazard distances obtained using an assumption of a single, coherent pool fire for very large diameters versus the assumption of several mass fires (flamelets) with maximum diameters on the order of 100 m. A solid flame model that accounts for view factors and transmissivity and the Moorhouse correlation for flame height to diameter was used. A low wind condition was assumed; therefore, flame tilt and drag were not required. A surface emissive power of 220 kW/m^2, a transmissivity value of 0.8, and a burn rate of 3 x 10^{-4} were used. The results indicate that there is a significant increase in the distance to 5 kW/m^2 when a single coherent pool fire is assumed. The thermal hazard distances from a mass fire (flamelets), which is physically more realistic for large spills, should be considered in evaluating thermal hazards from potential large spills.

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

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

Furthermore, studies discussed in Appendix C note that the missive power decreases with increasing fire size due to smoke shielding. Values significantly lower than 220KW/m^2 are possible. As improved data are collected, improvements in hazard analysis can be implemented. Other phenomena, such as the occurrence of fire whirls, may increase the hazard by generating large columnar flames with high emissive power. These structures most often form during non circular pool shapes exposed to light winds and rarely last more than a few seconds.

LNG Dispersion

In most of the scenarios identified, the thermal hazards from a spill are expected to manifest as a pool fire, based on the high probability that an ignition source will be available from most of the events identified. In some instances, such as an intentional spill without a tank breach, an immediate ignition source might not be available and the spilled LNG could, therefore, disperse as a vapor cloud. For large spills, the vapor cloud could extend to as much as 1600 m or more, depending on spill location and site atmospheric conditions. In congested or highly populated areas, an ignition source would be likely, as opposed to remote areas, in which an ignition source might be less likely.

If ignited close to the spill, the thermal loading from the vapor cloud ignition might not be significantly different from a pool fire, because the ignited vapor cloud would probably burn back to the source of liquid LNG and transition into a pool fire. If the cloud is ignited at a significant distance from the spill, the thermal hazard zones can be extended significantly. The thermal radiation from the ignition of a vapor cloud can be very high within the ignited cloud and, therefore, particularly hazardous to people.

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

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

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

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

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

In order to obtain LNG dispersion distances to LFL for accidental events, a low wind speed and highly stable atmospheric condition were chosen because this has shown to result in the greatest distances to LFL from experiment, and thus should be the most conservative. A wind speed of 2.33 m/s at 10 m above ground and an F stability class were used for these simulations. The time it took for LFL to be reached was approximately 20 min. for each calculation. Two cases were analyzed, one for the nominal case of a 5 m^2 hole and one tank breach, and the other for a 5 m^2 hole and three tanks breached at once. This last case is the largest expected spill; hence, it should give an upper bound of the LFL for vapor dispersion for intentional events. The results are summarized in the table below.

Table 43: Dispersion Distances to LFL for Potential Spills

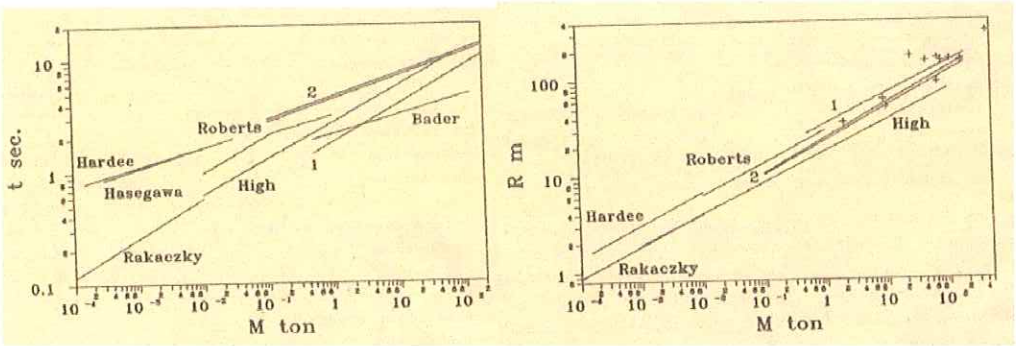
HOLE SIZE (m^2)	TANKS BREACHED	POOL DIAMETER (m)	SPILL DURATION (min)	DISTANCE TO LFL (m)
Accidental Events				
1	1	148	40	1536
2	1	209	20	1710
Intentional Events				
5	1	330	8.1	2450
5	3	572	8.1	3614

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

4.1 Fireballs Resulting from an LNG Spill

A fireball will result from an LNG spill only if some mixing of the fuel and air occurs prior to ignition. Thus, if ignition occurs immediately upon release, no fireball will result. For a fireball to occur there must be fuel release, spread, vaporization, and ignition after significant premixing. If all these events have occurred, a fireball is the most benign form of combustion that can result. The hazards are principally short-time thermal damage high in the air and away from structures and people.

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



(a) (b)

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

[Dorefeev et. al. 1991]

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

The duration of the fireball from combusting clouds is given as

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

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

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

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

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

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

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

4.2 Thermal Damage on Structures

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

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

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

4.3 Analysis of Fire Damage to LNG Cargo Tank Insulation

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

Foam used to insulate LNG is enclosed within a steel weather cover, or within the inner hull of the LNG tanker. Extensive burning of the foam is not expected, given the lack of sufficient air to support combustion in these regions, even in cases with limited damage to the hull or weather cover. Based on the foam being located within an enclosure, thermal decomposition of the LNG foam insulation is more likely. Heat transfer will result in thermal decomposition of the foam insulation, the products of which will burn if vented to the air, or cause an increase in the pressure in the region between the steel and the inner container.

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

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

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

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

5 LNG – AIR COMBUSTION TO GENERATE DAMAGING PRESSURE

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

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

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

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

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

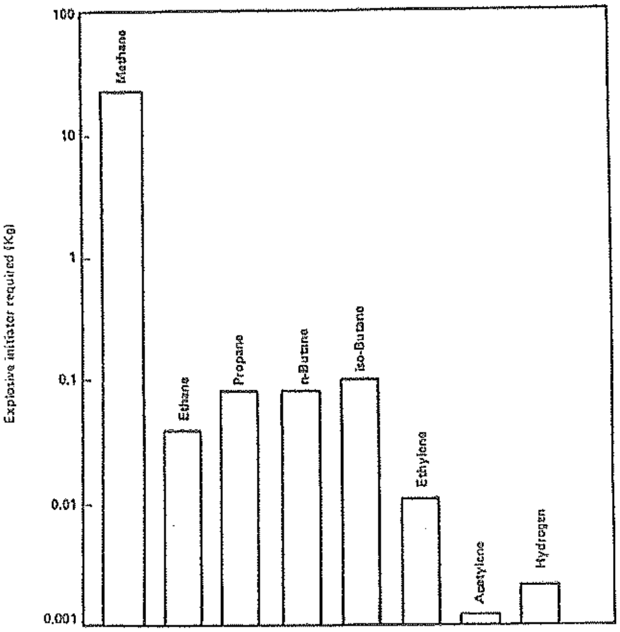


Figure 15. Relative Detonation Properties of Common Fuels

[Benedick et al 1986]

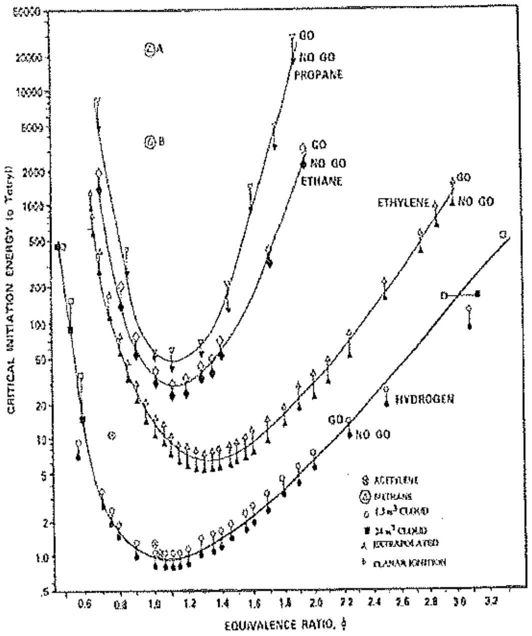


Figure 16. Initiation Energy Required to Detonate Common Fuels at Various Fuel-Air Ratios.

[Moen 1993]

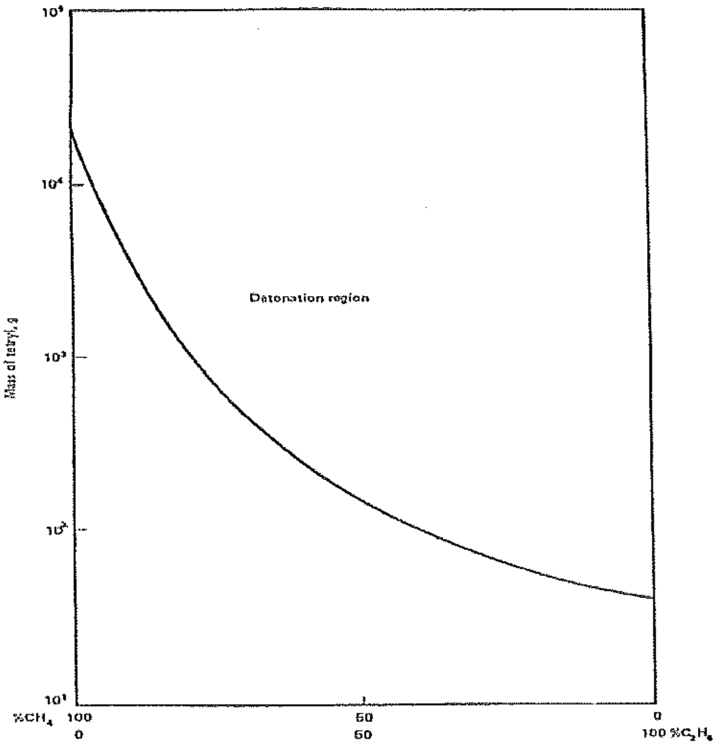


Figure 17. Effect of Ethane Concentration on the Detonability of Methane

[Moen 1993]

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

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

Table 44: Properties of Common Hydrocarbon Fuels

[AICE 1994] [Baker 1991]

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

5.1 Magnitude of LNG-Air Explosion Overpressure

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

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

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

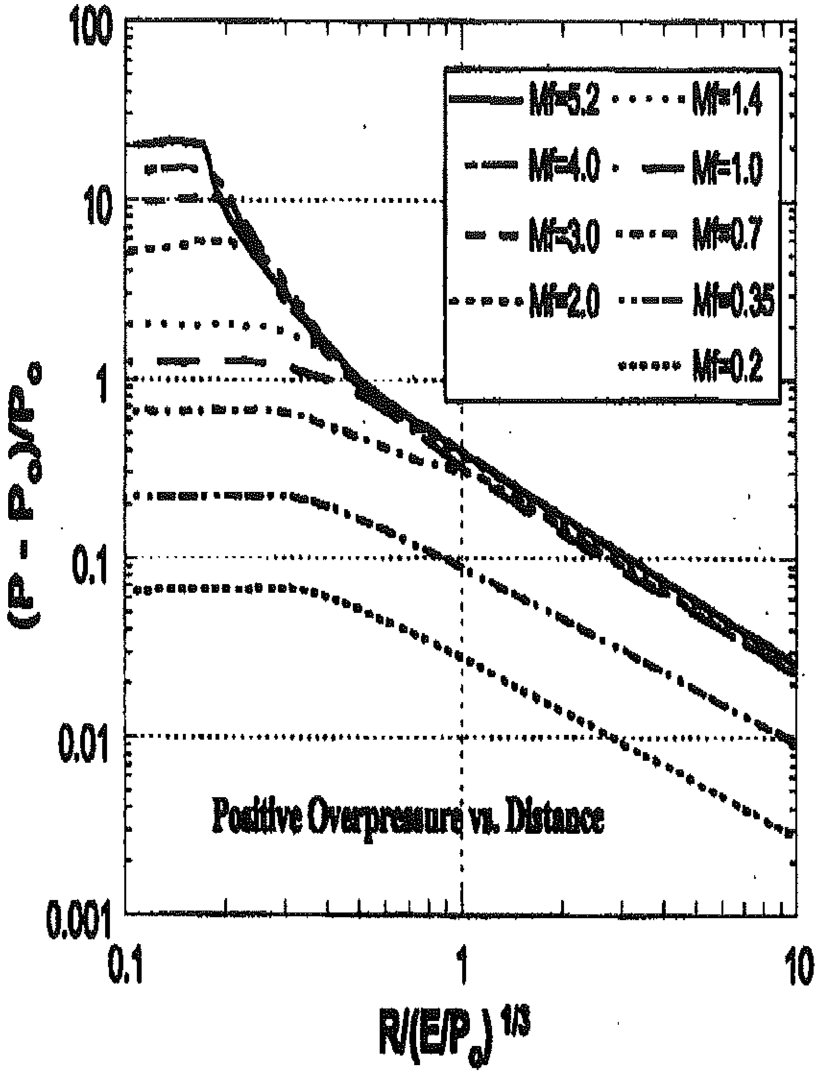


Figure 18. Scaled Blast Overpressure vs. Scaled Distance For Various Flame Mach Numbers

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

[Tang 1999]

APPENDIX E
LNG PLANT EXPLOSION IN SKIKDA, ALGERIA

REPORT OF THE U.S. GOVERNMENT TEAM SITE INSPECTION OF THE SONATRACH SKIKDA LNG PLANT IN SKIKDA, ALGERIA

MARCH 12-16, 2004

EXECUTIVE SUMMARY (only)

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

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

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

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

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

Deaths and injuries occurred only in the plant area. Damage outside the industrial area was limited to broken windows. Most deaths and injuries were due to the impact of the major explosion and flying debris, rather than from the resulting fire. The proximity of the train 40 control room to administrative, maintenance and security/fire control buildings was a major factor in the number of injuries and fatalities.

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

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

8 REFERENCES

[**Ammerman** 2002] Ammerman, D., "Marine Safety Systems, Control Ballast Tanker Interactive CD," SAND2002-3188P, Sandia National Laboratories, Albuquerque, NM, 2002.

[**Anderson** and **Armstrong** 1972] Anderson R.P. and Armstrong D.R. (1972) Experimental study of vapor explosions, third international conference on liquefied natural gas, Washington, DC.

[**ANSI** 1992] American National Standard for Respiratory Protection, ANSI Z88.2-1992. American National Standards Institute, New York, 1992.

[**Authen** 1976] Authen, T.K. et. al. (1976) "Gas Carriers – Effects of Fire on the Cargo Containment System," Proceedings, GASTECH 76, 1976.

[**Barry** 2002] Barry, Thomas (20021) Risk-Informed Performance-Based Industrial Fire Protection, Tennesse Valley Publishing, p. 50.

[**Barsom** 1987] Barsom, J. M. and Rolfe, S. T., "Fracture and Fatigue Control in Structures – Applications of Fracture Mechanics," second edition, Prentice Hall, N.J., 1987.

[**BBC** 2000] "Aeroplane Heart Attack Warning," November 16, 2000, British Broadcasting Corporation, 2000.

[**Beard** 1982] Beard, R., "Inorganic Compounds of Oxygen, Nitrogen, and Carbon," in Patty's Industrial Hygiene and Toxicology, Volume 2C: Toxicology, George D. Clayton and Florence E Clayton, editors, Wiley Interscience, New York, 1982.

[**Benedick** et al. 1987] Benedick, W. B., Tieszen, S. R, and Sherman, M. P., "Flame Acceleration and Transition to Detonation in Channels." Sandia National Laboratories Report SAND-87-1444C, 1987.

[**Berthoud** 2000] Berthoud, G. (2000) Vapor Explosions, Annu. Rev. Fluid Mech., 32, 673-611.

[**Blackmore** and **Summers**] 1982] Blackmore, D.R., Eyre, J.A. and Summers, G. G., (1982) Dispersion and Combustion Behavior of Gas Clouds Resulting from Large Spillages of LNG and LPG on to the Sea , Trans. I. Mar. E. (TM) 94, paper 29.

[**Blackmore** et al. 1982] Blackmore, D., et al., (1982) An Updated View of LNG Safety, American Gas Association Transmission Conference, Operation Section Proceedings, T226-T232.

[**Blevins** 1984] Blevins, R. D., Applied Fluid Dynamics Handbook, Van Nostrand Reinhold Company, Inc., 1984, pp. 136-141

[**Boe** 1998] Boe, R. (1998) Pool boiling of hydrocarbon mixtures on water, Int. J. Heat Mass Transfer, Vol. 41, No. 8-9, 1003-1011.

[**Boyler** and **Kneebone** 1973] Boyle, G.J. and Kneebone A. (1973) Laboratory investigations into the characteristics of LNG spills on water. Evaporation, spreading and vapor dispersion, Shell Research Ltd., Thornton Research Centre, Cester, England, Report 6-32, March.

[**Bradley** et al. 2001] Bradley, T.M. et al. (2001) Flame Acceleration Due to Flame-Induced Instabilities in Large-Scale Explosions, Comb. and Flame, 124, 551-559.

[**Brandeis** and **Ermak** 1983] Brandeis, J. and Ermak, D. L. (1983) Numerical simulation of liquefied fuel spills: II. Instantaneous and continuous LNG spills on an unconfined water surface, Int. J. for Num Meth. In Fluids, Vol. 3, 347-361.

[**Briscoe** and **Shaw** 1980] Briscoe, F. and Shaw P. (1980) Spread and Evaporation of Liquid, Prog. Energy Comb. Ci., Vol. 6, 127-140.

[**Brown** et al. 1974] Brown, L.E. et al. (1974) Predict LNG fire radiation, Hydrocarbon Processing, 141-143.

[**Burgess** et al. 1970] Burgess, D.S. et al. (1970) Hazards associated with the spillage of LNG on water, Report 7448, Bureau of Mines, Pittsburgh, PA.

[**Burgess** et al. 1970] Burgess, D.S. et al., (1970) Hazards of LNG spillage in marine transportation, U.S. Dept. of Interior, Bureau of Mines, SRS Report No S4105, February.

[**Carissimo** et al. 2001] Carissimo, et al. (2001) The SMEDIS database and validation exercise, Int. J. Env. and Pollution, Vol. 16, No. 1-6, 614-629.

[**Cavanaugh** et al. 1994] Cavanaugh, T. A. et al., (1994) Simulation of vapor emissions from liquid spills, J. Haz. Mat., 38, 41-63.

[**Chan** et al. 1983] Chan, et al. (1983) Influence of Confinement on Flame Acceleration Due to Repeated Obstacles, Comb. Flame, 49, 27-39.

[**Chan** et al. 1984] Chan, S. T. et al. (1984) Numerical Simulations of Atmospheric Releases of Heavy Gases Over Variable Terrain, Air Pollution Modeling and its Applications III, 295-328.

[**Chan** et al. 1987] Chan, S.T. et al. (1987) FEM3 Model Simulations of Selected Thorney Island Phase 1 Trials, J. Haz. Mat., 16, 267-292.

[**Chan** 1992] Chan, S. T. (1992) Numerical Simulations of LNG Vapor Dispersion from a Fenced Storage Area, J. Haz. Mat., 30, 195-224.

[**Chan** 1994] Chan, S.T., December (1994), FEM3C: An Improved Three-Dimensional Heavy-Gas Dispersion Model: User's Manual, UCRL-MA-116567Rev. 1, Lawrence Livermore National Laboratory.

[**Chan** 1997] Chan, S. T. September (1997) A Three-Dimensional Model for Simulating Atmospheric Dispersion of Heavy-Gases Over Complex Terrain, UCRL-JC-127475, Lawrence Livermore National Laboratory.

[**Colenbrander** and **Puttock** 1983] Colenbrander, G. W. and Puttock, J. S. (1983) Dense Gas Dispersion Behavior Experimental Observations and Model Developments, Fourth Int. Sym. on Loss Prev. and Safety, Vol. 90, F66-F76.

[**Conrado** and **Vesovic** 2000] Conrado C. an Vesovic, V. (2000) The influence of chemical composition on vaporization of LNG and LPG on unconfined water surfaces, Chem. Eng. Science, 4549-4562.

[**Corlett** 1974] Corlett, R. C. (1974) 'Velocity Distribution in Fires', in Heat Transfer in Fires (ed. P.L. Blackshear, pp. 239-255, John Wiley and Sons, New York.

[**Cox** and **Chitty** 1985] Cox, G. and Chitty, R. (1985) Some Source-dependent effects of unbounded fires, Comb. Flame 60, pp. 219-232.

[**Croce** et al 1984] Croce, P.A, Mudan, K. S., and Moorhouse, J. (1984) Thermal Radiation from LNG Trench Fires – Vol 1 and 2, Arthur D. Little, Inc., GRI Report No. 84/0151.1

[**Daish** 2000] Daish, N.C. (2000) SMEDIS: scientific model evaluation of dense gas dispersion models, Int. J. Env. and Pollution, Vol. 14, No. 1-6, 39-51.

[**DOE** 2003] *The Global Liquified Natural Gas Market; Status and Outlook,* DOE/EIA-0637, Energy Information Administration, U.S. Department of Energy, Washington, D.C., Dec. 2003.

[**Dorofeev** et al. 1991] Dorofeev, S. B., Matsukov, D. I., Sidorov, V. P., Efimenko, A. A., Kochurko, A. S., Kuznetsov, M. S., Pereverzev, A. K., Avenyan, V. A., Chaivanov, B. B., , "Experimental Investigation of Thermal Effect From Burning Fuel-Rich Clouds," Scientific Research & Development Organization Industrial Risk, Moscow, Russia, IRIS-91/3, 1991.

[**Drake** and **Wesson** 1976] Drake, E. M., Wesson, H.R., "Review of LNG Spill Vapor Dispersion and Fire Hazard Estimation and Control Methods", Conference: Am Gas Assoc Oper Sect Proc 1976, Transm Conf, Pap, 1976 Might 3-5, Las Vegas, NV, U.S.A..

[**Drake** et al. 1975] Drake, et al. (1975) Transient Boiling of Liquefied Cryogens on a Water Surface II Light hydrocarbon mixtures, Int. J. Heat Mass Transfer, Vol. 18, 1369-1375.

[**Enger** and **Hartman** 1972] Enger, T. and Hartman D. E. (1972) LNG Spillage on Water. II. Final Report on Rapid Phase Transitions. Shell Pipeline Corp, Research and Development Laboratory, Houston, Texas, Technical Progress Report No. 1-72.

[**Ermak** 1980] Ermak, D.L., (1980) User's Manual for SLAB: An Atmospheric Dispersion Model for Denser-Than-Air Releases, ACRL-MA-105607, Lawrence Livermore National Laboratory.

[**Ermak** 1982] Ermak, D.L. (1982) A Comparison of Dense-Gas Dispersion Model Simulations with Burro Series LNG Spill Test Results, J. Haz. Mat., 6, 129-160.

[**Ermak** et al. 1982] D. L. et al. (1982) LNG Spill Experiments: Dispersion, RPT, and Vapor Burn Analysis, American Gas Assoc. 1982 Operating Section Proc., T203-T209.

[**Ermak** et al. 1983] Ermak, D. L., et al. (1983) Results of 40 m3 LNG Spills Onto Water, Heavy Gas and Risk Assessment –II, S. Hartwig (ed.), 163-179.

[**Fay** 1973] Fay, J. A. (1973) Unusual fire hazard of LNG tanker spills, Comb. Sci. Tech., 7, 47-49.

[**Fay** 2003] Fay, J.A. "Model of spills and fires from LNG and oil tankers." Journal of Hazardous Materials, B96-2003, 171-188, 2003.

[**Feldbaur** et al. 1972] Feldbaur G.F. et al. (1972) Spills of LNG on water – vaporization and downwind drift of combustible mixtures, API Report EE61E-72.

[**Fletcher** and **Theofanous** 1994] Fletcher, D.F. and Theofanous, T.G. (1994) Recent progress in the understanding of steam explosions, J. Loss Prev. Process Ind., Vol. 7, no. 6, 457-462.

[**Georgakis** et al. 1979] Georgakis, C. et al. (1979) Model for non-instantaneous LNG and gasoline spills, Fuel, Vol. 58, 113-120.

[**Glasfeld** 1980] Glasfeld, R. D., Gastech 79, Some Aspects of LNG Ship Safety and Reliability, (1980), pp 137-145.

[**Glastone** and **Dolan** 1977] Glastone, S., Dolan, P. J. (1977) "The Effects of Nuclear Weapons", 3rd Ed, Tonbridge Wells: Castle House.

[**Goldwire** et al. 1983] Goldwire H.C. et al., (1983) Coyote Series Data Report, LLNL/NWC 1981 LNG Spill Tests Dispersion, Vapor Burn, and Rapid-Phase Transition, Vols. 1 and 2, UCID-19953 Lawrence Livermore National Laboratory, Livermore, California.

[**Goodier** 1937] Goodier, J. N., Thermal Stress, ASME Journal of Applied Mechanics, vol. 4, no. 1, March, 1937.

[**Gritzo** et al 1995] Gritzo, L.A., Nicolette, V.F., Tieszen, S.R., and Moya, J.L., "Heat Transfer to the Fuel Surface in Large Pool Fires," Transport Phenomenon in Combustion, Chan, S.H., ed., Taylor and Francis, 1995.

[**Gritzo** and **Nicolette** 1997] Gritzo, L.A., and Nicolette, V.F., (1997) "Coupling of Large Phenomenon with Object Geometry and Object Thermal Response," *Journal of Fire Sciences*, Vol. 15, 427-442, 1997.

[**Gritzo** et al. 1998] Gritzo, L.A., Gill, W., and Nicolette, V.F., "Estimates of the Extent and Character of the Oxygen-Starved Interior in Large Pool Fires," Very Large Scale Fires, ASTM STP 1336, N.R. Keltner, N.J. Alvares and S.J. Grayson, Eds., American Society for Testing and Materials, 1998.

[**Gritzo** et al. 2004] Gritzo, L. Tieszen, S., and Pilch, M "Establishing the Credibility of Modeled Length and Time Scaled in Fires, INTERFLAM, Edinburgh, July 5-8, 2004

[**Hankin** 2003] Hankin, R K.S. (2003) Heavy gas dispersion: integral models and shallow layer models, J. Haz. Mat., A102, 1-10.

[**Hankin** and **Britter** 1999] Hankin R.K.S. and Britter R.E. (1999) TWODEE: the Health and Safety Laboratory's Shallow Layer Model for Heavy Gas Dispersion Part 1. Mathematical Basis and Physical Assumptions, J. Haz. Mat., 66, 211-226.

[**Hanna** et al. 1993] Hanna, S.R. et al. (1993) Hazardous Gas Model Evaluation with Field Observations, Atmos. Environ., 27A, 2265-2285.

[**Harper** 2002] Harper, I., (2002) "Future Development Options for LNG Marine Transportation," American Institute of Chemical Engineering, Spring National Meeting, January 2002.

[**Harrison** and **Eyre** 1987] Harrison, A.J. and Eyre, J.A. (1987) The effect of obstacle arrays on the combustion of large pre-mixed gas/air clouds, Combust. Sci. and Tech., Vol. 52, 121-137.

[**Havens** 1981] Havens, J. A. (1980) An Assessment of Predictability of LNG Vapor Dispersion from Catastrophic Spills Onto Water, J. Haz. Mat. 3, , 267-278.

[**Havens** and **Spicer** 2002] Havens, J., and Spicer, T., "New Models Predict Consequences of LNG Releases." GTI GasTIPS Journal, Gas Technology Institute, pp. 27-30, Fall 2002.

[**Heskestad** 1998] 'Dynamics of the fire plume', Phil. Trans. R. Soc. Lond. A, 356, 2815-2833.

[**Hightower** 2004] Hightower, M. et al., (2004) "Threat and Breach Analysis of an LNG Ship Spill over Water," U.S. DOE and Sandia National Laboratories, Albuquerque, NM, SECRET (DRAFT), 2004.

[**Hirst** and **Eyre** 1983] Hirst, W. J. S. and Eyre, J.A., (1983) Maplin Sands Experiments 1980: Combustion of Large LNG and Refrigerated Liquid Propane Spills on the Sea, Heavy Gas Risk Assessment, 211-224.

[**Hoult** 1972] Hoult, D. (1972) The fire hazard of LNG spilled on water, Proc. Conference on LNG importation and safety, Boston, Mass. 87.

[**Jazayeri** 1975] Jazayeri, B. (1975) Impact Cryogenic Vapor Explosions. M.S. Thesis, MIT, Cambridge, Massachusetts.

[**Johnson** 1992] Johnson, A. D. (1992), "A Model for Predicting Thermal Radiation Hazards from Large-Scale LNG Pool Fires." Major Hazards Onshore and Offshore, Institute of Chemical Engineers, Symposium Series No. 130, EFCE Event No. 470, EFCE Publication No. 93, Manchester, October 20-22, pp: 507-524.

[**Kaplan** and **Marshal** 2003] Kaplan, A. and Marshall, G., "World LNG Trade Responding to Increased Natural Gas Demand," Oil and Gas Journal, Nov 24, 2003.

[**Katz** and **Sliepcevich** 1973] Katz, D.L. and Sliepcevich D. M. (1973) LNG: Water explosions, National Academy of Sciences, Report no. CG-D60-74.

[**Kawaski** 2003] Kawaski Panel System, Kawasaki Heavy Industries, Tokyo, Japan, 2003.

[**Khalil** et al. 1988] Khalil, A. et al. (1988) Modeling of Confined Cryogenic Fuel Spills over Water, 5th Miami int. sym. on Multi-Phase Transport and Particulate, p. 187-199.

[**Kneebone** and **Prew** 1974] Kneebone A. and Prew L.R. (1974) Shipboard Jettison Test of LNG onto the Sea, Proc. 4th Int. Conf. on LNG, Algiers, 1-25.

[**Koopman** et al. 1978] Koopman, R. P. et al. (1978) Data and Calculations on 5 m3 LNG Spill Tests, Lawrence Livermore Laboratory, UCRL-52976.

[**Koopman** et al. 1982a] Koopman, R. P. et al., (1982) Analysis of Burro Series 40 m^3 LNG Spill Experiments, J. Hazardous Materials, 6, 43-83.

[**Koopman** et al. 1982b] Burro Series Data Report LLNL/NWC 1980 LNG Spill Tests, UCID-19075, Lawrence Livermore National Laboratory.

[**Koopman** 2004] Personal communication, Livermore, CA, October 2004.

[**Koski** 1997] Koski, J.A., et. al., "Calculation of Shipboard Fire Conditions for Radioactive Materials Packages with the Methods of Computational Fluid Dynamics," SAND97-2182, Sandia National Laboratories, Albuquerque, NM, September 1997.

[**Krane** 2000] "Piracy Makes a Comeback," APBnews.com, June 9, 2000.

[**Kvaerner – Masa** 2003] LNG Carriers, Kvaerner-Masa Yards, Helsinki, Finland, 2003.

[**Kvaerner – Masa** 2004] LNG Carriers, Kvaerner-Masa Yards, Helsinki, Finland, 2004.

[**Lautaski** 1992] Lautkaski, R. (1992) Validation of flame drag correlations with data from large pool fires, J. Loss Prev. Process Ind., Vol. 5, No. 3, 175-180.

[**Lazaro** et al. 1997] Lazaro, M.A., Woodard, K., Hanna, S.R., Hesse, D.J., Huang, J.C., Lewis, J., and Mazzola, C.A., , "Model Review and Evaluation for Application in DOE Safety Basis Documentation of Chemical Accidents – Modeling Guidance for Atmospheric Dispersion and Consequence Assessment," ANL/EAD/TM-75, Argonne National Laboratory, Argonne, IL, 1997.

[**Lee** and **Moen** 1980] Lee, J.H.S. and Moen I.O. (1980) The mechanism of transition from deflagration to detonation in vapor cloud explosions, Prog. Energy Combust. Sci., Vol. 6, 359-389.

[**Lehr** and **Simicek-Beatty** 2003] Lehr, W. and Simecek-Beatty, D. "Comparison of Hypothetical LNG and Fuel Oil Fires on Water." DRAFT report by the National Oceanic and Atmospheric Administration [NOAA] , Office of Response and Restoration, Seattle, WA, 2003.

[Leone et al. 1985] Leone, J. M. et al. (1985) FEM3 Phase Change Model, Lawrence Livermore National Laboratory, Report No. UCID-20353, 22.

[Lind and **Witson** 1977] Lind, C. D., and Witson, J. C. (1977) Explosion Hazards Associated with Spills of large quantities of Hazardous Materials Phase II, Report No. CG-D-85-77.

[Linsner 2004] Linsner, E.W., Ltr. Dated March 12, 2004, PRONAV Ship Management, Inc., Greenwich, CT.

[Might and **Perumal** 1974] Might W.G. and Perumal P.V.K. (1974) The spreading and evaporation of LNG on water, 74-WA/PID-15, Winter Annual Meeting of ASME, N.Y. 17-22, Nov.

[McRae et al. 1984] McRae T.G. et al. (1984) Analysis of Large-Scale LNG/Water RPT Explosions, UCRL-91832, Lawrence Livermore National Laboratory, Livermore, California.

[Mercer et al. 1994] Mercer et al. (1994) Comparison of heavy gas dispersion models for instantaneous release, J. Haz. Mat., 36, 193-208.

[Mizner and **Eyre** 1982] Mizner, G. A., Eyre, J. A. (1982) Large-Scale LNG and LPG Pool Fires, EFCE Publication Series (European Federation of Chemical Engineering), no.25, p.147-163.

[Mizner and **Eyre** 1983] Mizner, G. A., and J. A. Eyre (1983), "Radiation from Liquefied Gas Fires on Water." Combustion Science and Technology, Volume 35, pp. 33-57.

[Moen et al. 1980] Moen, et al. (1980) Flame Acceleration Due to Turbulence Produced by Obstacles, Comb. Flame, 39, no. 1 21-32.

[Moen 1993] Moen, I.O. (1993) Transition to detonation in fuel-air explosive clouds, J. Haz. Mat., 33, 159-192.

[Moorehouse 1982] Moorhouse, J., (1982) "Scaling Criteria for Pool Fires Derived from Large-Scale Experiments." The Assessment of Major Hazards, Symposium Series No. 71, The Institution of Chemical Engineers, Pergamon Press Ltd., Oxford, United Kingdom, pp. 165-179.

[Morgan et al. 1984] Morgan, D. L. et al. (1984) Phenomenology and Modeling of Liquefied Natural Gas Vapor Dispersion, UCRL-53581, Lawrence Livermore National Laboratory, Livermore, California.

[Napier and **Roochland** 1984] Napier D.H. and Roochland, D.R. (1984) Ignition Characteristics of Rapid Phase Transition Explosions, Combustion Institute Canadian Section 1984 Spring Technical Meeting.

[Nedelka et al. 1989] Nedelka, D. et al., (1989) The Montoir 35 m diameter LNG pool fire experiments, Int. Conf. Liq. Nat. Gas, v. 2, 9th, 17-20 Oct 1989, Nice, France.

[Nettleton 2002] Nettleton, M.A. (2002) Recent work on gaseous detonations, Shock Waves, 12, 3-12.

[NFPA 2001] National Fire Protection Association – Standard 59A, "Standard for the Protection, Storage, and Handling o Liquefied Natural Gas", 2001 Edition, Quincy, MA.

[Opschoor 1980] Opschoor, G. (1980) The spreading and evaporation of LNG- and Burning LNG- spills on water, J. Haz. Mat., 3, 249-266.

[OTA 1977] Office of Technology Assessment, (1977) "Transportation of Liquified Natural Gas," Congress of the United States, Washington, D.C., NTIS-PB-273486, 1977.

[Otterman 1975] Otterman B. (1975) Analysis of large LNG spills on water Part 1: Liquid spread and evaporation, Cryogenics, 455-460.

[Parnarouskis et al. 1980] Parnarouskis, M.C. et al. (1980) Vapor Cloud Explosion Study. Six. Congr. Int. Gaz. Natl. Liq., v. 2, Sess 3, paper 12

[Pitblado 2004] Pitblado, R.M., et. al., (2004) "Consequences of LNG Marine Incidents, CCPS Conference, Orlando, Fl., June 2004.

[Porteous and **Blander** 1975] Porteous, W.M. and Blander, M., Limits of superheat and explosive boiling of light hydrocarbons, halocarbons and hydrocarbon mixtures, AIChE Journal, 1975, 31(3), 560-566.

[Pritchard and **Binding** 1992] Pritchard, M. J., and T. M. Binding (1992), "FIRE2: A New Approach for Predicting Thermal Radiation Levels from Hydrocarbon Pool Fires." IChemE Symposium Series, No. 130, pp. 491-505.

[**Puttock** and **Blackmore** 1982] Puttock J. S., Blackmore D. R., and Colenbrander G. W. (1982) Field experiments on dense gas dispersion. J. Haz. Mat. 6, 13-41.

[**Quest** 2003] "Modeling LNG Spills in Boston Harbor." Copyright© 2003 Quest Consultants, Inc., 908 26th Ave N.W., Norman, OK 73609; Letter from Quest Consultants to DOE (October 2, 2001); Letter from Quest Consultants to DOE (October 3, 2001); and Letter from Quest Consultants to DOE (November 17, 2003).

[**Raj** and **Atallah** 1975] Raj, P. and Atallah S. (1975) Thermal Radiation from LNG spill Fires, Advances in Cryogenic Engineering, 20, 143-150.

[**Raj** and **Kalelkar** 1974] Raj, P.P.K. and Kalelkar, A.S. (1974) Assessment models in support of the hazard assessment handbook, U.S. Coast Guard Report No., CC-D-65-74, Jan.

[**Raj** et al. 1979] Raj, P. K., Mudan, K. S., Moussa, A. N. (1979) Experiments Involving Pool and Vapor Fires from Spills of LNG on Water. Report #CG-D-55-79, NTIS AD077073, U.S. Coast Guard.

[**Raj** et al. 1979] Raj, P.K. et al., (1979) LNG Spill Fire Tests on Water: An Overview of the Results, Am. Gas Assoc., Oper. Sect., Proc., T246-T251.

[**Rodean** et al. 1984] Rodean, H. C. et al. (1984) Vapor Burn Analysis for the Coyote Series LNG Spill Experiments, UCRL-53530, Lawrence Livermore National Laboratory, Livermore, California.

[**Sandemeyer** 1981] Sandemeyer, E., "Alphatic Hydrocarbons." Patty's Industrial Hygiene and Toxicology, Volume 2B: Toxicology, George D. Clayton and Florence E Clayton, editors, Wiley Interscience, New York, 1981.

[**Schneider** 1979] Schneider, A.L. et al. (1979) U.S. Coast Guard Liquefied Natural Gas Research at China Lake, Gastech 78. Monte Carlo, France 5-8 October 1978.

[**Schneider** 1980] Schneider, A.L. (1980) Liquefied Natural Gas Spills on Water Fire Modeling, J. of Fire Flammability, v. 12, no. 4, 302-313.

[**Schubach** 1996] Schubach, . (1996) Some aspects of modeling steam explosions, J. Loss Prev. Process Ind., Vol. 9, no. 3, 193-197.

[**Scott** 2004] Scott, Capt. D.L., Personal Communication, June 18, 2004.

[**Shell** 2002] LNG Shipping, Shell Gas and Power External Affairs, London, England, 2002.

[**SIGTTO** 2003] "Safe Havens for Disabled Gas Carriers," Society of International Gas Tankers and Terminal Operators, February 2003.

[**Sparrow** 1963] Sparrow, E.M., J. (1963) Heat Transfer, Trans., ASME, 85, pp. 81-88.

[**Spicer** and **Havens** 1989] Spicer T.O. and Havens, J.A., (1989) User's Guide for the DEGADIS 2.1 Dense Gas Dispersion Model Environmental Protection Agency, EPA-450/4-89-019.

[**Suo-Anttila** and **Gritzo** 2001a] Suo-Anttila, J.M., and Gritzo, L.A., (2001) "Thermal measurements from a series of tests with a large cylindrical calorimeter on the leeward edge of a JP-8 pool fire in cross-flow" SAND 2001-1986, Sandia National Laboratories, Albuquerque, NM, 2001.

[**Suo-Anttila** and **Gritzo** 2001b] Suo-Anttila, J.M., and Gritzo, L.A., (2001) "Thermal Measurements for a JP-8 Pool Fire in Cross Flow with a C141 Fuselage Located on the Leeward Edge" SAND 2001-0313, Sandia National Laboratories, Albuquerque, NM, 2001.

[**Sykes** et al. 1999] Sykes, R. I. et al. (1999) The Representation of Dynamic Flow Effects in a Lagrangian Puff Dispersion Model, J. Haz. Mat. 64, 223-247.

[**Thomas** 1965] Thomas, P. H. (1965), F.R. Note 600, Fire Research Station, Borehamwood, England.

[**Thyer** 2003] Thyer, A.M., (2003), A Review of Data on Spreading and Vaporization of Cryogenic Liquid Spills, Journal of Hazardous Materials, A99, 32-40.

[**Tieszen** 1991] "Gaseous Hydrocarbon-Air Detonations," Combustion & Flames, Vol 84, pg 376-390, 1991.

[**Tieszen**, et al. 1996] "Vertical structures in pool fires: Observation, Speculation, and Simulation", Sandia National Laboratories, Albuquerque, NM, SAND96-207, November 19, 1996.

[**Urtiew** 1982] Urtiew, P. A. (1982) Flame propagation in Gaseous Fuel Mixtures in Semi-confined Geometries, Report H, Report No. PNL-4172.

[**Valencia-Chavez** and **Reid** 1979] Valencia-Chavez, J. A. and Reid, R.C. (1979) The effects of composition on the boiling rates of liquefied natural gas for confined spills on water, Int. J. Heat Mass Transfer, Vol. 22, 831-838.

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

[**Vander Molen** and **Nicholls** 1979] Vander Molen, R. Nicholls J. A. (1979) Blast Wave Initiation Energy for Detonation of Methane-Ethane-Air Mixture, Comb. Sci. Tech., Vol. 21, 75-78

[**Vaudolon** 2000] Vaudolon, Alain (2000) Liquified Gases: Marine Transportation and Storage, Witherby & Company, Limited, Longon, p. 162.

[**Waite** et al. 1983] Waite, P.J. et al. (1983) The spread and vaporization of cryogenic liquids on water, J. Haz. Mat., 8, 165-184.

[**Welker** and **Sliepcevich** 1970] Welker, J. R., and C. M. Sliepcevich (1970), Susceptibility of Potential Target Components to Defeat by Thermal Action. University of Oklahoma Research Institute, Report No. OURI-1578-FR, Norman, Oklahoma.

[**Wellman** 1983] Wellman, Gerald W. "Application of the CTOD Fracture Parameter to Failure Analysis of Notched Pressure Vessels", PhD Dissertation, University of Kansas, July, 1983.

[**Wiersma** and **Williams** 1989] Wiersma, S. J. and Williams T. A. (1989) Overview of LNG Vapor Dispersion Research, Int. Conf. Liq. Nat. Gas, v. 2, 9th, 17-20 Oct 1989, Nice, France.

[**Zukoski** 1986] Zukoski, E. E. (1986) Fire Safety Science – Proc. First Int. Sym., p 7.

[**Zukoski** 1995] Zukoski, E. E. (1995) 'Properties of fire plumes', in Combustion Fundamentals of Fire (ed. G. Cox), pp. 101-219. Academic Press, London

Exhibit 8

Innovative Safety Products

OBERON

UNDERSTANDING THE STOLL CURVE

Introduction

Alice Stoll and Maria Chianta conducted burn injury research on "sailors, pigs and rats" in the late 1950s and early 1960s at the Aerospace Medical Research Department, Naval Air Development Center. It is reported that Sailors of the U.S. Navy volunteered to be burned on their forearms for a weekend pass. Stoll and Chianta used heat exposures on human and animal skin to determine the level of heat energy that would create a second-degree burn. For their work, they defined a second-degree burn as the point at which a blister forms which is the point at which the outer layer of human skin, the epidermis, is destroyed. The blister is formed when the epidermis separates and lifts off the remaining skin structure (the dermis). The Stoll and Chianta data was presented in a landmark paper in 1969 and was later used to create the "Stoll curve" which quantifies the level of heat and the duration of time required for a second-degree burn for a wide range of exposure conditions. The range covers a high level of heat for a short time period to a low level of heat for a much longer time period. Table 1 provides the heat exposure level (heat flux) and the exposure times that make up the Stoll curve in the context of a particular type of sensor, a copper calorimeter using an iron constantan thermocouple. Figure 1 shows the same information plotted graphically.

Table 1 Human Tissue Tolerance to Heat, Second Degree Burn [A]

Exposure Time	Heat Flux		Total Heat		Calorimeter [B] Equivalent		
s	kW/m^2	cal/cm^{2}s	kWs/m^2	cal/cm^2	ΔT°C	ΔT°F	ΔmV
1	50	1.2	50	1.20	8.9	16.0	0.46
2	31	0.73	61	1.46	10.8	19.5	0.57
3	23	0.55	69	1.65	12.2	22.0	0.63
4	19	0.45	75	1.80	13.3	24.0	0.69
5	16	0.38	80	1.90	14.1	25.3	0.72
6	14	0.34	85	2.04	15.1	27.2	0.78
7	13	0.30	88	2.10	15.5	28.0	0.80
8	11.5	0.274	92	2.19	16.2	29.2	0.83
9	10.6	0.252	95	2.27	16.8	30.2	0.86
10	9.8	0.233	98	2.33	17.3	31.1	0.89
11	9.2	0.219	101	2.41	17.8	32.1	0.92
12	8.6	0.205	103	2.46	18.2	32.8	0.94
13	8.1	0.194	106	2.52	18.7	33.6	0.97
14	7.7	0.184	108	2.58	19.1	34.3	0.99
15	7.4	0.177	111	2.66	19.7	35.4	1.02
16	7.0	0.168	113	2.69	19.8	35.8	1.03
17	6.7	0.160	114	2.72	20.2	36.3	1.04
18	6.4	0.154	116	2.77	20.6	37.0	1.06
19	6.2	0.148	118	2.81	20.8	37.5	1.08
20	6.0	0.143	120	2.86	21.2	38.1	1.10
25	5.1	0.122	128	3.05	22.6	40.7	1.17
30	4.5	0.107	134	3.21	23.8	42.8	1.23

[A] Stoll, A. M. And Chianta, M. A., "Method and Rating System for Evaluation of Thermal Protection," Aerospace Medicine, Vol 40, 1969, pp.1232–1238.

[B] Iron/constantan thermocouple.

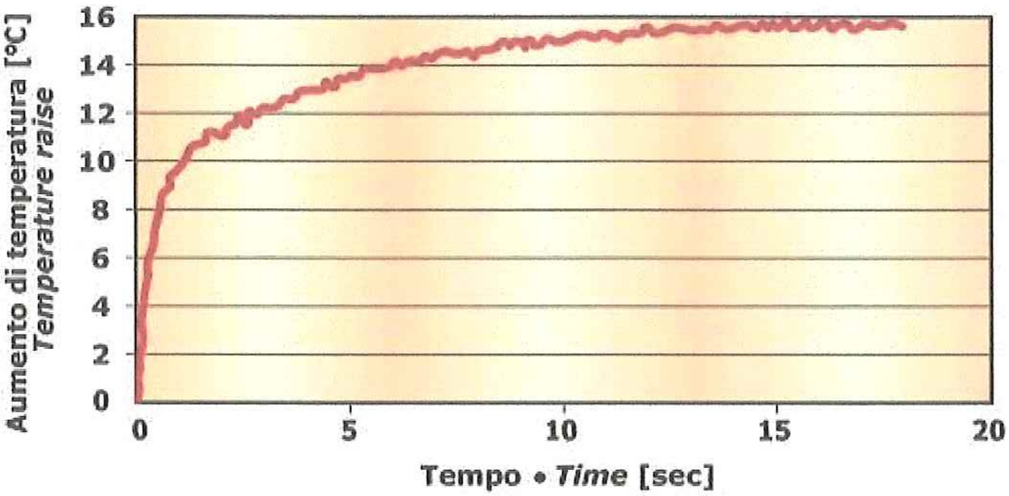


Figure 1 Stoll Curve for a copper calorimeter sensor as used in arc testing

Stoll Curve versus Skin Temperature

If the same heat exposures and times shown in Table 1 and Figure 1 were applied to human skin, the skin temperatures would be very different since human tissue is a poor conductor and copper is of course an excellent conductor. The genius of Stoll was to translate skin properties into the context of a simple and robust sensor that could be used to predict burn injury for a wide range of exposure conditions. The copper calorimeter is not intended to simulate human skin, but since its thermal properties are well known, and the thermal properties of skin are well known thanks to the work of Stoll and Chianta among others, a burn prediction can be made for human skin using date from the copper sensor.

It is also important to note that the temperatures in Table 1 and Figure 1 are delta T values or the change in temperature during the exposure time period and not the actual temperatures. For instance, if a heat flux of 1.2 cal/cm^{2}s were applied for one second we would predict a 50% probability that a burn injury would occur and we would measure a rise in temperature of 8.9^{O}C (16^{O}F) in the copper calorimeter. Since the copper would normally start at the human skin temperature or approximately 32^{O}C(89.6^{O}F), the final temperature of the copper calorimeter would be 40.9^{O}C (105.6^{O}F). Of course, we all know that if human skin were raised to a temperature of 105.6^{O}F in one second, no second-degree burn injury would occur.

Where is the Stoll Curve Used?

Many ASTM and NFPA standards utilize the Stoll curve to define a test method end point. These standards include the ones we are familiar with like ASTM F1959-99 Arc Test Method and F2178-02 as well as ASTM F1060 (Conductive Heat Test) and F1939 (Radiant Heat Test) and NFPA 1971 (Structural Firefighter Clothing and Equipment Standard), NFPA 1977 (Wildland Firefighter Clothing Standard) and NFPA 2112 (Industrial Flash Fire Protective Clothing Standard).

How is the Stoll Curve Used in Arc Testing?

As noted above, both ASTM F1959 (fabrics and systems) and ASTM F2178 Arc Test Methods (face protective products). Figure 2 shows an F2178 arc test using an instrumented head.

- The top graph provides the electrical parameters of the test, the arc current, voltage and duration in milliseconds and cycles. The horizontal axis is in milliseconds, i.e. 1000 milliseconds is equal to 1.0 second. This arc exposure is indicated to be 130.4 cycles which equates for our 60 cycle per second AC electrical system to approximately 2.2 seconds or 2200 milliseconds.

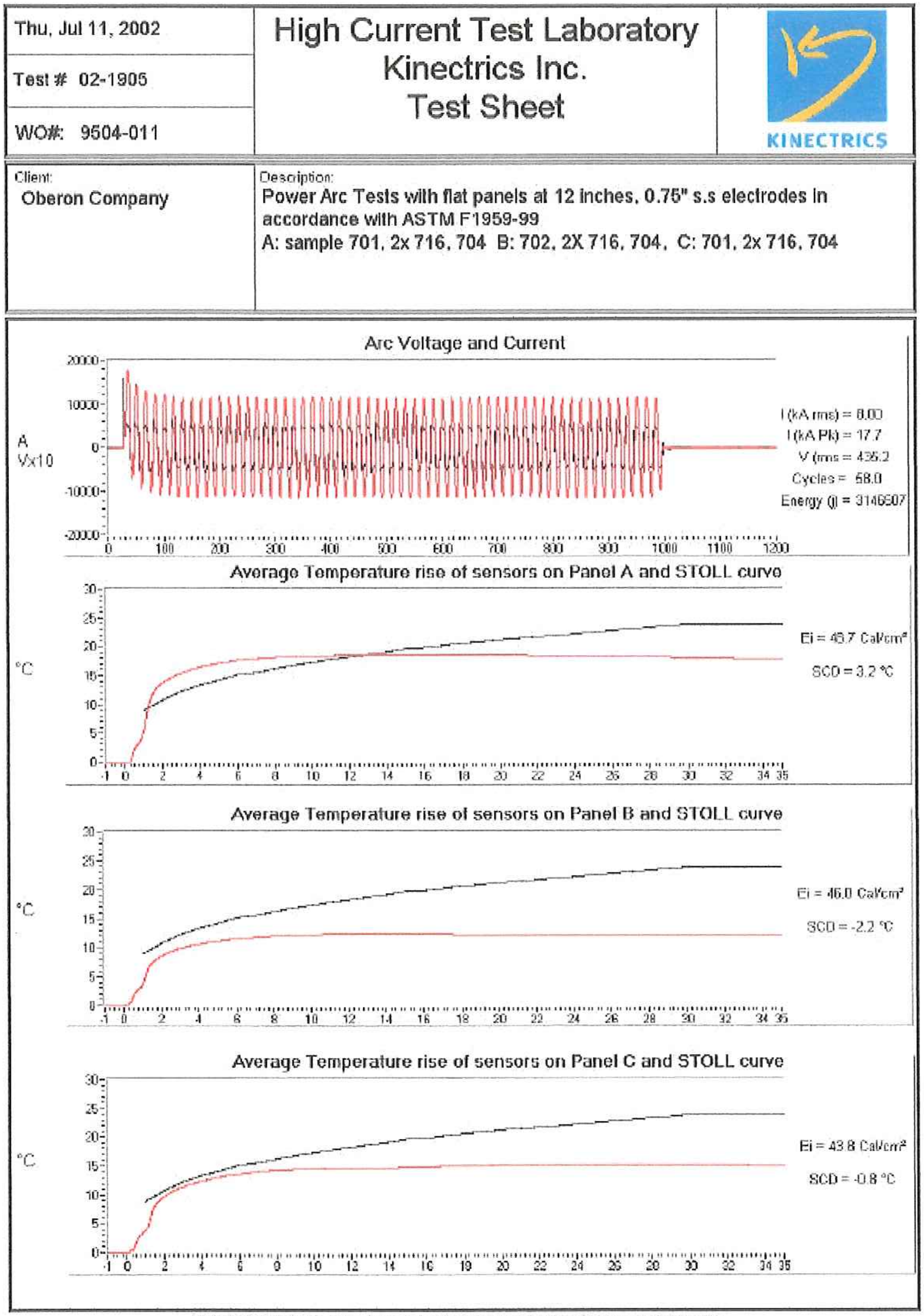
- The bottom graph shows no sensor responses (these were turned off or shielded for this test) but the graph does show the Stoll curve for Mannequin B

- The middle graph shows four sensor responses in addition to the Stoll curve for Mannequin A. The four sensor data plots are the two eye sensors, the mouth sensor and the chin sensor.

- The exposure on Mannequin Head A is determined by monitor sensors and is noted at the bottom of the chart at 95.6 cal/cm^2. This high level exposure is being used because we are testing an experimental 100 cal hood.

- For Mannequin A, we see only the chin sensor exceeds the Stoll curve. The eye and mouth sensors remain well below the Stoll curve. In this case, we would predict that the chin of Mannequin A would have likely received a second-degree burn, but the face in the areas of the eyes and mouth would not have received a second-degree burn injury.

In this test, we are using an R&D 100 cal hood and adding prolonged afterflame due to contamination of the sample with mineral oil. The intent is not what occurred in this particular test, but rather to understand how the Stoll curve is used in the F2178 Arc Test Method.



Thu, Jul 11, 2002	High Current Test Laboratory Kinectrics Inc. Test Sheet	KINECTRICS
Test # 02-1905		
WO#: 9504-011		

Client: Oberon Company	Description: Power Arc Tests with flat panels at 12 inches, 0.75" s.s electrodes in accordance with ASTM F1959-99 A: sample 701, 2x 716, 704 B: 702, 2X 716, 704, C: 701, 2x 716, 704

PRIVATE INFORMATION. This test data shall not be disclosed or distributed without permission of the client.

Figure 2 Applying the Stoll Curve to an ASTM F2178 Arc Test

Exhibit 9

CALIFORNIA PUBLIC UTILITIES COMMISSION

CPSD

Consumer Protection and Safety Division

An Assessment of the Potential Hazards to the Public Associated with Siting an LNG Import Terminal in the Port of Long Beach

Prepared By

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September 14, 2005

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report was prepared at the request of the Consumer Protection and Safety Division of the CPUC for an assessment of public safety issues that should be considered regarding the proposed siting of an LNG import terminal in the Port of Long Beach.

The history of LNG importation in the United States is reviewed, describing the siting and continuing operation of the present six LNG import terminals, and the proposal for a very large expansion in the country's LNG infrastructure - more than fifty proposals for LNG import terminals to be located in the continental United States, Southern Canada, Mexico, and the Caribbean Islands – is described. As there appear to be many more proposals than for which there is a demonstrated need, it is all the more important to ensure that the siting process involves, to the maximum extent possible, careful consideration of potential hazards to the public and adjacent infrastructure so as to give full consideration to the best alternatives available.

The potential hazards to the public of the proposed POLB terminal are defined as fire and explosion hazards, and an assessment is provided of the adequacy of the present regulation, 49 CFR 193, to protect the public.

Since the regulations were promulgated in the early Eighties, after the terminals now operating had been built and commenced operation, and since there was no rush to build additional LNG import terminals until about the year 2000, the regulations were largely unused for import terminal siting. As a result, the regulations did not, and still do not, give serious consideration to the terrorist threat that began in this country September 11, 2001. The current regulations do not effectively address the many serious questions posed by the present requirement to consider events that could be caused by malicious intent, nor is sufficient attention being paid to the reality that malicious intent changes the whole safety picture – hence the process has outrun the development of the regulations to deal with it, and the present regulations fail to address this most important new paradigm.

Most importantly in consideration of the post 9/11 threat, there is presently no requirement, much less enforcement, of exclusion zones to protect the public from LNG spills which could occur from the ships that serve the import terminal. The failure to provide for the protection of the public and surrounding infrastructure from major releases of LNG that could occur from the ships serving the facility must be considered all the more important now as a result of recent government sponsored reports, for which there is now scientific consensus, that indicate that the danger zones extending from large, but credible, spills on water are likely to pose greater threats than would either accidental or terrorist caused releases from the land part of the terminal.

The regulation does not provide for consideration of boiling liquid expanding vapor explosions (BLEVEs) or unconfined vapor cloud explosion (UVCE) hazards, although the proposed terminal is designed to import LNG containing natural gas liquids (NGL) in amounts sufficient to raise serious questions about the potential for UVCEs following large LNG spills. The possibility of BLEVEs of LNG ship tanks, particularly the ship tanks which rely on non-fire-resistive insulation to keep the LNG from vaporizing, is not considered, although it is clear that there is a significant potential for occurrence of cascading failures that could jeopardize the ship and all of its content of LNG.

The report then presents an assessment of the consequences to the public that could result from credible accidental or terrorist caused releases of flammable liquefied fuels, either from the land part of the facility or the ships that would serve it.

Accidents and Terrorist Actions

The current regulations, particularly regarding provisions for public safety, focus on the land based part of the terminal. There are specific requirements for liquid containment and impoundment systems that are designed to limit the spreading of LNG that might be released either from the LNG tanks themselves or from transfer lines in the facility. But such control and mitigation measures could not be effectively applied to releases that could occur from an LNG ship, either at the jetty or in transit thereto, because spills onto water could not be effectively contained.

For spills on water, there have been government sponsored studies that provide information sufficient to define the (credible) spills that could occur as well as the consequences that could result.

The ABS Group and Sandia reports agree that the release of LNG in the amount of approximately 3,000,000 gallons (half of one typical LNG ship tank) is credible,

- in that such a release could result from accidental collisions between ships with sufficient momentum (mass and speed) to cause such a breach of containment, or
- that such a release could be caused by terrorists with means that are readily available to them.

Furthermore, the ABS Group and Sandia reports agree that a release of 3,000,000 gallons of LNG onto water could result in:

- Pool fires which would expose persons with unprotected skin to thermal fluxes (5 KW/m^2) that could cause second degree burn injury in approximately 30 seconds at a distance of approximately 1 mile, and
- Flammable vapor clouds, if the spilled material were not ignited upon release, that could extend downwind to distances between 2 and 3 miles. It is reasonable to assume that persons caught in the fire if the cloud were ignited would be killed or seriously injured.

The author is in essential agreement with these consequence estimates but believes the following modifications are required if they are to be used to ensure public safety:

- Since the thermal radiation flux criterion (5 KW/m^2) used by Sandia and the ABS Group could cause second degree burns in thirty seconds, it is not sufficiently protective of public safety; a lower value, approximately 1.5 KW/m^2, is recommended here. This value is already being used by other segments of the regulatory system, both nationally and internationally, based on its definition as the highest thermal flux to which an unprotected person can be continuously exposed without injury. If the 1.5 KW/m^2 criterion is used, it is anticipated that the distance of 1 mile (associated with the higher flux level) would be increased to between 1 ½ and 2 miles.

- As the Sandia Report states unequivocably that cascading failures of ship tanks cannot be ruled out and further states that in their opinion failures of as many as 3 tanks could occur, this scenario must be considered credible. As Sandia estimates that the hazard distance from this scenario could be extended by approximately one-third, the distance to the 1.5 KW/m^2 flux level would then be increased to approximately 2 ½ to 3 miles.

- The ABS Group's high-end estimates for the vapor cloud distance to the 2.5 % gas concentration level (based on releases from a 5 meter diameter hole in the containment) are approximately 3 miles. The Sandia estimates for the credible scenario analyzed are closer to 2 miles, but their calculations reflect the distance to the 5% gas concentration level rather than the 2.5% level which is accepted to represent the better criterion for vapor cloud travel distance that could pose a hazard to the public. Use of the lower flammable gas concentration criteria would be expected to extend the hazard distance to about 3 miles.

Based on this information, which the author believes to be the best available, and which is in general agreement with widely held views in the scientific community, a minimum distance is specified here for the extent to which the public could be put in harm's way from the initial release of approximately 3,000,000 gallons of LNG onto water at the POLB. It is approximately 3 miles.

Consideration of Worst Possible Cases

A minimum 3 mile radius circle around the proposed terminal is proposed to demarcate the area in which events deemed credible could cause serious injury to the public. The minimum distance to demarcate expected damage to infrastructure would be of lesser extent, depending on the criterion selected for damage. Any consideration of the consequences to POLB infrastructure must consider the wide variety of flammable and other hazardous materials routinely handled, as the area in which significant damage to infrastructure could occur (beyond the terminal and the ship) encompasses sections of one of the largest and busiest ports in the country. The POLB receives very large crude oil carriers (VLCC) at a jetty located within several hundred feet of the eastern boundary of the proposed LNG facility, and a major container terminal which almost certainly receives hazardous cargo lies adjacent to the western side of the proposed site, along which the LNG ship will be berthed.

It must be emphasized that the 3 mile distance recommended here is based primarily on the assumption that approximately 3,000,000 gallons of LNG is spilled onto water, as it appears there is little doubt that either pool fire radiation thermal fluxes or flammable vapor clouds from such a spill could put the public in harm's way out to that distance. However, it is a minimum specification, because it does not address the possibility of more serious events which could occur.

There is very real concern that such events as provide the basis for the 3 mile consequence distance would be of such severity as to make it highly likely, if not almost certain, that further failures of containments would occur. In particular, there is serious concern that the exposure to the ship from such a pool fire would have the potential to cause cascading failures of the remaining tanks on the vessel, resulting in total loss of the vessel and burning of its contents. There can be no doubt that the consequences of such a worst-possible-case event could be more severe.

Finally, the report states that the vulnerability of the land based part of the facility needs to be considered more carefully, as the author believes that insufficient attention has been given to the vulnerability of the land based facility to such natural phenomena as earthquakes and tsunamis, as well as to the facility's vulnerability to terrorist attack.

CHAPTER 1

INTRODUCTION

This report was prepared for the Consumer Protection and Safety Division (CPSD) of the California Public Utilities Commission. The CPSD requested that I prepare a science-based assessment of public safety issues that should be considered regarding the proposed siting of an LNG import terminal in the Port of Long Beach, California.

My resume is attached as Exhibit A. I have been researching methods for assessing the potential consequences of major spills of liquefied natural gas (LNG) and natural gas liquids (NGL) for more than thirty years. As the history of LNG import terminal siting in the United States, indeed the world, is largely confined to a similar period, I believe that I have a unique perspective on the issue of the hazards which LNG terminal activities can pose to public safety. I also believe that it is important to consider LNG safety issues in the broader context of increasing usage by society of other liquefied fuel and chemical gases that pose similar hazards. I particularly appreciate this opportunity to put the issues of public safety surrounding the proposed siting of an LNG import terminal in the Port of Long Beach into a scientifically reasoned context - based on my observation and study during the last three decades to understand the consequences that could occur to the public as a result of major spills of liquefied gaseous fuels onto land or water.

In my view, the importance of careful and sober consideration of the potential threat to public safety and to critical infrastructure of the decision to site a large LNG import terminal in the Port of Long Beach cannot be overstated. No liquefied fuel import terminals have been sited in urban areas of the United States since the Distrigas plant began operation in Everett, MA, in Boston Harbor, in 1971. In the interim three decades the world has experienced several catastrophic industrial accidents which were so severe as to importantly influence worldwide regulatory controls intended to lessen the likelihood as well as the potential consequences of accidental releases. Most importantly, no LNG facilities at all have been sited in this country since 9/11, and I believe that 9/11 completely changed, or should and will change, our methods as well as our thinking about the new paradigm in which major hazards complexes must be considered.

It is important for the reader to understand that this assessment is intentionally and solely directed to the realistic definition of the consequences to the public and surrounding infrastructure that could occur from a major release of flammable liquids at the proposed terminal or from the ships that will serve it, with no consideration given to the likelihood of occurrence of the events which are considered I believe that the first step in determining a rationale for a decision whether or not to site the proposed LNG terminal in the Port of Long Beach is to define the possible (credible) consequences of major releases of hazardous materials, and I believe that such determination should be made independently of any arguments advanced regarding the probability (likelihood) of such events' occurrence.

This approach is all the more appropriate since the tragic events of 9/11, as historical experience regarding LNG accidents (or accidental occurrences of any kind) cannot be used to quantify the probability of a terrorist attack.

1.1 LNG Importation in the United States

Proposals for large scale importation into the United States are not new, importation of LNG into the States having begun in the early Seventies. Although the technology of LNG storage and shipping has advanced in several areas, there are many similarities between the storage and shipping methods utilized in the Seventies and those proposed today. Indeed, all of the import terminals built in the Seventies are still in operation, and are proposed for operation for at least two decades into the future.

By the early Seventies the marine carriage of LNG had been proven technologically, and several ventures were proposed to import LNG into the United States, at the time principally from Algeria to the east and gulf coasts and from far-east gas sources such as Indonesia to the west coast. By the end of the Seventies, four import terminals were operating on the east and gulf coasts of the United States – at Everett, Massachusetts, beginning in 1971; near Savanna (Elba Island), Georgia, beginning in 1978; at Cove Point, Maryland, beginning in 1978; and at Lake Charles, Louisiana, beginning in 1982. A fifth terminal, at Kenai, Alaska, intended for export, principally to Japan, began operation in 1969. The terminal in Everett has been in operation continuously; the terminals at Elba Island, Cove Point, and Lake Charles are currently operating after a period in mothballs (different for each) which resulted from decreased need for LNG importation. The fifth import terminal was constructed and began operating in Penuelas, Puerto Rico, in 2000, and the Gulf Gateway Energy Bridge deepwater port commenced operation this year in the Gulf of Mexico.

To serve the needs of these United States import terminals as well as the needs of even faster growing LNG importation by Japan and Europe, a fleet of LNG carriers was constructed. Currently, there are approximately 165 LNG carriers in service worldwide, several of which were built for the trade that began in the Seventies. Eighteen carriers have been retired from service, and approximately 85 new ones are on order. Typical LNG carriers built in the Seventies, some of which are in use today, carry approximately 125,000 cubic meters of LNG, but the proposed terminals today are planned to receive carriers with capacity up to 250,000 cubic meters (approximately 66 million gallons).

During the period in which the first four terminals (described above) were constructed, there were additional proposals to build and operate LNG import terminals in California, with three specific sites receiving principal consideration – Los Angeles Harbor (Terminal Island), Point Conception, and Oxnard. For all three of these proposed locations, detailed risk assessment studies were prepared to define the hazards to the public that might occur as a result of accidental spills of LNG. None of the proposed California terminals were built, presumably as a result of indications that they would not be profitable in view of a reassessment of the demand for natural gas. It is important to note that because the terminal project applications were withdrawn for reasons other than consideration of their safety hazards, it is fair to say that the issues of public safety were never effectively resolved, and consideration of the risks to the public of such ventures languished - until about the year 2000.

1.2 Proposed Expansion in LNG Importation

The United States is presently considering a very large expansion of its LNG import infrastructure. As addition to the five land and one offshore import terminals currently operating in this country, as many as fifty new LNG import terminals to be sited in the continental United States, Southern Canada, Mexico, and the Caribbean Islands have been proposed. Additional proposals have been announced during the preparation of this report. All of these plans are said to be based on projections for greatly increased LNG use, both in quantity and as a percentage of total energy use.

Although this report is not intended to address the need for new LNG import terminals, I think that it should be noted that there have been no projections of demand for LNG that suggest our need (before 2025) for more than perhaps as many as a third of this number, and quite likely fewer. Viewed thus, the large number of proposals appears to be in some important part the result of significant competition to "win" in the selection process.

Although the majority of these terminals have been proposed at onshore locations, including some proposed for urban areas, as in Long Beach, a significant number are now planned for installation offshore.

With more proposed terminals than for which there is a justified need, I believe it all the more important to ensure that the siting process involves, to the maximum extent possible, careful consideration of potential hazards to the public and adjacent infrastructure.

1.3 Public Safety Concerns about LNG Terminal Siting

To begin, let me define the terms liquefied natural gas (LNG) and natural gas liquids (NGL).

LNG is natural gas that has been cooled, at normal atmospheric pressure, to approximately -260 °F, its liquefaction temperature varying depending on the composition of the gas. Methane, the principal component of LNG, cannot be liquefied by pressure alone. Although liquefaction by cooling to higher temperatures (> -260 °F) at elevated pressure is possible (combinations of cooling and pressurization are utilized in some LNG applications, such as vehicle fuels), the LNG that would be received at the Long Beach Terminal would be contained in ship tanks designed for nominal atmospheric pressure operation, i.e., with design pressures not exceeding approximately one atmosphere, and stored in land tanks under similar, nominally atmospheric pressure, conditions. Based largely on historical precedent, most LNG safety and risk assessments have assumed LNG to be principally methane, and present regulatory requirements for determining danger zones around LNG spills allow, at least implicitly, description of its composition as pure methane.

However, the composition of the LNG that would arrive at the proposed Long Beach terminal will depend upon several variable factors, including the location of gas production (the composition of natural gas from different producing fields can vary significantly) and the degree of processing of the natural gas, either during liquefaction at the export terminal or following the receipt of the LNG at the import terminal, to remove heavier molecular weight hydrocarbons such as ethane, propane, and butane. Such heavier molecular weight compounds, mixed in varying concentrations, are commonly referred to as natural gas liquids (NGL). Since the proposed terminal in Long Beach could import LNG containing substantial amounts of natural gas liquids, and since the terminal is designed to process the LNG after receipt to separate the NGL for (separate) distribution, a thorough assessment of the hazards which could be posed to the public should consider both the LNG and NGL components of the facility. Furthermore, since the degrees of hazard to the public depend, beyond the most immediate and compelling factor of the very large quantities of LNG, on important differences that are known to exist in the fire and explosion hazard potentials of LNG and NGL, any assessment of the potential hazards to the public from the proposed terminal should consider the hazards specific to LNG and NGL, as well as any potential for more serious events which could result from the storage and handling of the materials in combination.

The concerns for public safety associated with the current proposals to site new LNG terminals are essentially the same as those identified in the Seventies when LNG terminals were introduced to the United States. I have observed that the degree to which the public raised concerns about public safety varied considerably in the gulf, east, and west coast regions. There appeared to be the least opposition in the gulf coast region, with somewhat greater resistance on the east coast, particularly in New York and New England, and perhaps greatest regarding the siting of the three terminals proposed in California. It is significant, I believe, to the present discussion to note (again) that the Distrigas terminal in Everett, Massachusetts, is the only terminal constructed to date in a major urban area in the United States. There have been voiced far more concerns about the Everett facility than for the other terminals, which by comparison are located more remotely (from the public).

It is also my observation that similar variations exist in these same regions today in their response to LNG terminal siting proposals – least in the gulf region (with the notable exception of Mobile, Alabama, where Exxon Mobil has withdrawn its proposal for a terminal in Mobile Bay), followed by similar responses (both for and against the projects) from the public to proposals on the east and west coasts. So far, the proposals for terminals to be sited in unarguably urban areas, notably Fall River, Massachusetts, on the east coast, and Long Beach on the west coast, appear to be among the most contentious (regarding the public safety issue) of the proposals under active evaluation.

But there are present today (at least) three new and significant factors that require careful consideration before reaching a decision to site a liquefied gas import terminal, particularly if the site is in an urban area.

The first is the aforementioned offshore placement of LNG import terminals. Although at the beginning of the current expansion phase, there were many objections advanced to the offshore alternative, including most prominently issues of economy (it was suggested that offshore installations would be too expensive) and increased vulnerability to scheduling interruptions caused by weather, the offshore option appears to be gaining acceptance, with several terminals proposed for offshore locations off of the west, gulf, and east coasts. At least one offshore LNG facility (The Gulf Gateway Energy Bridge deepwater port, owned by Excelerate Energy Limited Partnership) has commenced operation this year in the Gulf of Mexico. It appears that the viability, of at least this type of offshore importation project (Energy Bridge), is no longer in question.

Second, during the ensuing three decades since the LNG terminals on the east and west coasts commenced operation, the world has experienced several catastrophic industrial accidents, the major consequences of which should be seriously considered before reaching a decision to site a potential major hazard industrial facility, such as the proposed LNG terminal, in a congested area such as the Port of Long Beach. Most importantly to the present in that regard, there have been a substantial number of liquefied gaseous fuel accidents involving containment failures due to boiling liquid expanding vapor explosions (BLEVEs) as well as unconfined vapor cloud explosions (UCVEs), the most severe in this hemisphere (in terms of human casualties) having occurred in an outlying area of Mexico City in 1984. That event resulted in more than 600 deaths, thousands of serious injuries, and the complete devastation of an entire NGL storage and distribution facility.

Third, and perhaps of greatest importance to the present consideration of siting an LNG terminal in the Port of Long Beach, is the terrorist threat, which the public perceives with growing concern. Although sabotage appears to have been given some consideration in the siting of terminals in the Seventies, to my knowledge no organized efforts were undertaken at that time to quantify the consequences that might result from sabotage or to attempt to quantify the likelihood of such occurrences. But, since 9/11, concerns about terrorist attacks that could pose significant threats to public safety are very real, and they are fast growing. The energy infrastructure of our country is of particular concern, because of the potential for terrorist attacks to cause events that could directly endanger the public as well as deprive us of energy that we require.

The Department of Homeland Security has identified LNG infrastructure, one component of the much larger chemical/energy infrastructure, as a potential terrorist target of concern. The Department's concern results, primarily I believe, from the recognition that liquefied gas fuel storage tanks, either on land or on ships, must necessarily concentrate very large amounts of energy (as LNG and NGL) in individual containment systems in order to be economical. The terminal proposed for the POLB will have storage capacity for approximately 86,000,000 gallons of LNG, and the ships that are initially planned to serve the terminal will carry approximately 38,500,000 gallons of LNG. However, the facility is being constructed so as to enable it to receive ships carrying up to about 53,000,000 gallons of LNG, and possibly more. The potential for terrorist attack to release large quantities of highly flammable fuels from such large storage vessels thus is seen to carry with it the potential for such attacks to endanger the public offsite as well as to effect horrendous damage to infrastructure. In my opinion, these factors demand that LNG infrastructure such as the proposed Long Beach terminal be identified as potential terrorist targets of opportunity.

I believe, and have so testified before Congress, that since 9/11 we no longer have the luxury of considering only means for reducing the probability of accidents (through more effective management strategies) to a level that is considered to justify the attendant risk – we now are forced to consider malicious acts as well. And, I believe that it is imperative that the dangers to the public from possible spills that could occur as a result of terrorist attack, particularly those spills which might occur from a tankship and thus onto water (for which there are few if any control measures), be most carefully considered in the current rush to site additional LNG import terminals in our country. Finally, in this regard, I have notified the Secretary of Homeland Security (Exhibit B) of my concerns about specific features of LNG carriers which I believe may make those ships vulnerable to terrorist attack. The specific issues, which I will address later in order to put them into a proper context, are the use of non-fire-resistive insulation on the containment vessels (LNG tanks) and the potential for major failures of the ship's structure due to direct contact with spilled LNG, which, having temperatures as low as (minus) 260 °F, has been demonstrated repeatedly to cause brittle fracture of carbon steels. Since my appeal to the Department of Homeland Security, there have appeared important reports of studies designed to clarify several outstanding issues, particularly those issues regarding the consequences that can be anticipated from large releases of LNG onto water; I will attempt to summarize the current state of our knowledge regarding these critically important matters in this report.

Finally, I have tried to prepare this report in a form which will be useful to policy makers, whom I believe are not always sufficiently informed on such matters, and to the public, whom I believe are becoming increasingly concerned, as I am, that issues of public safety surrounding the nation's chemical/energy infrastructure are not receiving the attention that is demanded, particularly post 9/11. Quoting from the foreword which I wrote for the chapter on Major Hazard Control, in Lee's Loss Prevention in the Process Industries, "It is my belief that the major hazards problems society faces are less a problem of insufficient information about those hazards and more a problem of insufficient application of the tools that we have in hand." In this regard, I believe it is important to note that the reports on LNG hazards which have been recently prepared and mentioned above, especially the reports by the ABS Group and the Sandia Group, do provide information which provides effective answers to several technical questions concerning large spills of LNG onto water which have been particularly contentious. It is in that vein that I have prepared this report with a view to cutting through the technical details to provide the public with my summary of the information which is now available, along with my candid view of what that information should mean to the public and its policy makers whom are considering the siting of an LNG import terminal in the POLB. I believe it is absolutely imperative that we get this one right, as it will have the potential for setting extremely important precedents in our attempts to balance the risks and benefits of increased LNG importation, that task having been made immensely more difficult by the threat of terrorist attack.

CHAPTER 2

POTENTIAL HAZARDS TO THE PUBLIC OF THE PROPOSED LNG TERMINAL IN THE PORT OF LONG BEACH

2.1 Location and Description of the Proposed Terminal

Location

The satellite photo below shows the harbors of Los Angeles and Long Beach, with adjacent cities of Los Angeles to the west and north and Long Beach to the north and east. The proposed location of the LNG terminal in the Port of Long Beach is on an approximately twenty-five acre site on the east side of Pier T. For purposes of scaling, a circle with one mile radius is centered on the location of the tanker offloading site, which will be on the west side of the land parcel designated "TERMINAL".[1]

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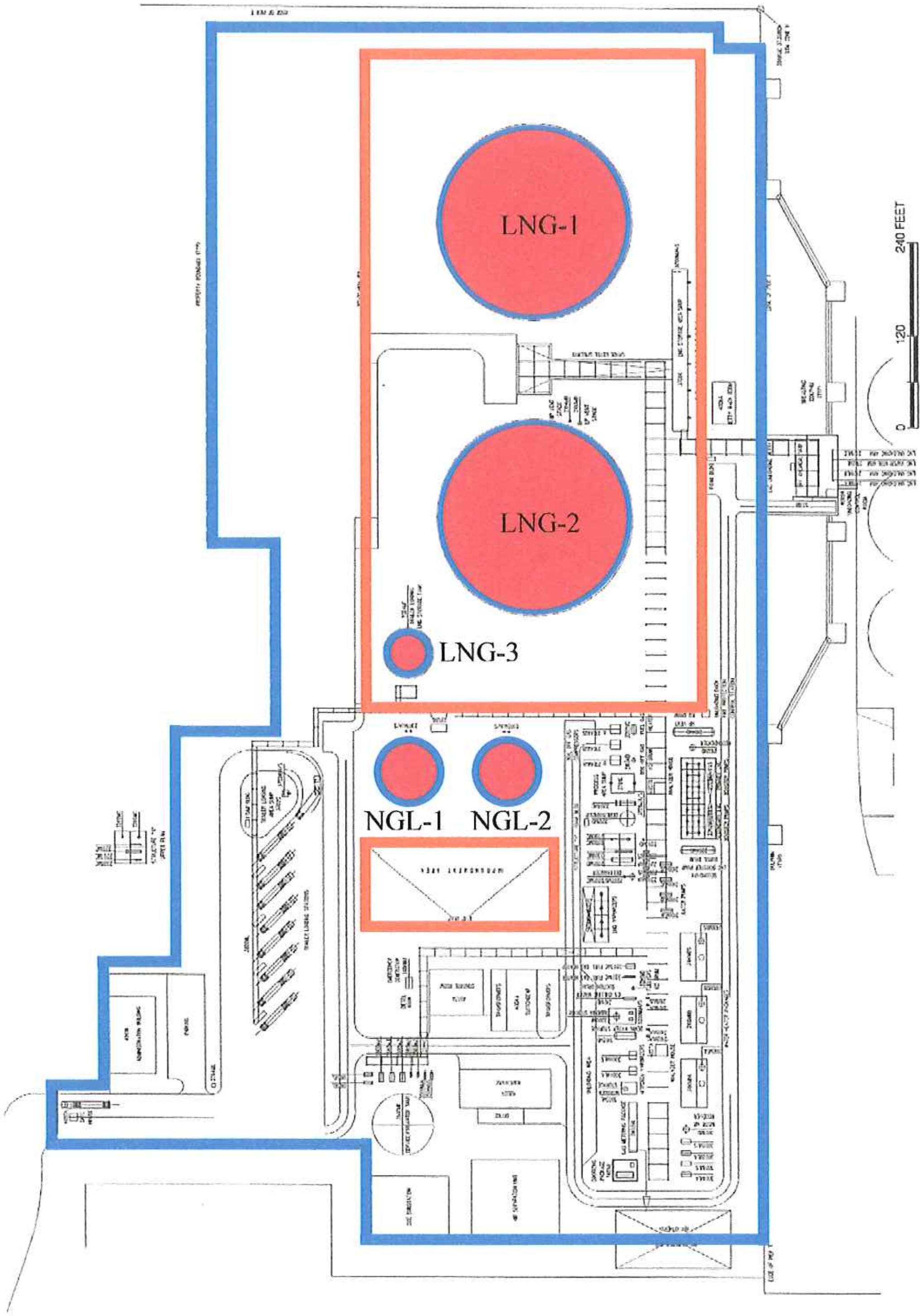
[1] This satellite view, which extends to distances of three to four miles from the proposed terminal, will be used later in this report to delineate the minimum extent of zones in which the public and infrastructure could be endangered by major releases from containment of flammable liquefied gases - for which there is now good scientific agreement that are deemed to be credible.

Descripton

For purposes of this report, which is primarily directed to consideration of public safety issues, the principal components of the LNG terminal are summarized below.

- An LNG ship berth with 4 LNG unloading arms;
  - 2 liquid arms designed for a capacity of 24,150 gallons per minute (gpm) each, allowing ship offloading at 48,300 gpm,
  - 1 liquid/vapor hybrid arm, and
  - 1 vapor arm.
- 2 LNG receiving tanks, each with a gross volume of 42.3 million gallons of LNG at a temperature of -260 F and a normal pressure of 1 to 3 psig. (LNG-1, LNG-2 on plot plan);
- 6 in-tank LNG pumps, each sized for 2,500 gpm;
- Seven LNG primary booster pumps, each sized for 1,830 gpm;
- Seven LNG secondary booster pumps; each sized for 1980 gpm;
- Four shell and tube vaporizers, each sized for 350 million standard cubic feet of gas per day using a primary closed loop water system heated with three direct-fired heaters and circulation pumps;
- Three boiloff gas compressors and associated condensing systems;
- An LNG trailer truck loading facility, including an LNG receiving/storage tank with a capacity of 1,000,000 gallons of vehicle quality LNG for distribution via eight trailer loading bays (LNG-3 on plot plan). An average of 45 trucks will be loaded per day.
- An NGL recovery system, for which the final design appears to remain under consideration, will provide for the recovery and distribution off site of natural gas liquids, principally ethane and propane, via pipeline and/or trailer truck loading;

The terminal plot plan follows, with designation of the location of the primary storage tanks (in red), spill impoundments (in orange), and site boundary in blue. The total area of the site is approximately 25 acres. (Information from Sound Energy Solutions Long Beach LNG Import Project Resource Report 1, General Project Description, Jan. 2004)



[***] The author is aware that consideration is being given to altering the requirements for NGL storage, perhaps even eliminating it. As the author is not privy to any final decision in this regard, this description is based on the site description from SES' January 2004 report.

2.2 LNG (Liquefied Natural Gas) and NGL (Natural Gas Liquids) Hazards

The primary hazards (to the public) that can result from the errant release of liquefied gas fuels such as LNG and NGL from the proposed terminal activities in the POLB are:

- Fire hazard
    - Liquid pool fires
    - Vapor cloud fires
- Explosion hazards
    - Confined vapor cloud explosions
    - Unconfined vapor cloud explosions (UVCE)
    - Boiling liquid expanding vapor explosions (BLEVE)

There are other hazards that require identification and consideration. However it is noted here that they can be of different degrees of concern for LNG and NGL and, in any case, are of less concern than the fire and explosion hazards because, with caveats noted in the specific descriptions that follow, these hazards would not be expected to extend offsite and therefore would not directly affect the public:

- Toxicity hazard
- Cryogenic ("cold" burn) hazard
- Rapid phase transition (flameless explosion) hazard

These last three hazards will be described briefly, for completeness, and then relegated to secondary importance in order to prioritize the main concerns for public safety.

2.2.1 Toxicity Hazards

LNG is natural gas that has been cooled to its condensation temperature; its composition can vary significantly depending upon the source of the gas. However, LNG normally contains as its principal component methane, with heavier hydrocarbons such as ethane, propane, butane, etc., comprising the much smaller remainder.

For purposes of assessing the hazards of LNG, it is appropriate to consider the toxicity of LNG vapor to be that of methane, the principal component, with modification as deemed necessary to allow for consideration of the toxicity of the heavier components which may be present.

Since methane is not a toxic material, it normally poses a hazard only if breathed in sufficient quantity to displace necessary quantities of oxygen (asphyxiation). Consequently methane is not expected to pose a toxicity hazard to the public at the proposed terminal since the public would not be expected to be exposed to high enough concentrations to result in severe displacement of oxygen. Furthermore, the toxicity of the heavier components contained in the LNG, which for our purposes here also can be considered to be simple asphyxiants, is not expected to pose a hazard to the public because of the low concentrations to which the public would be exposed.

Similarly to LNG, which usually contains small amounts of NGL, the components of NGL (ethane and propane are suggested to be the primary natural gas liquids to be stored at the Long Beach Terminal) are not expected to pose a primary hazard to the public, since concentrations of these gases sufficient to asphyxiate people would not be expected to extend off site except in the most extreme conditions, and in such cases the fire and explosion hazards pose much greater hazards.

2.2.2 Cryogenic ("Cold Burn") Hazards

LNG, as pure methane, has a temperature of approximately -260 F. It is a cryogenic liquid, and exposure of human tissue to such temperatures can cause immediate severe injury. The author investigated an accidental release of LNG that occurred in 1977 in Arzew, Algeria, where a man was killed as a result of being deluged with LNG from a ruptured cryogenic valve. However, injury to the public is not expected to occur by exposure to such extreme temperatures because the region near a release of LNG where contact with either the liquid or cold vapor could cause such "cold" burns would not be expected to extend to distances where the public could be exposed.

Natural gas liquids such as ethane and propane, unlike methane, can be liquefied by pressure alone. Consequently, NGL can be stored either under pressure, refrigerated, or in combination. However, since refrigerated NGL is at a much higher temperature than LNG, and since low gas temperatures that could result due to depressurization of (pressurized) NGL would not be expected to extend to distances where the public could be exposed, NGL is not expected to pose "cold burn" hazards to the public at the POLB.

2.2.3 Rapid Phase Transition (Flameless Explosion) Hazards

If a small volume of LNG is rapidly poured into water, the LNG can be heated by the water to temperatures greater than its normal boiling point while remaining in the liquid state. The (liquid) LNG is then said to be *superheated.* If several degrees of superheat are achieved, the evaporation (boiling) process which follows can be essentially instantaneous, with the result that significant pressure increases (overpressures) can result. Such overpressures can cause damage similar to the overpressures caused by more *conventional explosions* which are normally associated with rapid combustion of a chemical or fuel.

The rapid phase transition (RPT) of LNG added to water was first observed, unexpectedly, in a laboratory experiment performed in the Sixties at the U. S. Bureau of Mines. Subsequent research into the phenomenon has been performed by several organizations, most prominently by inhouse industry research programs. All of the work of which I am aware is relatively small scale, but there have been calls for additional research to better determine the scaling characteristics of rapid phase transitions.

As in the case of cryogenic (cold burn) hazards, the damaging overpressures that could occur from rapid phase transitions would be local, and the resulting overpressures are not expected to extend to distances which could endanger the public.

However, there is continuing interest in, and a need for, further research to study the scaling characteristics of RPT's. Although dangers to the public are not expected to result directly from RPT overpressures, their importance in the public safety context lies in the potential for RPT's to cause secondary damage which could lead to cascading failures and further releases of LNG.

The author is not aware of damaging rapid phase transitions having occurred for spills of NGL onto water, although the NGL content of LNG, which is much colder, appears to have some relation to RPT occurrence (as it does as well to UVCE occurrence, as we will see). In any case, as large spills onto water at the POLB terminal are expected primarily from the LNG carrier, and since impoundment areas are expected to be provided for any NGL storage tanks, large spills onto water of NGL at the terminal are not expected.

2.2.4 Fire Hazards

There are two ways that very large fires (that could endanger the public) can result from a major LNG spill – pool fires and vapor cloud fires.

Pool Fires on Land

Spilled LNG will evaporate rapidly due to high rates of heat transfer from the warm surroundings (primarily the earth's surface) to the cold liquid. The vapor evolving from the liquid pool will mix with air to form a gas-air mixture which will burn in the concentration range of approximately 5% to 15% LNG vapor (the concentration range that is flammable for methane-air mixtures). Such mixtures of LNG vapor and air will inevitably form when LNG is spilled, and if an ignition source such as an open flame or spark is present at a location where the gas mixture is within the flammable range a large pool fire will result. In this instance the fire will immediately burn through the gas mixture from the point of ignition to the liquid pool. The resulting "pool fire" is similar in many ways to any other pool fire where liquid hydrocarbons, such as gasoline, are burning – but it should be noted that because the LNG is so cold, heat transferred from the surroundings will cause the LNG to evaporate much faster, thus effectively "feeding" the fire at much higher rates than would occur from a gasoline spill, and even faster than would occur for a refrigerated NGL spill (because the NGL is not nearly as cold). In any case, the fire results from the combustion of the fuel vapors which have evaporated from the liquid pool and have been mixed with air to result in flammable concentrations. An LNG pool fire, which has the potential to burn significantly "faster" than higher boiling point hydrocarbons, can seriously endanger the public, either through direct contact with the fire, or through heat radiated by the fire.

It should be noted here that it is in this context that the statement that "LNG does not burn", or variations thereon, is frequently found in the literature purporting to educate the public regarding LNG safety. While the statement is literally true, it is not helpful, and it can be seriously misleading, as the statement is also (literally) true if applied to any other liquid hydrocarbon fuel such as gasoline or NGL. It can be misleading because the statement that LNG does not burn could imply that there is something different in the combustion mechanism of LNG from other hydrocarbon fuels – in this sense, there is not.

Because very large releases of LNG, attended as they would likely be by violent circumstances which could result in ignition (thus preventing the formation of a flammable vapor cloud that could leave the site), I believe that the potential danger to the public from LNG spills is probably greatest from the very large pool fires that would more likely occur. I emphasize that I am talking about fires resulting from the spillage of several millions of gallons of LNG (each of the two primary storage tanks at the POLB terminal will contain more than 40,000,000 gallons of LNG). We have no experience with such fires, but we do know that they could not be extinguished and would just have to burn themselves out, and the radiant heat extending outward from the fires edge could ignite combustible materials as well as cause serious burns to people at considerable distances from the fire's edge. The distances from such fires to which harm to the public could extend will be a primary focus of this report.

NGL pool fires on land may be considered similarly with LNG pool fires, with at least two potentially important differences, the implications of which are not completely understood, especially for very large fires:

- NGL, whether it be pressurized or refrigerated, will not evaporate as fast as LNG will due to heat transfer from the ground surface, hence the burning rate (and associated heat flux from the fire) may be somewhat smaller.

- NGL fires have been observed to produce more smoke than LNG fires, with the result that the heat flux radiated out from the fires edge can be significantly changed.

Vapor Cloud Fires

If LNG is spilled and evaporates to form a gas/air mixture in which there are located no sources of ignition (an ignition source is a high temperature "point" source of energy such as a spark or flame), the gas-air mixture ("gas cloud") which forms, although possibly containing a large amount of gas that is in the flammable concentration range, will not ignite, and the cloud will drift until it either contacts an ignition source or all of the cloud becomes diluted below its *lower flammable limit* (approximately 5% methane in air) - it will then disperse harmlessly. If ignition occurs during the drifting of the cloud the result is a vapor cloud fire.

If the gas cloud formed is not ignited immediately it will be carried downwind, or will spread more or less radially (due to gravity forces on the heavier-than-air gas mixture) in the absence of wind. Both spreading by the wind and gravity spreading are accompanied by gas-air mixing and thus dilution of the cloud.[2]

If, however, an ignition source is encountered at a location where the gas concentration is within the flammable concentration range, ignition will occur (at that location) and the fire will spread throughout the part of the cloud which is in the flammable concentration range. This is the so-called "flash fire" or vapor cloud fire. An LNG vapor cloud fire can endanger the public, either through direct contact with the fire, or through radiated heat from the burning cloud.

I think it important to state here again that my opinion that pool fires pose a greater risk than vapor cloud fires (see above) is based on the potential for high consequences *accompanied by the high probability that ignition will occur* as a result of the violent circumstances that would be expected to effect such a release. However, as I have said above, the consequences of credible events that might occur that could impact public safety require determination *independently* of consideration of the likelihood of the occurrence. Finally, I note here that the current federal regulations for siting LNG facilities require the determination of vapor cloud dispersion exclusion zones to protect the public safety, and no consideration is given to ignition probability in the determination of those exclusion zones. Therefore, it remains critically important to

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[2] Photograph of an LNG spill onto water at Maplin Sands, UK, in the Eighties. The LNG spill volume was of order 10,000 gallons, with a moderate wind from top right to bottom left. White objects are floating instrument platforms. For scaling, radius of circle (dike) is approximately 450 feet. This spill volume is representative of the largest LNG spills that have been conducted on water to study vapor dispersion.

determine the potential consequences of delayed ignition of large flammable vapor clouds.[3]

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[3] Sequence of photographs (top to bottom) showing an LNG vapor cloud fire over water – tests conducted at Maplin Sands, UK, in the Eighties. Wind is from right to left with maximum visible cloud extent at the left of the top picture. Ignition occurred near the left side of the gap in the cloud in the top photograph, and the cloud has burned nearly back to the liquid pool in the bottom photograph. Spill volumes are similar to the photograph in footnote 1, and the diameter of the circular dike is approximately 900 feet.

Vapor cloud fires that would result if an NGL vapor cloud were ignited may be also considered similarly to LNG fires, with at least three potentially important differences:

- The flammability range for NGL is significantly different than for methane, the principal component of LNG. Most importantly here, the lower flammable limit for NGL is lower than that for LNG; for ethane it is about 3%, and for propane it is just over 2%. This is significant because it means that NGL vapor clouds will remain flammable at lower concentrations, and therefore will have the potential to remain flammable for greater distances (than for an equivalent volume of methane vapor). As a result, the extent of potential danger to the public is increased.

- NGL vapors may be heavier than air because of their higher molecular weights. For example, propane's molecular weight is 44, causing its density to be about 50% greater than air at the same temperature and pressure. This is important because the density stratification in such a vapor cloud decreases the dispersion rate (by decreased mixing with air) and can result in increased downwind travel before the gas cloud concentration falls below the lower flammable limit, thus increasing the extent of potential danger to the public.

- As will be discussed in more detail below, NGL vapor clouds are known to be susceptible to high-order explosion if ignited, even in the absence of confinement. Therefore, the improbability of explosion due to absence of confinement, a factor which is considered highly important in the assessment of LNG safety, does not apply to NGL vapor clouds. As there have been several catastrophic explosions of NGL vapor clouds, this hazard will be considered prominently in this report.

2.2.5 Confined Vapor Cloud Explosion Hazards

There is no need here to further define the potential for explosions of confined LNG or NGL vapor/air mixtures, of which we are all aware. However, the potential for explosions of confined LNG or NGL vapors are important to this hazard assessment because they have the potential for release of energy and ejection of projectiles that could jeopardize other NGL or LNG containments.

2.2.6 Unconfined Vapor Cloud Explosion (UVCE) Hazards

The term explosion is used here to describe combustion reactions (that we normally call "burning", i.e., reaction of the gas in question with the oxygen in the air) which achieve such rapid rates that significant overpressures (local pressures higher than the atmospheric pressure) develop. Such overpressures can cause severe damage – they constitute the "blast" effect in conventional explosions.

The forces released in conventional explosive materials (such as dynamite) typically result from very rapid *reactions of materials that are totally contained in the explosive* *material.* In such materials both the "fuel" and the "oxidizer" are already present. In contrast, explosions of fuel gases such as methane or propane cannot occur unless the gas (fuel) is mixed with air (containing oxygen) such that the mixture has a concentration within the flammable range (for methane this is approximately 5% to 15% in air). Such *physical* processes (as mixing with air), which are necessary for the gas to burn (or explode), place gas/air fires and explosions in a lower hazard class than materials like dynamite, which are "ready to go" if ignited, i.e., without the necessity that the material first be mixed with anything else. Furthermore, if the methane concentration is less than 5% (the *lower flammable limit*) concentration, the mixture will not burn, much less explode – it is said to be too *lean.* Similarly, if the methane concentration is higher than 15% (*the upper flammable limit*) concentration, the mixture will not burn (or explode) – it is said to be too *rich.*

If a methane/air mixture within the flammable concentration range is ignited, the rate of reaction (the burning rate, i.e., how fast the flame moves through the gas mixture) varies depending on a number of factors, one of the most important of which is *confinement.* We all know that natural gas (normally principally composed of methane) explodes all of the time – *when it is confined.* We all have read about, and many have experienced, the blast effect that occurs when leaking (flammable) gas is released into a confined volume (say the kitchen) and its ignition (say by a light switch) blows the building apart.

Conventional wisdom, even scientific opinion, held until fairly recently (the Seventies) that unconfined gas/air clouds such as are formed by gases such as methane, propane, and the higher molecular weight hydrocarbon, will not explode if unconfined. This is important to the present discussion because it goes straight to the question of whether the cloud formed by LNG vapors mixing with air following a major LNG spill could explode (develop damaging overpressures) when the cloud is not confined.

Today, damaging explosions of hydrocarbon gas/air mixtures are of very great concern because of accidents which have demonstrated the propensity of some hydrocarbon gases, when mixed to the correct proportions with air, to explode with devastating damage, *even when unconfined.* There is not time or space here to provide the details, but it can be stated that at least three such unconfined vapor cloud explosions (UVCEs) that occurred at Flixborough, England, in 1974; Mexico City in 1984; and in Pasadena, Texas, in 1989, were so devastating that they resulted in extensive changes in the national and international regulatory requirements for dealing with chemical hazards.

What does this have to do with LNG? There is a scientific consensus (supported by experimental data) that methane/air mixtures which are unconfined are very unlikely to explode. The LNG industry and the Government are sufficiently confident of this fact that the explosion of an unconfined LNG vapor/air cloud is not considered credible. As a result, the most severe hazard is considered to be fire. I have studied this question, and I agree with the contention that unconfined methane/air mixtures are very unlikely (but not impossible) to explode.

But the story doesn't end there. It has already been stated that the composition of LNG imported into the United States varies significantly depending on several factors, most prominently the gas source location. LNG is imported from some locations that provide nearly pure methane. LNG is also imported from some other locations with concentrations of heavier hydrocarbons as high as 15-20%. Such gas is termed "hot gas" in the industry because its calorific value (energy content) is higher than an equivalent volume of methane. Typical heavy hydrocarbon gases present in LNG are ethane and propane, but others are present as well.

We know now that even unconfined vapor cloud explosions (UVCEs) cannot be dismissed for LNG spills if the gas contains significant amounts (say greater than about 12 to 18%, based on Coast Guard sponsored tests at China Lake in the Eighties) of gas components heavier than methane. Furthermore, enrichment in higher boiling point components of the liquid remaining as the LNG vaporizes can lead to vapor cloud concentrations that could pose a UVCE hazard, even if the concentration of the heavies in the liquid initially spilled do not. Since the LNG terminal proposed to be located in the POLB is planned to receive "hot gas"[4], and to engage in the storage and distribution of natural gas liquids (NGL) that are separated from the imported LNG, *questions of whether major releases of LNG at the terminal might pose an unconfined vapor cloud explosion hazard, with the attendant potential to initiate further cascading effects, remain highly relevant.*

There is now no question that GNL vapor clouds can explode with devastating force. Consequently, as the POLB terminal will have some, perhaps yet to be determined, quantities of GNL on the site (primarily ethane and propane), the potential for releases at the terminal to result in high order vapor cloud explosions must be given primary consideration in the assessment of potential hazards to the public and surrounding infrastructure.

Although there are numerous examples of unconfined vapor cloud explosions that have occurred in the chemical manufacturing, storage, and transportation sectors, it is not necessary, nor is there time here, to give a complete list of occurrences. Two events which appear to be highly relevant to this POLB hazard assessment will be highlighted here:

- A fire and explosion occurred in 2004 at the LNG export terminal in Skikda, Algeria. Preliminary reports indicate that damaging unconfined vapor cloud explosions appear to have occurred. If so, this would be the first UVCE which has been reported in an LNG terminal (to the author's knowledge). Final reports have not been released, so there is admittedly some speculation involved here. That said, it appears to the author that damaging explosions did occur both in confined spaces and in unconfined spaces in the export terminal at Skikda. It is important to point out that since the releases are believed to have occurred in parts

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[4] The author is aware of consideration being given to changing the specifications of the LNG that would be accepted by the proposed terminal. As stated earlier, this report has been prepared based on the descriptions made available from the SES Resource Report dated January 2004.

of the facility which would not have been handling LNG, but rather natural gas liquids, that the unconfined vapor cloud explosions experienced probably involved NGL. Nevertheless, particularly since the POLB will handle similar natural gas liquids, the recent experience in Algeria is highly relevant.

- The disaster which occurred on November 19, 1984, in San Juan Ixhuatepec (Mexico City), Mexico, is directly relevant to the consideration of the POLB LNG terminal, because the Mexico City facility provided for storage of quantities of NGL which are very similar to the quantities that could be stored at the NGL component of the POLB terminal. The Mexico City terminal, built for the distribution of LPG which came by pipeline from distant refineries, had an overall storage capacity of approximately 4,200,000 gallons of LPG in 6 large spherical tanks and 48 horizontal cylindrical tanks. The catastrophe started with the rupture, due to pumping overpressure, of an eight inch transfer line. The LPG thus released caught fire, causing fire impingement on one of the spherical tanks. The resulting cascading failure involved multiple unconfined vapor cloud explosions (UCVEs) accompanying the large fires which occurred. 574 people are reported to have been killed and more than 7,000 injured, of whom 144 later died in the hospital. Some 39,000 people were rendered homeless or were evacuated, and the terminal was destroyed.

2.2.7 Boiling Liquid Expanding Vapor Explosion (BLEVE) Hazards

The acronym BLEVE is short for "Boiling Liquid Expanding Vapor Explosion". There have been a large number of devastating BLEVEs in the chemical process industry and in the transportation sector, including railroad and highway truck incidents. BLEVEs occur when a pressure vessel containing a flammable liquid is exposed to fire so that the metal comprising the containment loses strength and ruptures. When a vessel containing liquid under pressure is exposed to fire, the liquid heats up and the vapor pressure rises, increasing the pressure in the vessel. When this pressure reaches the set pressure of the pressure relief valve (PRV), the valve opens to relieve the pressure. The liquid level in the vessel falls as the vapor is released to the atmosphere. While the liquid is effective in cooling that part of the vessel wall which is in contact with it, those parts of the wall (above the liquid) that are exposed to vapor are not as effectively cooled. After a time, as metal which is not cooled by liquid is exposed to fire, the metal becomes hot and weakens and is subject to rupture. It is important to note that rupture can occur even though the pressure relief valve is operating correctly as designed. This is because a pressure vessel is designed to withstand the relief valve set pressure, but only at the design temperature conditions. If the metal is heated to higher temperature, it may lose strength sufficiently to rupture. Further, and most importantly to the consideration of the failure of LNG tanks to fire exposure, the pressure relief valves must be sized to allow relief of the vapor produced with fire exposure to the tank. I will return to this question when the vulnerability of LNG containments is considered.

Just as the conventional wisdom before about 1970 minimized the potential for explosion of unconfined LNG vapor clouds, that wisdom has also held that boiling liquid expanding vapor explosions of LNG containments are not possible. It appears that the conventional wisdom may have to be updated for BLEVEs of LNG as well.

An LNG road tanker exploded on 22 June 2002 near Tivissa, Catalonia (Spain), after the driver lost control on a downhill section of the C-44 road.[5] The tanker turned over, tipping onto its left side. Witnesses said that flames[6] appeared immediately between the cabin and the trailer, and after approximately 20 minutes, the tank exploded. There was a small explosion, then a strong hiss and then a much larger explosion. Immediately after the small explosion, the fire disappeared and a white cloud appeared. This cloud ignited immediately, giving rise to the larger explosion, a fireball. Assuming that all of the mass initially contained in the tank was involved in the fireball, approximately 12,700 gallons of LNG would have burned. Accepted mathematical modeling techniques suggest that the fireball diameter would have been about 500 feet, the height about 370 feet, and the duration approximately 12 seconds. These model predictions appear to be consistent with the facts that the fireball resulted in serious burns to two persons at a distance of 650 feet from the tanker. Major parts of the truck were projected to significant distances. The rear part of the tank, including the rear undercarriage of the truck, was ejected to a distance of 260 feet. A section of the front of the truck with maximum dimension of approximately 12 feet was projected more than 400 feet, and the motor and cabin covered a distance of more than 840 feet from the explosion.

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[5] Planas-Cuchi, E., et.al, "Explosion of a road tanker containing liquefied natural gas", Journal of Loss Prevention in the Process Industries, 17 (2004), pp 315-321.

[6] The photograph shows the jet fire from the tanker 2 minutes after the accident and approximately 18 min before the BLEVE. The author is not aware of any photographs of the fireball (but see footnote 7).

This LNG truck accident has been described in some detail because its occurrence suggests, if not demands, that renewed consideration be given to the potential for BLEVEs of LNG containers to occur. Perhaps most importantly, the road tanker was insulated with polyurethane insulation, and the early failure of the insulation would be expected to allow the container to more quickly reach temperatures giving rise to failure as well as allow heat transfer to the cargo which would significantly elevate the pressure in the tank beyond the ability of the PRV to relieve the greatly increased LNG vaporization. It is this mechanism, failure of the insulation followed by overpressure of the tank leading to rupture, which may have been exemplified in the Spanish road tanker explosion, that I have appealed to the Department of Homeland Security to consider as being applicable to LNG ships whose containers are insulated with foamed plastic insulation materials such as polystyrene and polyurethane[7].

There have been repeated incidents of BLEVEs of truck and rail containers of NGL, many having occurred in the Seventies and Eighties before the mechanism of the occurrence was understood. And, as was stated earlier, there have been devastating occurrences of BLEVEs in industrial storage and distribution facilities, perhaps most appropriately exemplified here by the disaster of November 19, 1984, in San Juan Ixhuatepec (Mexico City), Mexico. The Mexico City disaster is particularly relevant to the present considerations because the quantity of NGL stored in the Mexico City facility was similar to the quantity that could be stored in the POLB LNG terminal. Although the catastrophe started with the rupture of an eight inch transfer line, the first subsequent major failure is thought to have been a BLEVE of one of the NGL storage spheres, and the subsequent cascading failures involved multiple large BLEVEs.

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[7] On July 5, 1973, in Kingman, AZ, a rail car containing approximately 10,000 gallons of propane began leaking during unloading, and the gas ignited. About a half hour later the tank BLEVE'd. The diameter of the fireball was approximately 400 feet, similar, if somewhat smaller, than the size predicted for the LNG BLEVE described in footnote 6. Note telephone poles for scaling and the railcar end being projected.

2.2.8 Special Hazards of LNG and NGL Spills on Water

There are special hazards of spills of LNG or NGL that could result from spills of either material on water, because, in addition to the (lesser) hazards of rapid phase transitions that could result from LNG spills considered earlier, it would be impracticable, if not impossible, to contain the spread of either of these liquid fuels on water. Consequently, there would be nothing to limit the size of the liquid pool that would result except the limiting amount of material spilled and the physical constraints which would limit its spread on the water. Since the size of the liquid fuel pool would determine the size (areal extent) of the fire, large spills on water could easily result in fires much larger than those which would be contained in the purpose-designed spill impoundment areas on land.[8]

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[8] The photograph illustrates an LNG pool fire on water. Somewhat less than 10,000 gallons of LNG was spilled; the resulting fire is about 50 feet in diameter and 250 feet high. This test, conducted by the U.S. Coast Guard at China Lake, CA, in the Eighties, is also representative of the largest LNG pool fires that have been studied.

As will be described and justified in more detail subsequently in this report, there is now scientific consensus that rapid spillage of at least one half of a typical single LNG ship container, approximately 3,000,000 gallons, is a "credible event", as it has been determined that it could be caused by an intentional (terrorist) act with means that are readily available to such groups. The fire from such a spill, particularly if it occurred onto water and was therefore uncontained, would be very large, perhaps up to a half-mile in diameter, or larger if more of the containment system failed. We have no experience with such fires, but we do know that they could not be extinguished and would just have to burn themselves out, and the radiant heat extending outward from the fires edge could ignite combustible materials as well as cause serious burns to people at substantial distances from the fire's edge. The distances from such fires to which harm to the public, as well as damage to infrastructure, could extend will be a primary focus of this report.

Furthermore, although it is considered highly likely (but we do not know enough to say impossible) that early, if not immediate, ignition of the gas air mixtures above such a spill would occur as a result of the violent circumstances (as in an allision or collision of a ship or a terrorist attack) that would be expected to accompany such a major release, it is imperative that the extents of flammable vapor cloud travel that might result from major spills of LNG onto water (which are most likely to occur from the ship) be considered in the assessment of hazards that could result at the POLB LNG terminal.

CHAPTER 3

ADEQUACY OF CURRENT REGULATIONS TO PROVIDE FOR PUBLIC SAFETY

This part of my report gives my answer to the question: *To what extent do present U.S. regulations that govern LNG terminal siting adequately protect the public from the consequences of LNG releases that could occur?*

Although U.S. Regulations currently require enforcement of <u>some</u> safety exclusion zones intended for the protection of the public (by prohibiting their presence therein), I believe they fall seriously short of achieving the intended objective:

- The regulations were promulgated in the early Eighties largely as a result of concerns for public safety that arose in the Seventies. Since there was no rush to build additional LNG import terminals until about the year 2000, the regulations were largely unused for import terminal siting. As a result, the regulations did not, and still do not, give serious consideration to the terrorist threat that began in this country September 11, 2001. Instead, the regulation method and approach relied on, and still relies on, consideration only of accidental occurrences that could affect the public. Hence, the current regulations do not effectively address the many serious questions posed by the present requirement to consider events that could be caused by malicious intent. Nor is sufficient attention being paid to the reality that malicious intent changes the whole safety picture. We no longer have the option to just "better" manage the risks involved so as to reduce the probability of occurrence of accidents to an acceptable level. The siting in an urban area of an LNG terminal, with its requirements to concentrate immense quantities of hazardous materials, takes on a new dimension. Unfortunately, the process has outrun the development of the regulations to deal with it, and the present regulations fail to address this most important new paradigm.

- Perhaps most importantly, in consideration of the post 9/11 threat, there is presently no requirement, much less enforcement, of exclusion zones to protect the public from LNG spills which could occur from the ships that serve the import terminal. The failure to provide for the protection of the public and surrounding infrastructure from major releases of LNG that could occur from the ships serving the facility must be considered all the more important now as a result of recent government sponsored reports, for which there is now scientific consensus, that indicate that the danger zones extending from large, but credible, spills on water are likely to pose greater threats than would either accidental or terrorist caused releases from the land part of the terminal.

3.1 49 CFR 193 LNG Terminal Siting Provisions for Public Safety

The regulation that specifies requirements for siting LNG import terminals in the United States is 49 CFR 193, entitled *Liquefied natural gas facilities: Federal standards.*

Part 193 -- *Liquefied natural gas facilities: Federal standards* contains numerous sections describing requirements designed to provide for safe operation of an LNG import terminal. However, most of these sections are directed to the attainment of safe operation of the plant, and therefore they do not directly address the public safety issue. There are two sections of the regulation that directly address requirements to provide for safety of the public (offsite):

193.2057 *Thermal Radiation Protection,*

and

193.2059 *Flammable vapor dispersion protection.*

It is noted that the three other LNG hazards described earlier; toxicity, cryogenic ("cold burn"), and rapid phase transition, are not addressed, as these three potential hazards are not expected to affect the public offsite. Explosion hazards (not covered by the regulation) will be considered herein.

Before proceeding to the description of Sections 193.2057 and 193.2059, and to the question of their adequacy to provide protection to the public, I believe it will be helpful to briefly summarize the development of these two sections of the regulation.

During the Seventies, when the four presently operating LNG facilities were constructed in the United States, 49 CFR 193 had not yet been promulgated. The applications for certification of the terminals that were built in Everett, Massachusetts; Cove Point, Maryland; Elba Island, Georgia; and Lake Charles, Louisiana, were decided largely based on guidance contained in industry consensus standards, notably NFPA (National Fire Protection Agency) 59A – *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG).*

However, as a result of public concerns that arose during the Seventies about LNG terminal siting safety issues, notably those that arose in California regarding the proposals to site terminals at Los Angeles, Oxnard, and Point Conception, Congress mandated a research program on LNG safety, and authorized an expenditure of approximately $40,000,000 (in 1977 dollars) on LNG safety studies. That research program carried out basic LNG safety research directed to development of methods to define more accurately and realistically the consequences that could result from major spills of LNG. The research effort was directed to three hazards which were considered highest priority;

- liquid pool fires,
- vapor cloud fires, and
- vapor cloud explosions.

Following completion of these research programs, which still constitute much if not most of the research results and data relating to LNG spill consequences that are available in the public domain, 49 CFR 193 was promulgated - in the early Eighties.

I was called upon from time to time for advice by persons in the U.S. Department of Transportation who were preparing the draft regulations that evolved into 49 CFR 193, primarily in the area of my principal expertise, LNG vapor dispersion. My association (with DOT, at that time) was with Mr. Walter Dennis. Walter Dennis was actively involved in the drafting of the sections of 49 CFR 193 identified above (Sections 2057 and 2059), and I had several conversations with him regarding these sections of the regulation, particularly regarding the selection and application of methods for determining vapor dispersion distances. I believe that Walter Dennis was the person primarily responsible for developing Sections 193.2057 and 2059. This is important to the present discussion because Mr. Dennis subsequently advised industry (at their request) regarding the methods to be followed in the determination of exclusion zones required by the regulation. Walter Dennis died (in the late Eighties, I believe) when interest in LNG importation was languishing. I believe that his advice regarding the determination of vapor cloud exclusion zones has been used improperly so as to downplay the severity of the hazards which the regulation is designed to protect against.

(At least partly) as a result, there remains confusion even today about the correct determination of vapor cloud dispersion exclusion zones for spills of LNG which could occur into impoundments on the land terminal. I have prepared reports for the City of Fall River, MA, and I have filed testimony with FERC as well, which describe errors that I believe were made in the preparation of the Draft Environmental Impact Statement for the Weaver's Cove Project proposed to be sited in the Taunton River at Fall River.

With that background, I return to consideration of 49 CFR 193. When 49 CFR 193 was promulgated in the Eighties, it provided for the determination of *exclusions zones* for *vapor dispersion* and *thermal radiation*. The term *exclusion zone* is defined in the current regulation:

"Exclusion zone means an area surrounding an LNG facility in which an operator or government agency legally controls all activities in accordance with Sec. 193.2057 and Sec. 193.2059 for as long as the facility is in operation."

This definition is critically important because it follows that the intent of the regulation is that the *consequences* of vapor cloud dispersion and fire radiation scenarios must be specified by determination of the distances to which each of these hazards would extend from the spill, and once those distances are determined, the resulting exclusion zones must be controlled by the owner of the facility or the government. Thus the regulation provides for the prevention of members of the public from occupying the areas included by the exclusion zones, and therefore prevents them from being exposed to the associated hazards. Importantly, no consideration is given to the probability of such hazards being realized (the regulation is *consequence* driven, i.e. it gives no consideration to the probability of the occurrence), it simply defines the extents of the *exclusion zones* which are enforced to ensure that the public is not exposed to danger. *As I have stated earlier, I believe that such a consequence driven requirement for the establishment of exclusion zones to protect the public is all the more appropriate today in view of the potential* *severity of the terrorist threat, for which historical accident experience, however good, provides little assurance to the public.*

It is noted here that there is no mention in 49 CFR 193 of explosions, either vapor cloud explosions (confined or unconfined) or boiling liquid expanding vapor explosions. I will return to this important omission later.

3.1.1 Exclusion Zones for LNG Pool Fires

Section 193.2057 of the Federal Standard is excerpted below.

Sec. 193.2057 Thermal radiation protection.

Each LNG container and LNG transfer system must have a thermal exclusion zone in accordance with section 2-2.3.1 of ANSI/NFPA 59A with the following exceptions:

(a) The thermal radiation distances shall be calculated using Gas Research Institute's (GRI) report GRI-89/0176, which is also available as the "LNGFIRE III" computer model produced by GRI. The use of other alternate models which take into account the same physical factors and have been validated by experimental test data shall be permitted subject to the Administrator's approval.

(b) In calculating exclusion distances, the wind speed producing the maximum exclusion distances shall be used except for wind speeds that occur less than 5 percent of the time based on recorded data for the area.

(c) In calculating exclusion distances, the ambient temperature and relative humidity that produce the maximum exclusion distances shall be used except for values that occur less than five percent of the time based on recorded data for the area.

Amdt. 193-17, 65 FR 10958, Mar. 1, 2000]

It is critically important to note here that the determination of exclusion zones for LNG pool fires requires specification of the criterion to be used to define the extent of the thermal flux hazard, i.e., a criteria for determining how far away from the fire must the public be to be protected. 49 CFR 193 presently requires that thermal exclusion zones be defined by the (mathematical model) prediction of the distance to which a person, at ground level, would be exposed to thermal radiation flux of 5 KW/m^2 (~1600 Btu/hr/ft^2). This thermal flux has been determined to have the potential to cause second degree burns to unprotected skin in approximately 30 seconds.

But, as I have previously testified to FERC, I believe that the criterion of a 5 KW/m^2 flux level merits further consideration, because exposure at this intensity to persons could result in serious burns within time periods which would not be sufficient for evacuation or escape. Further, although fire fighting personnel equipped with protective gear could work in such an environment for considerable time, they would not be able to provide evacuation or removal of unprotected persons in time to prevent injury. It is known that the flux level would have to be reduced to about 1.5 KW/m^2 before unprotected persons could be exposed continuously without thermal radiation injury. Consequently, I believe that serious consideration should be given to defining exclusion zones to protect the public from thermal radiation hazards using such a lower (~1.5 KW/m^2) thermal radiation flux criterion. However, whether or not DOT defines the exclusion zone using such a lower thermal radiation flux criterion, I believe that FERC should use the lower thermal flux criteria in order to protect the public from such very large fires. It is very important to recognize that a policy which prevents public presence only where there would be exposure to 5 KW/m^2 or greater is not consistent with the public interest, because the public could receive serious injuries at lower flux levels if exposed for longer time periods (including time periods that would still be insufficient to provide for sheltering or evacuation). That is why I have suggested that serious consideration of the lower value of 1.5 KW/m^2 as the "safety" criterion – as this value is widely recognized as being the highest value of thermal radiation exposure from which the public would not receive serious injury even if exposed for longer time periods."

For the determination of thermal radiation exclusion zones for the land side of the facility, the credible spill scenario must be defined for input to the LNGFIRE III model. The scenario then is defined by specifying the dimensions of the impoundment area that will contain the spill, and then specifying the rate and total amount of LNG that is spilled. Two types of spill scenarios are possible:

- Spillage from the LNG storage tank

and

- Spillage from a part of the piping system external to the storage tank.

Spillage from the LNG Storage tank

It is my understanding that the storage tank design proposed for the Long Beach Long Beach facility is a Total Containment design, which means essentially that the inner tank in contact with the LNG is surrounded by a prestressed concrete outer tank wall and covered with a similarly constructed roof. To my knowledge, no tanks of the this type have so far been constructed in the continental United States (the Penuelas, Puerto Rico, tank has a prestressed concrete outer tank, but I do not believe it has a concrete roof), but such tanks are currently being proposed for several other locations. It is my understanding that there remain some questions about the procedures to be followed for such installations, even questions relating to the lack of "definitions" for the various tank systems that are being considered. Nevertheless, 49 CFR 193 appears to have been interpreted by DOT, at least in the case of the DEIS and EIS's prepared for the Weaver's Cove terminal in Fall River, MA, in such a manner that the regulation does not require consideration of LNG spills that would penetrate the outer containment wall. It is my understanding, based on DEIS's that have been produced for terminals with similar tank design proposals, that the thermal radiation zones for fires associated with spills from the inner tank are (therefore) to be determined by assuming that the spilled LNG would be *contained* by the concrete outer wall. As a result, the fire scenario envisioned is an elevated, or "tank-top", fire with the diameter (size) of the fire determined by the diameter of the outer concrete tank. For such determinations, I believe that application of the prescribed method (LNGFIRE III) is adequate.

However, there remains a question about the validity of the assumption that failure of the outer concrete wall is incredible. Although I agree that such a failure due to accident would seem to be extremely remote, I cannot agree that such an event is impossible for a terrorist to achieve – witness our tragic experience on 9/11 when two large airliners were highjacked and flown into the World Trade Towers with devastating results. To my knowledge no analyses have been made available to the public which address the possibility of complete failure of a "total containment" LNG storage tank. I will return to the consideration of "worst case" events after consideration of the current requirements for determination of exclusion zones.

Spillage from the Piping System

Here, also, the regulations prescribe detail that cannot be adequately described here. However, it is my understanding that the intent of the regulation is to prescribe the credible spill events (for determination of exclusion zones) by identifying the portions of the pipeline systems that carry LNG at the largest rates in the facility, and then to assume a guillotine break in said line with flow at the maximum rate maintained for a period of ten minutes. It appears that negotiations with DOT in the past have in some cases resulted in approval of procedures which will ensure limiting the duration of flow (by automatic shut-off systems) to shorter periods, but I assume here the requirement for a ten-minute spill duration.

In either case, LNGFIRE III application is straightforward, since the fire size is prescribed by the outer boundary of the area (impoundment) into which the spill occurs. In summary, I believe the application of LNGFIRE III, to LNG pool fires contained in liquid impoundment areas, adequately describes the thermal radiation hazard for the purpose of determining exclusion zones to protect the public.

3.1.2 Exclusion Zones for Vapor Cloud Dispersion

Section 193.2059 of the Federal Standard is excerpted below.

Sec. 193.2059 Flammable vapor-gas dispersion protection.

Each LNG container and LNG transfer system must have a dispersion exclusion zone in accordance with section 2-2.3.2 of ANSI/NFPA 59A with the following exceptions:

(a) Flammable vapor-gas dispersion distances must be determined in accordance with the model described in the Gas Research Institute report GRI-89/0242, ``LNG Vapor Dispersion Prediction with the DEGADIS Dense Gas Dispersion Model." Alternatively, in order to account for additional cloud dilution which may be caused by the complex flow patterns induced by tank and dike structure, dispersion distances may be calculated in accordance with the model described in the Gas Research Institute report GRI 96/0396.5, ``Evaluation of Mitigation Methods for Accidental LNG Releases. Volume 5: Using FEM3A for LNG Accident Consequence Analyses". The use of alternate models which take into account the same physical factors and have been validated by experimental test data shall be permitted, subject to the Administrator's approval.

(b) The following dispersion parameters must be used in computing dispersion distances:

(1) Average gas concentration in air = 2.5 percent.[9]

(2) Dispersion conditions are a combination of those which result in longer predicted downwind dispersion distances than other weather conditions at the site at least 90 percent of the time, based on figures maintained by National Weather Service of the U.S. Department of Commerce, or as an alternative where the model used gives longer distances at lower wind speeds, Atmospheric Stability (Pasquill Class) F, wind speed = 4.5 miles per hour (2.01 meters/sec) at reference height of 10 meters, relative humidity = 50.0 percent, and atmospheric temperature = average in the region.

(3) The elevation for contour (receptor) output H = 0.5 meters.

(4) A surface roughness factor of 0.03 meters shall be used. Higher values for the roughness factor may be used if it can be shown that the terrain both upwind and downwind of the vapor cloud has dense vegetation and that the vapor cloud height is more than ten times the height of the obstacles encountered by the vapor cloud.

(c) The design spill shall be determined in accordance with section 2-2.3.3 of ANSI/NFPA 59A.

[Amdt. 193-17, 65 FR 10959, Mar. 1, 2000]

Again, it is important to note that the DEGADIS and FEM3A model(s) for calculating the exclusion zones for vapor cloud dispersion are *prescribed.* The DEGADIS model was promulgated in the regulation in an amendment dated in the early Nineties, and the

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[9] The 2.5 percent concentration represents one half the lower flammable limit concentration of methane (5%). This concentration level is intended to define the cloud average concentration at a point which would prevent the presence of flammable (greater than or equal to 5 %) "pockets" of gas which could be ignited. Hence this concentration level is used as the criterion for delineating the hazard distance.

(alternate) FEM3A model was promulgated in the regulation in the amendment dated Mar. 1, 2000. I am the co-author, with Dr. Tom Spicer, of the DEGADIS model, and Dr. Spicer and I directed the research program sponsored by GRI (since about 1985) to validate a computational fluid dynamics model (FEM3A was ultimately selected, based on consideration of several candidate models) for LNG vapor dispersion application. I support the use of the DEGADIS and FEM3A models. Based on my knowledge of the models and my review of the development of both, I believe that, together, they incorporate reasonably the latest information obtained in the federally sponsored large scale LNG field test programs conducted by the Coast Guard at China Lake, CA, and at the Liquefied Gaseous Fuels Spill Test Facility (LGFSTF) located near Mercury, Nevada, in the Seventies and Eighties, as well as the results of other research programs that have been conducted, principally in the Chemical Hazards Research Center Wind Tunnel at the University of Arkansas.

The DEGADIS model is limited to application to dispersion of vapor clouds (including LNG vapor clouds) resulting from spills onto a flat surface (ground or water) with dispersion over flat, obstacle-free terrain. FEM3A was developed in a followup effort (to DEGADIS) to provide a mathematical model applicable to the determination of the effects on dispersion of manmade obstacles (such as tanks, dikes, or process equipment and structures) and/or significant terrain features. I believe that these two models, correctly applied for the situations for which they are designed, are adequate tools for determining vapor cloud exclusion zones which will ensure public safety. And, similarly to the previous discussion on thermal radiation exclusion zones, I believe that the application of these models, *respecting the limitations of each*, is relatively straightforward for the determination of vapor cloud exclusion zones extending from spills bounded by containment structures (dikes and impoundments) on land.

It is clearly the intent of 49 CFR 193 that enforcement of a vapor cloud dispersion protection exclusion zone implies that the area included be controlled by the facility operator or an agency of the government. It is also clear that the intent of the regulation is to provide for the enforcement of vapor cloud dispersion protection zones as the method for ensuring the safety of the public, since such exclusion zones clearly prohibit the presence of the public therein.

For the determination of vapor cloud dispersion exclusion zones for the land side of the facility, the credible spill scenario must be defined for input to either the DEGADIS model or the FEM3A model. The scenario is defined by specifying the dimensions of the impoundment area that will contain the spill, and then specifying the rate and total amount of LNG that is spilled. Again, two types of spill scenarios are possible:

- Spillage from the LNG storage tank

and

- Spillage from a part of the piping system external to the storage tank.

Spillage from the LNG Storage tank

As stated before, it is my understanding that the storage tank design proposed for the Long Beach Long Beach facility is a Total Containment design, which means essentially that the inner tank in contact with the LNG is surrounded by a prestressed concrete outer tank wall.

Further, it is my understanding, based on DEIS's that have been produced for terminals with similar tank design proposals, that the vapor cloud dispersion exclusion zones associated with spills from the inner tank are to be determined by assuming that the spilled LNG would be *contained* by the concrete outer wall. As a result the vapor cloud dispersion scenario envisioned is an elevated, "tank-top" vapor release, with the diameter (size) of the release determined by the diameter of the outer concrete tank. For such determinations, I believe that application of the FEM3A method, although untested for such use, is appropriate. However, the DEGADIS model was designed for applications to *ground level* releases, and I cannot recommend it to describe the tank-top release scenario.

I do note that vapor releases from the top of the tank would be expected to pose significantly less hazard to the public than would equivalent releases at ground level, particularly if accompanied by high wind conditions.

However, as in the case of the determination of fire radiation exclusion zones, there remains a question about the validity of the assumption that failure of the outer concrete wall is incredible, as (to my knowledge) no analyses have been made available to the public which address the possibility of complete failure of a "total containment" LNG storage tank. I will return to the consideration of "worst case" events after consideration of the current requirements for determination of exclusion zones.

Spillage from the Piping System

Here, also, the regulations prescribe detail that cannot be adequately described here. However I believe that the intent of the regulation was, and remains, to prescribe the credible spill events (for determination of exclusion zones) by identifying the portions of the LNG transfer systems (pipes) that carry LNG at the largest rates in the facility, and then to assume a guillotine break in said (pipe)line with flow at the maximum rate maintained for a period of ten minutes. I do note here that DOT has considered, and approved, procedures which would ensure limiting the duration of flow (by automatic shut-off systems) to shorter periods, but here I assume the requirement for a ten-minute spill duration.

For such spillage into an impounded (or diked) area, the containment afforded limits the liquid (LNG) spreading that can occur, and therefore effectively determines the area extent of the source of vapor (evolving from the spilled LNG).

But, there remain questions even about the requirements for specification of the leak rates that have not been resolved. I have filed testimony with FERC which describes my complaints that the present specification of "accidental leakage rate" design spills by NFPA 59A (which has been incorporated in 49 CFR 193 since the year 2000, effectively replacing the previous requirement for 10 minute full flow spills from the largest transfer line in the facility), have the effect of reducing the requirement for consideration of these (larger spills) that were the intent of the regulation - with the final result that the downwind vapor hazard is downplayed. FERC has not even been consistent in this regard, since they have given approval for submissions from facility applicants that contained transfer line spills with volumes ranging from 28,900 gallons (3-inch line break) all the way to 812,000 gallons (guillotine rupture of ship unloading line).

But, however the spill rate and volume is determined, the vapor cloud dispersion protection exclusion zone determination is not as straightforward as that for the determination of the thermal radiation protection exclusion zone, because:

- DEGADIS was designed to predict dispersion from spills on a flat surface, with dispersion proceeding on a flat surface, *in the absence of significant terrain features or manmade structures that would obstruct the wind or gas cloud flow.* A dike (or the vertical walls of an impoundment) designed to contain the spilled LNG (liquid) causes "holdup" of the gas until the gas overflows the impounded volume. The DEGADIS model does not allow direct accounting for the effect of the vapor "holdup" that occurs within the impounded/diked area. Although provisional methods have been suggested in the past for using DEGADIS under such conditions, such methods have been demonstrated to be in error, as will be discussed subsequently. It is now clear that utilization of certain methods provisionally suggested in the Eighties (for determining gas "holdup") can lead to serious errors in the determination of vapor cloud dispersion protection exclusion zones.

- Research conducted during the last two decades has resulted in the Department of Transportation's acceptance and approval of the use of the FEM3A vapor dispersion model. The FEM3A model *provides for prediction of the holdup that occurs in an impoundment area* as well as for other effects of obstacles or terrain features on dispersion of an LNG vapor cloud.

3.2 The Potentials for Unconfined Vapor Cloud Explosions and Boiling Liquid Expanding Vapor Explosions are not Addressed

Unconfined Vapor Cloud Explosion Hazard

The concern for the potential of unconfined vapor cloud explosion hazards at the proposed LNG terminal in Long Beach is directly related to the composition of the LNG that will be imported to the facility. It is anticipated that significant quantities of "hot gas", i.e., LNG containing significant quantities of hydrocarbons heavier than methane will be received at the terminal., and the plant is being designed to remove such heavy components (ethane, propane, etc.) for marketing and distribution from the facility.

Since it does not appear practicable to remove the heavier components of the gas *as it is being unloaded from the tanker into the storage tanks*, it is presumed that the "hot gas" NGL components will have to be stored, at least temporarily, prior to their distribution off site. Consequently, it is presumed that there could be significant quantities of LNG containing heavier hydrocarbons such as ethane, propane, etc., that will be stored and handled in the facility.

The problem of explosion potential of LNG vapor clouds has been studied. I quote directly from U.S. Coast Guard Report CG-M-03-80 entitled *U.S. Coast Guard Liquefied Natural Gas Research at China Lake*, dated January 1, 1980 (pages 12-13):

"Since unconfined vapor clouds composed of LPG have detonated after tank car and pipeline accidents, the next group of high explosive direct initiator tests involved the system methane-propane stoichiometric in air, always using a 1.35 kg Composition B initiator in a 5 m hemisphere.

....

The test series was run in the sequence 90% methane-10% propane, 57.6%-42.4%, 76.8%-23.2%, 81.6%-18.4%, and 86.4%-13.6%. Only methane concentrations above 81.6% failed to produce a vapor cloud detonation. The velocity of the fuel-air detonation wave was 1800 m/s and the maximum pressure was 15.5 bars in the 81.6%-18.4% test. Clearly, for the 1.35 kg initiator, the critical percentage of propane for the methane-propane-air detonation is between 13.6% and 18.4% propane; financial restrictions prevented the determination of critical concentrations for other initiator sizes. Theory suggests that the use of propane as a sensitizer is representative of all hydrocarbons heavier than methane. The 13.6% sensitizer concentration has special consideration as the commercial LNG being imported into the U.S. east coast has about 14% higher hydrocarbons."

Based on this report, which to my knowledge has not been called into question, it is clear that there is a potential unconfined vapor cloud explosion (UVCE) hazard associated with the errant release of LNG containing heavier (than methane) hydrocarbons in amounts in the range 13 -18% (and higher).

Furthermore, it is important to note that the explosions described in the Coast Guard Report were gas phase *detonations*, which means that the flame (reaction front) speeds were greater than the speed of sound in the unburned gas mixture. It is now well understood that damaging overpressures can occur in unconfined vapor cloud explosions even when flame speeds are well below those which result in detonations. The bottom line here is that LNG with concentrations above the range 13-18% has been shown to have the potential to *detonate when unconfined*, and there is consequently a very real potential for UVCE's to occur with damaging overpressures when such (unconfined) gas-air mixtures are ignited.

Consequently, although the present regulations do not require consideration of the UVCE hazard associated with vapor clouds that might result from spills of LNG, consideration of the UVCE hazard is relevant for the proposed Sound Energy Solutions terminal *if it is to import "hot gas" that may have concentrations of heavier components in the range above approximately 13-18%.*

Finally, it is noted that enrichment in higher boiling point components of the liquid remaining on the water as the LNG vaporizes can lead to vapor cloud concentrations that pose a UVCE hazard, even if the concentration of the heavies in the liquid initially spilled do not.

Boiling Liquid Expanding Vapor Explosions

If the decision is made to install NGL storage at the facility, consideration must be given to the potential for BLEVEs to occur in the event that the storage tanks are exposed to fire. The potential for NGL BLEVEs to threaten either public safety or infrastructure to distances greater than are already anticipated to be credible for large LNG pool fire or vapor cloud dispersion hazards appears to be low; however there is very real potential for severe mechanical damage (by explosive force or due to ejected missile impact) to the primary LNG storage facilities (or a ship at the jetty) that could cause cascading events that would worsen the situation.

In view of the recent apparent occurrence of a BLEVE of an LNG tank truck in Spain, the potential for BLEVEs of the trucks serving the facility, as well as LNG storage tanks, cannot be ruled out. However, the potential for BLEVE-like explosions appear to be much more likely from the ship containers than from the more heavily constructed and more fire-resistively insulated LNG storage tanks on land.

3.3 There is a Critical Need for Exclusion Zones for LNG Spills on Water

The potential for catastrophic releases from LNG carriers that service an LNG import terminal are acknowledged by FERC in several Draft and Final Environmental Impact Statements, including both for the Weaver's Cove Project in Fall River, MA. FERC has consistently stated that such catastrophic releases would be most likely caused by terrorist attack, and FERC's own analyses have shown that the consequences of such ship-side releases that have been identified tentatively as "credible" are far greater than the hazards posed by the land-side LNG spill scenarios. Nevertheless, the Commission continues to dismiss these hazards on the grounds that the threat of such events (large pool fires on water, or large vapor cloud formation following a spill on water) can be "managed".

I cannot support FERC's statement (from the Weaver's Cove and other Impact Statements) that "While the risks associated with the transportation of any hazardous cargo can never be entirely eliminated, they can be managed". In my opinion, this statement, with no justification provided, does nothing to provide the public confidence in FERC's ability to "manage" these risks. Indeed, I believe that it downplays the importance of the principal threat to public safety that is associated with the operation of any LNG import terminal – a terrorist attack that could result in catastrophic spills of LNG onto water.

I believe my recent testimony before the Subcommittee on Energy Policy, Natural Resources and Regulatory Affairs, provides adequate explanation of my view on this matter. Although the inclusion here of that testimony is repetitive of my earlier comments, I believe such repetition is warranted:

Testimony of Dr. Jerry Havens
Before the Congressional Subcommittee on Energy Policy, Natural Resources and Regulatory Affairs
Tuesday, June 22, 2004

Mr. Chairman and Members of the Committee: My name is Jerry Havens. I am a Distinguished Professor of Chemical Engineering at the University of Arkansas. I appreciate this opportunity to address this hearing on Federal and State Roles in LNG Import Terminal and Deepwater Port Siting. I am speaking here today as a citizen-scientist, and not as an agent of my University.

I have for some thirty years been studying methods for assessing the potential consequences of major accidental releases of LNG. My remarks here today are about the estimation of the extents of danger to the public around such spills.

I believe that the potential danger to the public from LNG spills is mainly from the very large fires that could occur. I want to emphasize that I am talking about fires resulting from the spillage of several millions of gallons of LNG – a single tank on a typical LNG carrier contains six or more million gallons of liquefied natural gas. The fire from such a spill, if it occurred onto water and was therefore uncontained, would be very large, perhaps up to a half-mile in diameter, or larger if more of the containment system failed. We have no experience with fires this large, but we do know that they could not be extinguished, they would just have to burn themselves out, and the radiant heat extending outward from the fires edge could cause serious burns to people even at larger distances.

There are two ways that very large fires can follow a major LNG spill. If LNG is spilled it will rapidly evaporate and the vapors will mix with air to form a mixture which will burn in the concentration range of approximately 5% to 15% LNG vapor. Such mixtures of LNG vapor and air will inevitably form when LNG is spilled, and if an ignition source such as an open flame or spark are present, as would be highly likely to accompany the violent circumstances that would cause a major release, a large pool fire will result. However, if no ignition sources are present in the flammable gas mixture a vapor cloud will result, and the cloud will spread downwind from the spill until it either contacts an ignition source or becomes diluted below its flammable concentration - it will then disperse harmlessly.

The maximum distances of the danger zones extending from a pool fire or a flammable vapor cloud determine the zones which would endanger the public. It is the estimation of these distances, which are identified in 49 CFR 193 as <u>*pool fire radiation*</u> *and* <u>*vapor cloud dispersion exclusion zones*</u>*, that I want to inform you about, because such exclusion zones are required in order to ensure that people are not exposed to danger if such a fire should occur, and such requirements determine the effectiveness of the LNG siting regulations to provide for public safety.*

I first began studying the prediction with mathematical models of vapor cloud travel distances in the 1970's, when as this Committee knows, the first wave of interest in LNG importation arrived in the United States. I am privileged to have had an important role in the development of the current regulatory requirements for determining vapor cloud exclusion zones to support requests to FERC for LNG terminal siting. Both of the computer models currently required by 49 CFR 193 for calculating vapor cloud exclusion distances were the result of developments by my Associates and I at the University of Arkansas. I have also followed closely and have been involved in, if less directly, the development of the methods required by 49 CFR 193 for determining pool fire radiation exclusion zones.

In my opinion the current requirements in 49 CFR 193 for determining both pool fire radiation and vapor cloud dispersion exclusion zones around LNG terminals are based on good science, and they are adequate for their purpose. Indeed, the present regulations are the result of considerably more research on LNG safety than has been performed for many other hazardous materials that are routinely transported and stored in very large quantity. Furthermore, I believe it is important to emphasize that the hazards associated with LNG, aside from the localized dangers involved with handling any cryogenic fluid, are neither unique nor extreme when compared with other hazardous materials handled in bulk. The potential dangers we are discussing today are brought into the present focus because of the enormous amount of energy that must necessarily be concentrated to enable economical transport of liquefied natural gas across the world's oceans.

However, the suitability of the methods required by the regulations for determining exclusion zone distances is not in serious dispute. The problem lies in the specification of the LNG spill scenarios that must be considered.

Current U.S. regulations require that exclusion zones be calculated for spills in the land-based portion of an LNG import terminal only – the regulations do not currently apply to spills that might occur from the LNG vessel onto water.

Because spills on land are subject to a variety of control measures to limit the area extent of the spill, such as dikes or impoundment systems, exclusion zones in support of requests for siting land-based LNG terminals are typically, in my experience, less than one thousand feet. However, if exclusion zones were required to protect the public from LNG spills onto water from an LNG vessel at the jetty or in route to or from the terminal, there is good scientific consensus that the fire radiation exclusion zones could extend to a mile *or more if the entire contents of a single tank were rapidly spilled, and the vapor cloud dispersion zone could extend for a similar spill to several miles. Obviously, if the regulations were applied to the determination of exclusion zones to protect the public from LNG tanker spills onto water, it would have a very important effect on siting decisions. It seems clear to me that such consideration would raise very serious concerns about the siting of LNG terminals where people within the exclusion zone distances would be endangered. It is very sobering to me to realize that the ongoing LNG siting debate regarding public safety comes down to this, and I sincerely hope that those responsible for protecting the public recognize and seriously consider this very important question.*

Since 911 we no longer have the luxury of considering only means for reducing the probability of accidents to a level that justifies the attendant risk. I believe that it is imperative that the dangers to the public from possible releases from a LNG carrier onto water be considered in the siting of LNG terminals in our country.

I must also tell you that I am very concerned that spills from LNG vessels caused by terrorist attack might not be limited to the partial contents of a single tank on the vessel, as is widely assumed. Because of those concerns, I wrote to the Secretary of Homeland Security in late February to urge the Department to consider the vulnerability of LNG carriers to terrorist attacks as part of their deliberations on LNG terminal siting. Because some of the matters that I believed worthy of consideration are sensitive, I do not think it is appropriate to discuss them in detail here, but I will try as best I can to address any questions you may have about this subject. I am very disappointed that I have not received any response from the Department of Homeland Security regarding my concerns.

Thank you, that concludes my comments.

I stand by this statement, and I believe it is particularly relevant to the consideration of siting the Sound Energy Solutions LNG Project in Long Beach Harbor.

Today, although the science community has acknowledged the need for additional experimental data that can be used to address some uncertainties which remain in the extrapolation of consequence distances from the approximately 10,000 gallon spill range that has been studied to the approximately 10,000,000 gallon range that has been determined to be credible to result from a terrorist attack on an LNG ship, it is clear that there is scientific (and government) consensus that methods which have recently been evaluated by the ABS Group for FERC and by the Sandia National Laboratory for the Department of Energy are suitable for the estimation of the extent of the thermal radiation or vapor cloud dispersion hazard distances that would extend from major releases of LNG onto water in the Port of Long Beach.

It is not necessary to repeat in detail the findings of either the ABS Group or Sandia Lab reports, both of which are attached as exhibits to this report. I will just summarize my reading of the conclusions of both reports which I believe are germane to the consideration of the proposed LNG terminal in the POLB.

The ABS Group and Sandia Lab reports, which appear to be now largely accepted by all of the regulatory agencies involved, including the Coast Guard, as being the best current guidance on these matters, emphasize for their extensive analyses of the consequences of marine spills just one (size) spill scenario. That is the spillage onto water of 12,500 cubic meters LNG – this figure being representative of approximately one half of a single tank on a typical LNG ship. The choice of spillage of half a tank (rather than a full tank) appears to be the result of the reports' authors' consideration of the extreme implausibility if not impossibility of the rapid spillage of the entire tank as an <u>initial result</u> of a terrorist attack.

Thermal Radiation from LNG Pool Fires on Water

Setting aside unnecessary precision, I believe that the ABS Group and Sandia Lab reports are in essential agreement that persons exposed to the thermal radiation from a pool fire burning on a 12,500 cubic meter (approximately 3,000,000 gallons) spill on water could receive second degree burns on unprotected skin in about 30 seconds at a distance of approximately one mile from the center of the spill.

I endorse these findings on thermal radiation consequences of LNG pool fires on waters from the ABSG and Sandia Reports, as far as they go.

But, as I have stated before, I do not think these predictions address sufficiently the real requirements to provide for public safety. I am convinced that the use of a thermal flux criterion that would result in second degree burns in 30 seconds is not appropriate for delineating distances necessary to ensure public safety. This (second degree burn criteria) is not sufficient because such exposure essentially ensures that serious burns will occur at that distance to persons who cannot gain shelter within 30 seconds. In addition to the obvious difficulties that would confront any able-bodied individual's attempt to flee from such a threat, there remain very serious questions about the almost certain inability of those less able to do so. As considerably lower thermal flux criteria (~1.5 KW/m^2) are prescribed in other national and international regulations designed to provide safe separation distances for the public from fires, I believe that FERC should consider such a lower thermal flux criteria, which could increase the distances prescribed in the ABSG and Sandia reports by as much as one and a half to two times, to ensure the public safety from such large LNG fires.

Finally, regarding calls for more research in this area, I have already stated that there are some important needs. It is my understanding that Sandia and others are considering the need for more large scale LNG fire testing. If such tests were conducted with appropriate scientific planning, and if such tests were conducted for the purpose of obtaining experimental data which could be used to verify mathematical modeling methods (as opposed to one-time "demonstration" tests), I would endorse them, as I feel that additional testing would be worthwhile to provide better means of predicting the consequences of very large fires that could follow massive LNG spillage onto water.

LNG Vapor Cloud Dispersion from Spills on Water

I here also endorse the estimates of LNG vapor cloud dispersion presented in the Sandia and ABS Group reports, which range, considering all of the uncertainties identified in the reports, between approximately two and three miles. I note that while I have reviewed and am in agreement with the methodology used by the ABS Group for making these estimates (they in part used DEGADIS, of which I am a co-author), the Sandia report estimates were reportedly obtained using a CFD model called VULCAN, which I have not had the opportunity to evaluate, and which to my knowledge has not been independently evaluated for such use. I believe that the estimate of two to three miles of flammable vapor cloud travel that could result from an unignited spill of one half of the LNG contained in a single containment is at once reasonable and sufficient for consideration of the consequences of such spills of LNG in the POLB.

There is a Real Concern for Cascading Failures to Occur

But, I believe that limiting our consideration of the potential consequences of a very large LNG release and fire on water to the initial result of a terrorist attack is not sufficient. That would be like ignoring the collapse of the Twin Towers, because their collapse was not the initial result of the attack. Lest I neglect the consideration due of the worst case consequences of large scale tanker spills, it is important to note that the Sandia report states unequivocably that cascading events that could result either from brittle fracture of structural steel on the ship (due to LNG contact with the steel) or failure of the vaporization of the cargo at rates exceeding the capability of the pressure relief valves, cannot be ruled out.

We know that foamed plastic insulation, widely used on LNG carriers, including ships with both of these tank types, would be highly susceptible to failure by melting or decomposition. It is a cardinal safety rule that the pressure limits on tanks carrying flammable or reactive materials not be exceeded, as such exceedance portends catastrophic rupture of the containment. Such a rupture could lead to the release of a full tank of roughly 6,000,000 gallons of LNG, as well as the release from multiple tanks. While, as has been stated, the Sandia report concludes that such cascading events would be very unlikely to involve more than three of the five tanks on a typical LNG carrier – for a total release of 18,000,000 gallons (or more from the larger carriers now proposed) compared to the 3,000,000 gallon release on which all the modeling has been based – the basis for the Sandia report's "optimism" in this regard is unexplained. Once cascading failures begin, I do not know what would stop the process from resulting in the total loss and burning of all of the LNG aboard the carrier.

CHAPTER 4

CONCLUSIONS

CONSEQUENCES OF CREDIBLE ACCIDENTS AND TERRORIST ACTIONS, AND CONSIDERATION OF WORST POSSIBLE CASES

The objective here is to specify, based on observations of historical and experimental data, and supported by science-based guidance regarding the possibility of occurrence of postulated scenarios, the distances from such credible events to which the public as well as important infrastructure could be in harm's way.

Such a *consequence assessment* is a two step process:

1. The credibility (meaning here, the consistency of the event's occurrence with natural laws which we know to control such processes) of the postulated event must be established. For example, we can respond quickly and certainly to statements that an LNG ship contains the equivalent of fifty or more Hiroshima-size atomic bombs (a literal truth) with a certainty, based on physical laws, that the energy contained in an LNG storage tank cannot be released in a time frame sufficiently short to allow a meaningful comparison with the effects of fifty nuclear weapons each with a nominal 20 kiloton explosive energy release. It just cannot happen. However, we cannot dismiss the hazard on that basis either; instead we must consider the physical limitations which determine the length of time during which that energy could be released (in this case, by fire) in order to objectively define the consequences which could result.

2. Starting with the defined credible event, it is then required to determine the distance to which the hazard would extend. This process typically requires specification of both the total amount (of the hazardous material, measured here as energy content) released and the time frame over which the release occurs. As is true of many of the arguments advanced in this report, this is really just application of common sense - a very small spill rate, even continued for a very long time, would not be expected to pose the fire hazard that would result from the more rapid release of the same amount of material. An objective quantitative determination of the (hazard) distance is also a two step process.

    a. First a criterion for damage must be selected. For the present case these criteria are; for fires, specification of the permissible level of thermal flux exposure; and for vapor clouds, specification of the concentration level below which the cloud does not pose a flammable hazard because it could not be ignited.

    b. Finally, as the scenario being considered often involves releases with magnitudes potentially much more damaging than have been experienced, we have to extrapolate our experience to determine an

> objective measure of the consequence that can be expected. The best, if not the only, tools we have for such extrapolations are physical (such as wind tunnel) or mathematical models.

Utilizing information summarized in Chapters 2 and 3 of this report, I will summarize what I believe to be the present state of information about the quantities (and rates of release) of liquefied energy fuels that could occur associated with the operation of the proposed LNG terminal in the POLB, as well as the consequences to the public and infrastructure that could result.

Accidents and Terrorist Actions

The current regulations, particularly regarding provisions for public safety, focus on the land based part of the terminal. There are specific requirements for liquid containment and impoundment systems that are designed to limit the spreading of LNG that might be released either from the LNG tanks themselves or from transfer lines in the facility. But such control and mitigation measures could not be effectively applied to releases that could occur from an LNG ship, either at the jetty or in transit thereto, because spills onto water could not be effectively contained, and these concerns appear to have spurred the government's completion of two recent reports that deal with the tanker safety issue.

Before moving to consideration of the potential for, and consequences of, large LNG spills on water, I think it important to state that, in contrast to the attention given to the potential for large spills on water, very little attention is presently given to the vulnerability of land storage tanks to terrorist attack, or even to the vulnerability of land storage tanks to natural events such as earthquakes and tsunamis, consideration of which would appear to be highly relevant for the proposed POLB terminal. I believe that the vulnerability of the land tanks to such accidental or terrorist caused events, as well as to natural events such as earthquakes and tsunamis, needs to be considered carefully in order to provide the public assurance that we understand the potential consequences of releases that could occur on land as well as we now know them for spills on water. Fortunately, we have much more complete information regarding LNG spills onto water.

The ABS Group and Sandia reports agree that the release of LNG in the amount of approximately 3,000,000 gallons (half of one typical LNG ship tank) is credible,

- in that such a release could result from accidental collisions between ships with sufficient momentum (mass and speed) to cause such a breach of containment, or
- that such a release could be caused by terrorists with means that are readily available to them.

Furthermore, the ABS Group and Sandia reports agree, within the precision required here, that a release of 3,000,000 gallons of LNG onto water could result in:

- Pool fires which would expose persons with unprotected skin to thermal fluxes that could cause second degree burn injury in approximately 30 seconds (5 KW/m^2) at a distance of approximately 1 mile.

- Flammable vapor clouds, if the spilled material were not ignited upon release, that could extend downwind to distances between 2 and 3 miles. It is assumed here that persons that were caught in such a fire as might occur if the flammable cloud were ignited would be seriously injured, if not killed.

The author is in essential agreement with these consequence estimates but believes the following modifications are required if they are to be used to ensure public safety:

- Since the thermal radiation flux criterion (5 KW/m^2) used by Sandia and the ABS Group could cause second degree burns in thirty seconds, it is not sufficiently protective of public safety; a lower value, approximately 1.5 KW/m^2, is recommended here. This value is already being used by other segments of the regulatory system, both nationally and internationally, based on its definition as the highest thermal flux to which an unprotected person can be continuously exposed without injury. If the 1.5 KW/m^2 criterion is used, it is anticipated that the distance of 1 mile (associated with the higher flux level) would be increased to between 1 ½ and 2 miles.

- As the Sandia Report states unequivocably that cascading failures of ship tanks cannot be ruled out and further states that in their opinion failures of as many as 3 tanks could occur, this scenario must be considered credible. As Sandia estimates that the hazard distance from this scenario could be extended by approximately one-third, the distance to the 1.5 KW/m^2 flux level would then be increased to approximately 2 ½ to 3 miles.

- The ABS Group's high-end estimates for the vapor cloud distance to the 2.5 % gas concentration level (based on releases from a 5 meter diameter hole in the containment) are approximately 3 miles. The Sandia estimates for the credible scenario analyzed are closer to 2 miles, but their calculations reflect the distance to the 5% gas concentration level rather than the 2.5% level which is accepted to represent the better criterion for vapor cloud travel distance that could pose a hazard to the public. Use of the lower flammable gas concentration criteria would be expected to extend the hazard distance to about 3 miles.

Based on this information, which is believed to be the best that is available - and is in general agreement with widely held views in the scientific community, a <u>minimum</u> distance is specified here for the extent to which the public could be exposed to injury from the initial release of approximately 3,000,000 gallons of LNG onto water at the POLB. It is approximately 3 miles.

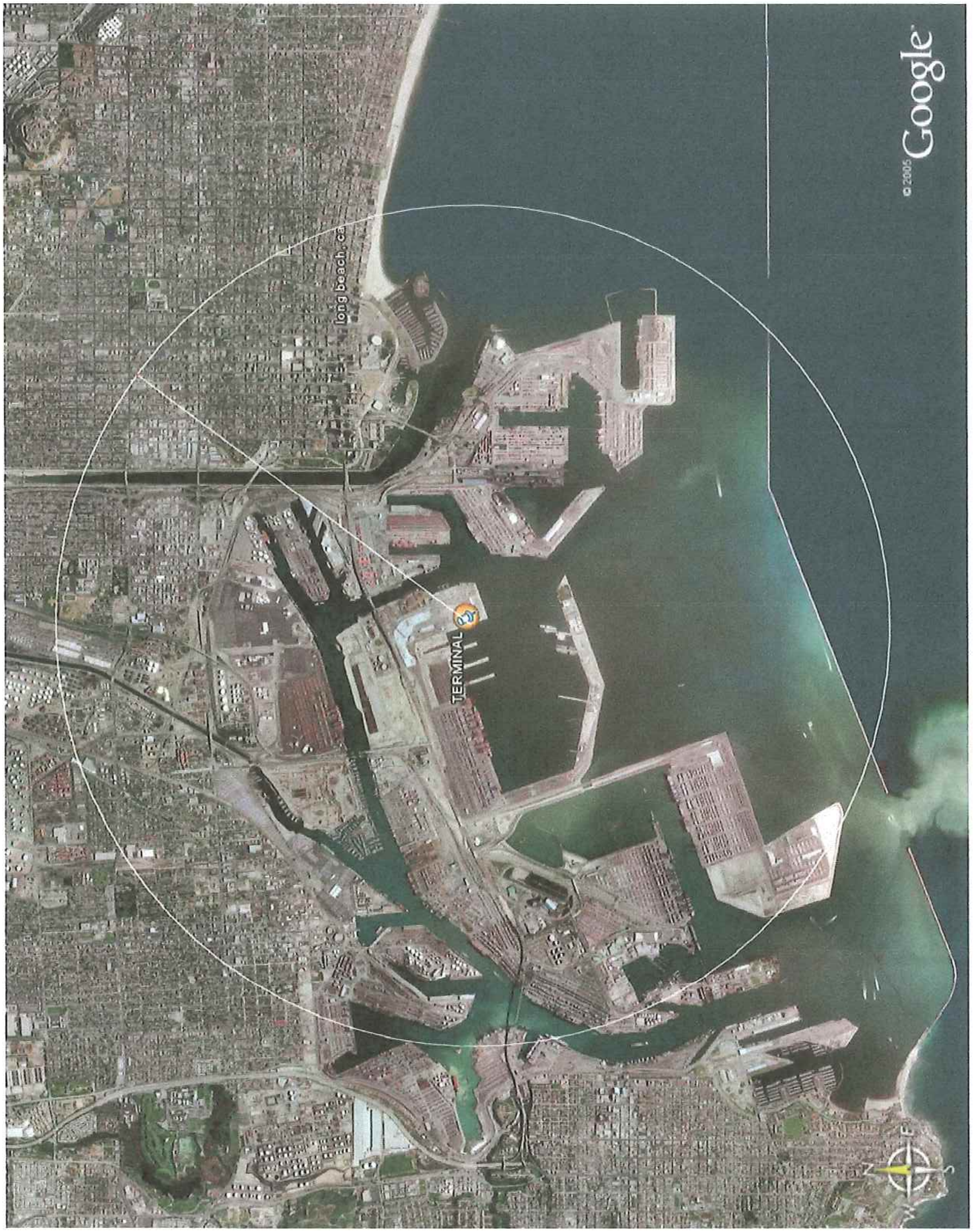
Consideration of Worst Possible Cases

I am recommending a minimum 3 mile radius circle around the proposed terminal to demarcate the area in which events deemed credible could cause serious injury to the public. The minimum distance to demarcate expected damage to infrastructure would be of lesser extent, depending on the criterion selected for damage.

As I have stated that the danger zone around the tanker extends to the route of the tanker approach to the facility, I observe that exposure of the public from incidents of spillage onto the water from the ship appears to be greatest when the ship is at the terminal jetty, rather than during its approach, since the terminal appears to be closer to populated areas than is any segment of its route to the terminal. Exposure of port infrastructure during the approach, based on my observation of the aerial view, would seem to be similarly concentrated at the terminal site, but such a conclusion does not consider any special hazards or vulnerabilities at different locations in the port. Estimation of the consequences to the POLB of a large release of LNG in the port must consider the wide variety of flammable and other hazardous materials routinely handled, as the area in which significant damage to infrastructure could occur (beyond the terminal and the ship) encompasses large sections of one of the largest and busiest ports in the country. The POLB receives very large crude oil carriers (VLCC) at a jetty located within several hundred feet of the eastern boundary of the proposed LNG facility, and a major container terminal which almost certainly receives hazardous cargo lies adjacent to the western side of the proposed site, along which the LNG ship will be berthed. It is noted that the area designated for the terminal's construction, approximately 25 acres, appears to be significantly smaller than the other (existing) terminals in the United States (with the possible exception of the Everett terminal – I do not know at the time of writing what the Everett terminal's area is). In any case, there is very minimal separation between the LNG spill impoundments and the facility's property line in the proposed terminal in the POLB; indeed, it is difficult for me to see how the applicant can meet the exclusion zone requirements of 49 CFR 193, much less provide a reasonable safety zone for the public or surrounding infrastructure.

It must be emphasized that the 3 mile zone is based primarily on the assumption that approximately 3,000,000 gallons of LNG is spilled onto water, as it appears there is little doubt that either pool fire radiation thermal fluxes or flammable vapor clouds from such a spill could put the public in harms way at that distance. However, it is a minimum specification, because it does not address the possibility of even more serious events.

I am very concerned that such events as provide the basis for the 3 mile consequence distance would be of such severity as to make it highly likely, if not almost certain, that further failures of containments, either of LNG or NGL, would occur. In particular, I repeat here my concern that the exposure to the ship of such a pool fire would have the potential to cause cascading failures of the remaining tanks on the vessel, resulting in total loss of the vessel and burning of its contents. There can be no doubt that the consequences of such a worst-possible-case event could be more severe than the rapid release of approximately 3,000,000 gallons of LNG onto water considered in this report.



The radius of the circle extending from the terminal location is three miles.

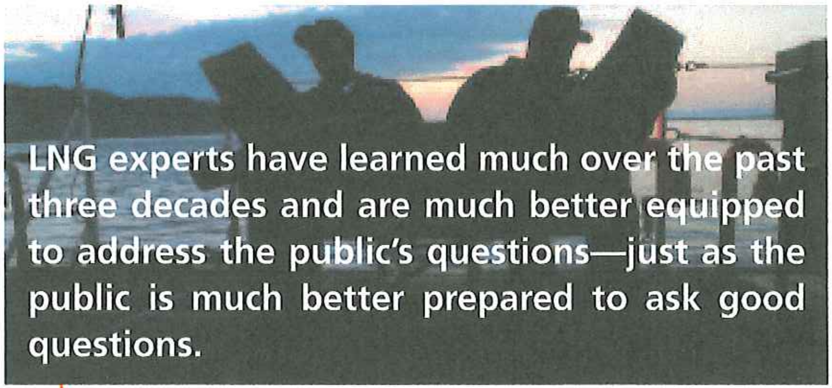
Exhibit 10

LNG and Public Safety Issues

Summarizing current knowledge about potential worst-case consequences of LNG spills onto water.

by Jerry Havens
Professor, Chemical Engineering, University of Arkansas

In 1976 Coast Guard Admirals were being called to Capitol Hill to answer the question: If 25,000 m^3 of liquefied natural gas (LNG) were spilled on water without ignition, how far might a flammable cloud travel before it would not pose a hazard? As technical advisor to the Office of Merchant Marine Safety in the Coast Guard's Bulk Hazardous Cargo Division, I was assigned to provide an answer on the LNG vapor cloud issue within a couple of weeks. Although no longer with the Coast Guard, I am still working on the problem 30 years later.



LNG experts have learned much over the past three decades and are much better equipped to address the public's questions—just as the public is much better prepared to ask good questions.

Past Lessons

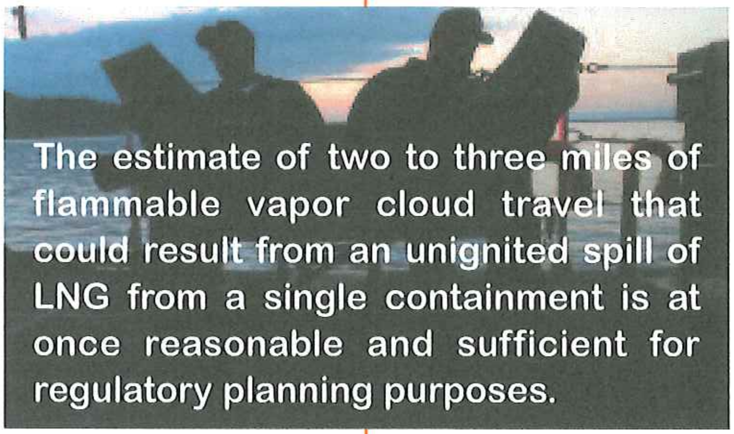
The tragic events of September 11, 2001, changed everything. Watching the World Trade Towers fall sharply focused my research of LNG spills on water. It is understood now that the towers fell because the insulation was knocked off the steel, which could then not withstand the extreme fire exposure. The lesson from this is to understand the consequences of such events, not only in planning for decisions that are within our control, but in planning for events over which we may have little or no control.

LNG experts have learned much over the past three decades and are much better equipped to address the public's questions—just as the public is much better prepared to ask good questions. For space constraints this discussion sidesteps many important issues in the LNG debate; however, it summarizes what is currently known about potential worst-case consequences for public safety of LNG spills onto water.

The description of current LNG knowledge is aided by reference to reports prepared in 2004 by the ABS Shipping Group for the Federal Energy Regulatory Commission[1] and by the Sandia National Laboratory for the Department of Energy.[2] These two reports, which appear to be largely accepted by all of the regulatory agencies involved, emphasize for their analyses one scenario of the consequences of LNG marine spills—spillage onto water of 12,500 m^3 of LNG, which is representative of approximately one half of a single tank on a typical LNG ship. While the Sandia report does provide some consideration of multiple-tank spills, it suggests that such occurrences would not involve more than three tanks at one time. The choice of spillage of only half a tank appears to be the result of the report's consideration of the extreme implausibility of the rapid spillage of the entire tank as an initial result of a terrorist attack. However, limiting discussion to the initial results of a terrorist attack is not necessarily sufficient.

LNG Vapor Cloud Dispersion

My year-long look at the LNG vapor dispersion issue for the Coast Guard produced a report[3] in 1978 that reviewed several predictions by leading authorities of the vapor cloud extent, following spillage of 25,000 m³ LNG onto water. Those estimates ranged from 0.75 mile to a little over 50 miles. The range was narrowed by showing the errors in reasoning underlying the lowest and highest estimates, but the uncertainty range could not be tightened closer than three to 10 miles.



The estimate of two to three miles of flammable vapor cloud travel that could result from an unignited spill of LNG from a single containment is at once reasonable and sufficient for regulatory planning purposes.

The estimates, which range between approximately two and three miles, presented in the Sandia and ABS Group reports are endorsable. Note, though, that these estimates are for the spillage of 12,500 m³ of LNG, half the amount considered in the Coast Guard report produced in 1978. Nonetheless, the estimate of two to three miles of flammable vapor cloud travel that could result from an unignited spill of LNG from a single containment is at once reasonable and sufficient for regulatory planning purposes. Indeed, given the uncertainties involved, the point of diminishing returns has been reached on this scenario for vapor dispersion from a 12,500 m³ LNG spill on water.

Thermal Radiation from LNG Pool Fires

For thermal radiation from pool fires, the findings of the ABS Group and Sandia reports are also endorsable. Both reports appear to provide estimates of approximately one mile as the distance from a pool fire on a 12,500 m³ spill on water to which unprotected persons could receive second-degree burns in 30 seconds (based on a thermal flux criterion of 5 KW/m²). Although this estimate is reasonably representative of the best available estimates of the distance to which the public could be exposed (to this damage criterion), the endorsement is qualified as follows.

First, the use of a thermal flux criterion that would result in second-degree burns in 30 seconds is not necessarily appropriate to ensure public safety, as such exposure essentially ensures that serious burns will occur at that distance to persons who cannot gain shelter within 30 seconds. Aside from questions about the ability of even the most able to gain shelter in such a short time, questions are also raised about the safety of those less able. Lower thermal flux criteria (~1.5 KW/m²) are prescribed in other national and international regulations designed to provide safe separation distances for the public from fires. Since such lower thermal flux level criteria could increase the distances prescribed in the ABS Group and Sandia reports by as much as one and a half to two times, this end point criteria for ensuring public safety from LNG fires should be reconsidered, especially if the goal is to provide for public safety.

Second, the mathematical modeling methods in the reports that predict the various levels of thermal radiation intensity from a massive LNG pool fire are not on as firm scientific ground as are the methods for predicting vapor cloud dispersion. The vapor cloud question has been more extensively studied to provide data for the models' verification. The physical basis for extrapolation from small-scale experimental data is better understood for vapor dispersion than are the methods in present predictions of thermal radiation extent from pool fires. Sandia and others are considering the need for further large-scale LNG fire testing. Such tests should be conducted with appropriate scientific planning and for the purpose of obtaining experimental data that could be used to verify mathematical modeling methods; this additional testing is advised to provide a better understanding of large LNG fires on water.

However, the Sandia report states that cascading events, resulting either from brittle fracture of structural steel on the ship or failure of the insulation that results in LNG vaporization at rates exceeding the capability of the relief valves, cannot be ruled out. Foamed plastic insulation, widely used on LNG carriers, would be highly susceptible to failure by melting or decomposition. It is a cardinal safety rule that the pressure limits on tanks carrying flammable or reactive materials should not be exceeded, as such excess portends catastrophic rupture of the containment. While the Sandia report concludes that such cascading events would be very unlikely to involve more than three of the five tanks on a typical LNG carrier, the report's optimism in this regard is unexplained. Once cascading failures begin, what would stop the process from resulting in the total loss of all LNG aboard the carrier? More research is required.

Other Hazards

Other hazards associated with spilling LNG onto water include oxygen deprivation, cold-burns, rapid phase transitions, and explosions in confined spaces, as well as the potential for unconfined vapor cloud explosions (UVCEs) if the LNG contains significant heavies. As the hazards of oxygen deprivation and cryogenic burns are not expected to affect the public, they will not be considered further here.

Explosions in confined spaces, either combustion events or events of rapid phase transition, may have the potential for causing secondary damage that could lead to further spillage of LNG. Unconfined vapor cloud explosions cannot be dismissed if the cargo contains significant amounts—perhaps greater than 12 to 18 percent, based on Coast Guard-sponsored tests at China Lake in the 1980s—of gas components heavier than methane. Enrichment in higher boiling point components of LNG remaining on the water can lead to vapor cloud concentrations that pose a UCVE hazard, even if the concentration of liquid initially spilled does not. LNG contact with ship structural steel, rapid phase transitions, and gas explosions in confined spaces on the ship are not expected to pose hazards to the public, except as they may relate to the ship's vulnerability to further damage following the cryogenic cargo spillage onto ship structures, with or without ignition.

Vulnerability Issues

Coast Guard Navigation and Vessel Inspection Circular No. 05-05, "Guidance on Assessing the Suitability of a Waterway for Liquefied Natural Gas (LNG) Marine Traffic," incorporates requirements for a vulnerability assessment that identifies the exposures that might be exploited to ensure the success of an attempted terrorist attack.[4] Two types of vulnerabilities are considered: system and asset. System vulnerabilities consider the ability of the terrorist to successfully launch an attack; asset vulnerabilities consider the physical properties of the target that may influence the likelihood of success of a terrorist attack.

Worst Case?

The hazards of brittle fracture, rapid phase transitions, and explosions in confined ship spaces, as well as cascading events that may result from the extreme fire exposure a ship would experience if a nominal 12,500 m^3 spill on water around the ship was ignited, will require careful consideration. The definition of the worst case event that could be realized as a result of a terrorist attack is likely to hinge on the assessment of the asset vulnerabilities that is required to be considered in NVIC 05-05. This is largely where our unfinished work remains.

References

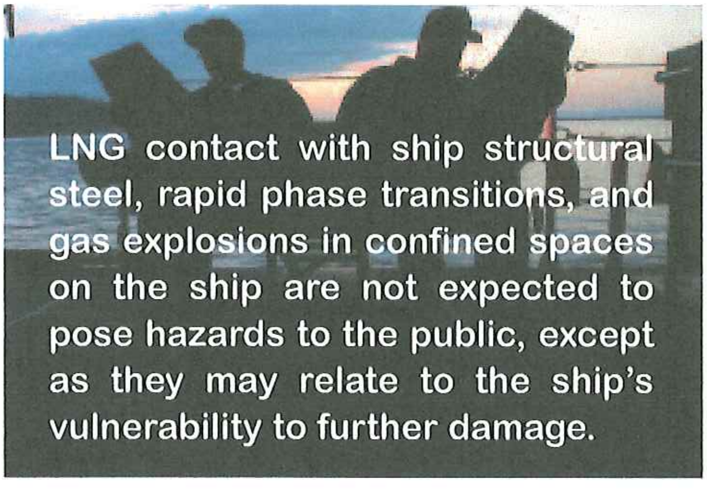
1. ABS Consulting, "Consequence Assessment Methods for Incidents Involving Releases from LNG Carriers," FERC contract FERC04C40196, May 2004.

2. Hightower, M., et al., "Guidance on Risk Analysis and Safety Implications of a Large LNG Spill Over Water," Sandia Report SAND2004-6258, December 2004.

3. Havens, J. A., "Predictability of LNG Vapor Dispersion from Catastrophic Spills onto Water," Report CG-M-09-77, Office of Merchant Marine Safety, USCG HQ, 1978.

4. Navigation and Vessel Inspection Circular No. 05-05, "Guidance on Assessing the Suitability of a Waterway for Liquefied Natural Gas (LNG) Marine Traffic," Commandant, United States Coast Guard, June 2005.

About the author: *Jerry Havens is a chemical engineering professor at the University of Arkansas. He has three decades of experience researching LNG spills onto water.*



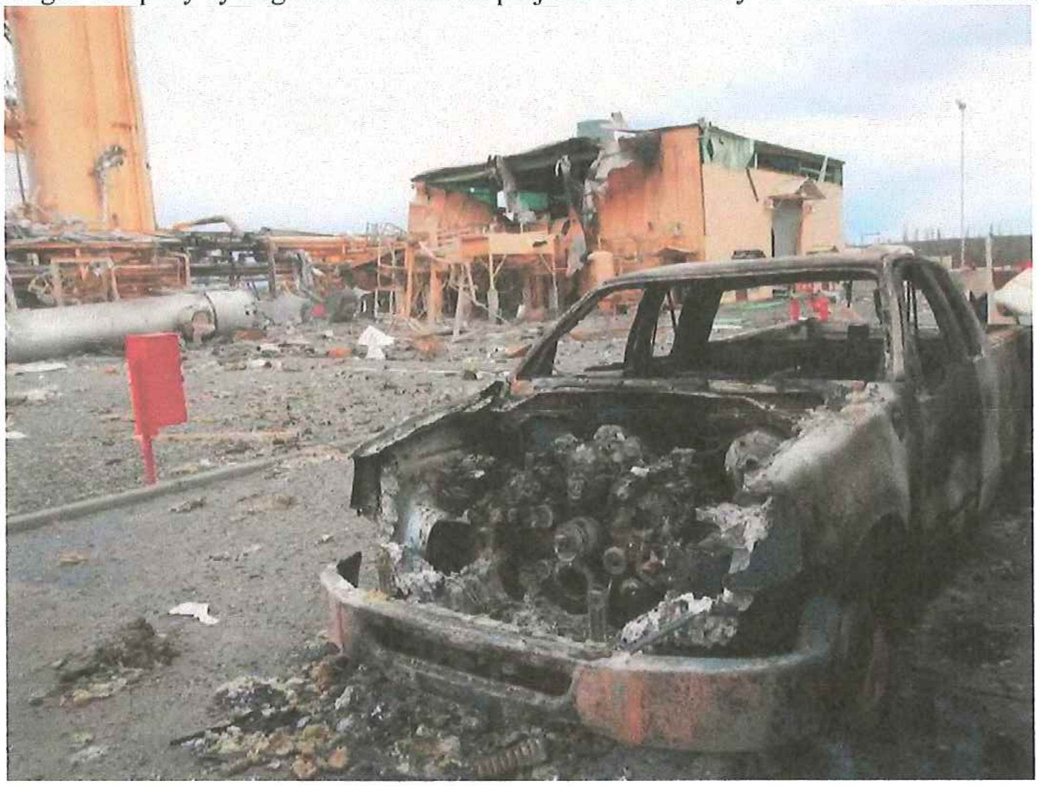
LNG contact with ship structural steel, rapid phase transitions, and gas explosions in confined spaces on the ship are not expected to pose hazards to the public, except as they may relate to the ship's vulnerability to further damage.

Exhibit 11

https://www.sightline.org/2016/06/03/williams-companies-failed-to-protect-employees-in-plymouth-lng-explosion/

WILLIAMS COMPANIES FAILED TO PROTECT EMPLOYEES IN PLYMOUTH LNG EXPLOSION

The natural gas company eyeing other Northwest projects has a history of unsafe work conditions.



Two employees were inside the compressor building (rear) at the time of the explosion. One sustained severe injuries. by Washington Utilities and Transportation Commission (Used with permission.)

Author: **Tarika Powell**
(@) on June 3, 2016 at 6:30 am

This article is part of the series Fracked Fuel & Petrochemical Projects in the Pacific Northwest

Two years ago, an explosion at a liquefied natural gas (LNG) plant in eastern Washington forced hundreds to evacuate their homes, injured five workers, and caused $69 million in damages. It was one in a string of accidents at The Williams Companies' natural gas facilities that in the last three years has killed five workers and injured at least 120 people.

Through a public records request, Sightline obtained documents from the Washington Department of Labor and Industries (Washington L&I), which conducted an investigation into the safety of employees at the Plymouth plant where the explosion occurred. The agency found that Williams endangered its employees, lacked an adequate emergency response plan, and had deficient safety training. The company's track record—not just in the Northwest, but throughout the US—reveals a pattern of failing to heed safety regulations. It also illustrates why we should not underestimate the fire and explosion hazards of natural gas processing plants such as LNG facilities.

The Williams Plymouth LNG explosion

The explosion happened shortly after 8:00 a.m. on March 31, 2014 at the Plymouth LNG plant in eastern Washington, about 30 miles south of the Tri-Cities, where the company stores natural gas in liquid form in two 14-million-gallon tanks. Natural gas ignited inside the LNG processing equipment, creating a "rolling detonation" that generated a mushroom-shaped cloud and large fire. Members of the public felt the rumble of the explosion up to six miles away, and employees near the explosion were knocked off their feet by its force. Employees saw a ball of fire as large pieces of exploded metal equipment and piping flew by them.

The blast completely fragmented a large piece of the natural gas processing equipment called an adsorber, propelling 250 pounds of debris and shrapnel up to 900 feet away and injuring 5 employees. One employee's injuries were so extensive that a coworker who helped him evacuate the grounds did not initially recognize him. The explosion caused extensive physical damage to buildings and electrical equipment and even bent the BNSF rail line near the perimeter of the facility's property.

Employees saw a ball of fire as large pieces of exploded metal equipment and piping flew by them.

To make matters worse, on the morning of the explosion, plant operators had shut down two safety monitoring systems. Facility operators disabled both the system that detects gas releases and the emergency shutdown system, which is designed to put facility equipment in "safe mode" should the plant experience hazardous conditions.

Shutting down these systems disabled detectors that would have automatically shut down the plant in an emergency. Instead, employees who were trying to flee the site had to locate and manually pull two separate emergency shutdown switches. Shutting down the systems may have also disabled the plant's alarms, which explains why many employees did not hear alarms after the explosion.

The last remaining employees on site were able to successfully engage the emergency shutdown only after realizing that the system had been disabled. While the shutdown stopped at least one gas leak, other leaks continued for more than 24 hours. Shrapnel from the explosion had pierced multiple gas pipes as well as one of the facility's two 90-foot-tall LNG tanks, resulting in a "roaring noise" as pressurized gas escaped from multiple locations on site. Residents within a two-mile radius were evacuated to the local fairgrounds, but not before the smell of gas had spread at least a quarter-mile from the plant.

Employees evacuated to the nearest fire station, but officials in charge of responding to the incident asked three Williams workers to reenter the premises multiple times while gas continued to leak so they could help plug, patch, or stop the leaks by closing valves at the site. The shutdown valves employees used to stop the leaks were 150 to 450 feet from the original explosion and fire, the area with the highest potential for exposure to hazards. While these employees rather selflessly agreed to assist, it was against the law to put them back into the "hot zone," the portion of a hazard site that is immediately dangerous to life and health, because Williams had not given them adequate emergency training.

Fires burn at site of Plymouth LNG explosion, by Washington Utilities and Transportation Commission (Used with permission.)

A disaster months in the making

Notably, plant operators had set the explosion in motion several months earlier, in November 2013, when they closed off the end of a pipeline with plastic and tape rather than proper sealing equipment, a move that allowed an explosive mixture of air and gas to enter the LNG processing system.

Next, system operators, following the company's written procedures, failed to properly purge excess oxygen from the equipment. The procedure for purging oxygen did not meet industry standards, and investigators with the Washington Utilities and Transportation Commission (UTC) later determined that the instruction manual lacked details that were clear enough for employees to follow with consistent and safe results. The Pipeline and Hazardous Materials Safety Administration's safety violation report notes that the company had been using the inadequate oxygen purge procedure for many years.

Williams' deficient safety training compounded this negligence. Federal workplace safety and health standards require Williams to adequately train employees for emergency response before asking them to participate in a real emergency scenario. To ensure their safety, only employees who have been highly trained in hazardous materials emergency response are permitted to enter a hazard site for the purpose of stopping a gas release. Guidance by the National Fire Protection Association and the International Association of Fire Chiefs supports these laws.

Yet Williams failed to adequately train its workers to enter the area of immediate threat, thereby gravely endangering them. On paper, the company's procedures align with workplace safety regulations, stating that only employees who have received advanced training in hazardous materials and emergency response will be sent into a hot zone or participate in an actual emergency response operation. In fact, the employees who were sent into the hot zone had not received the legally required training, so facility managers had a duty to make sure they remained evacuated from the site.

These workers faced many hazards in the hot zone: in addition to the gas leaking from pipes and the LNG storage tank, the facility houses liquid propane and butane tanks that each hold about 3,000 gallons and that are susceptible to expanding vapor explosions in circumstances such as those that followed the Plymouth explosion. The pipeline leak closest to the original explosion abutted a warehouse that gas had most likely entered, and as a 2010 overview of LNG properties and hazards notes, "explosions occur with noticeable frequency from a buildup of natural gas vapors indoors."

In addition to failing to adequately train its employees, Williams did not provide them with the protective clothing and equipment necessary to enter an area containing fire and explosion hazards. Workplace safety laws require that employers provide appropriate protective equipment to any personnel who enter a hazardous site, including a respirator and protective clothing that would cover all parts of the body that could be harmed by the hazard. While firefighters wore full protective gear and respirators, Williams provided only one of the employees with comparable protective equipment to enter the hot zone. Another was only given a flame-resistant shirt and pants, while the third employee was only provided with a flame-resistant shirt.

Washington L&I found that Williams placed its employees in close proximity to gas leaks that were likely to cause injury from a fire or explosion. The state determined that Williams' emergency response plan was not effective in practice because the company only provided limited emergency response training. Further, the agency noted deficiencies in Williams' written health and safety programs. Washington L&I fined Williams $1,000 (later adjusted down to $300) and ordered the company to correct the violations by giving the employees appropriate emergency response and hazardous materials training.

Rocky inspection record at Plymouth LNG

Past inspections at the eastern Washington facility foreshadowed Williams' lack of preparation for fire hazards or natural gas releases. A 2002 inspection by the UTC found fully ten areas of concern at the facility. Some of the fire detectors were too weak to detect hazards more than a couple feet from the equipment, and another was out of alignment with the area it was supposed to monitor. The company's procedures did not require that gas detection systems meet the National Fire Protection Association's minimum LNG fire protection requirements, and plant operators were not able to provide documentation that staff regularly checked the equipment for leaks. Further, the company lacked procedures to minimize the recurrence of safety incidents.

A V-shaped ice formation develops above the puncture on Plymouth LNG tank while pipe (lower left) spews LNG and gas vapor. By Washington Utilities and Transportation Commission (Used with permission.)

In other failings, a 2007 inspection by the UTC noted that for at least two years, Williams technicians had not correctly read the output for one of the cathodic protection devices, which help prevent leaks by monitoring corrosion in metal structures such as liquid gas storage tanks and pipes. They hadn't done so because the technicians themselves were confused about the configuration of the equipment.

In 2008, the UTC issued a violation to facility operators because they did not inspect and test fire control systems within six-month intervals, as required by federal LNG standards. Two of Williams' senior officials at the plant were "surprised that there was no grace period in the code" that allowed them to exceed the six-month minimum requirement for testing fire equipment.

Company's workplace safety problems have triggered federal probes

The Williams Companies is a natural gas corporation with hundreds of miles of pipeline in the western states and along the Atlantic coast. The company was set to build 232 miles of pipeline through Oregon for the Jordan Cove LNG export project, which federal regulators rejected in March 2016, and 85 miles of pipeline for the proposed Oregon LNG export facility, which developers withdrew from consideration in April 2016.

Both federal and state agencies have fined the company on numerous occasions for poor operations of natural gas plants and pipelines, but in the past three years, an alarming number of explosions and fires have broken out at The Williams Companies' natural gas and petrochemicals facilities, suggesting a pattern of recklessness that reaches far beyond Plymouth.

For example, a flash fire at one of the company's natural gas compression facilities injured fifteen people in New Jersey in May 2013. That same month, a Pennsylvania gas compressor station caught fire with eleven employees on site. In June 2013, an explosion at a Louisiana olefins plant killed two workers and injured more than 100 others. Then in October 2013, another explosion killed three contractors at a different Louisiana facility. A month after the March 2014 explosion at Plymouth LNG, an explosion at a Williams gas gathering facility in a small Wyoming town forced residents to evacuate.

The Occupational Safety and Health Administration found that the company failed in its responsibility to find and fix safety violations and ensure the safety of workers at its Louisiana olefins plant. The string of accidents also triggered the US Chemical Safety

Board to initiate a federal probe into Williams' safety practices. That investigation has been slow-going.

Williams resumes business as usual in Washington

Williams failed to properly train and equip its employees for emergency response, and it did not adequately coordinate with local first responders so that they could address the hazard without endangering employees. The company's failure increased the dangers of the hazard not only for employees and first responders, but also for the broader community.

There is reason to worry The Williams Companies will continue to shirk safety standards.

After paying a very small fine for its actions, Williams has moved forward. The company has now completed all the repairs necessary to resume full operations at Plymouth, and it is slated to build the pipeline for a proposed methanol facility at the Port of Kalama, Washington. But the company's record, along with ongoing investigations into the company's practices by Washington L&I and the UTC, demonstrate there is reason to worry The Williams Companies will continue to shirk safety standards—potentially endangering Williams' employees and nearby communities once again.

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Exhibit 12

https://www.bostonmagazine.com/2010/06/28/safe-harbor/

Safe Harbor?

Ships bringing liquefied natural gas from the Middle East pass regularly through Boston Harbor. Experts say there's little chance of an LNG tanker going up in a fireball. Then why are city officials so worried? Should you be?

by **JASON SCHWARTZ**. *6/28/2010, 7:21 a.m.*

At 2:30 a.m. on a Tuesday in May, a 53-foot pilot boat called the *Mystic* motored out to just beyond Boston Harbor and came alongside the GDF *Suez Neptune*. Like all ships entering the harbor, the *Neptune* — 928 feet long and 141 feet wide — required a licensed Boston Harbor pilot on the bridge, and Frank Morton was on the job. Stepping to the edge of the *Mystic*'s bow, he reached for the rope ladder that dangled from the *Neptune* like something on a pirate ship, then clambered up the side and onto the state-of-the-art tanker.

As he directed the ship into the harbor, blue lights whirred in every direction: on law-enforcement escort boats, on police cruisers parked at the end of nearly every pier. A chopper hovered as the tanker sailed past the airport, past downtown, and up the Mystic River. The security detail was a spectacular acknowledgment of the ship's cargo: 38 million gallons of liquefied natural gas, or LNG, enough fuel to power a region or, in the wrong hands and under the right conditions, incinerate half a city.

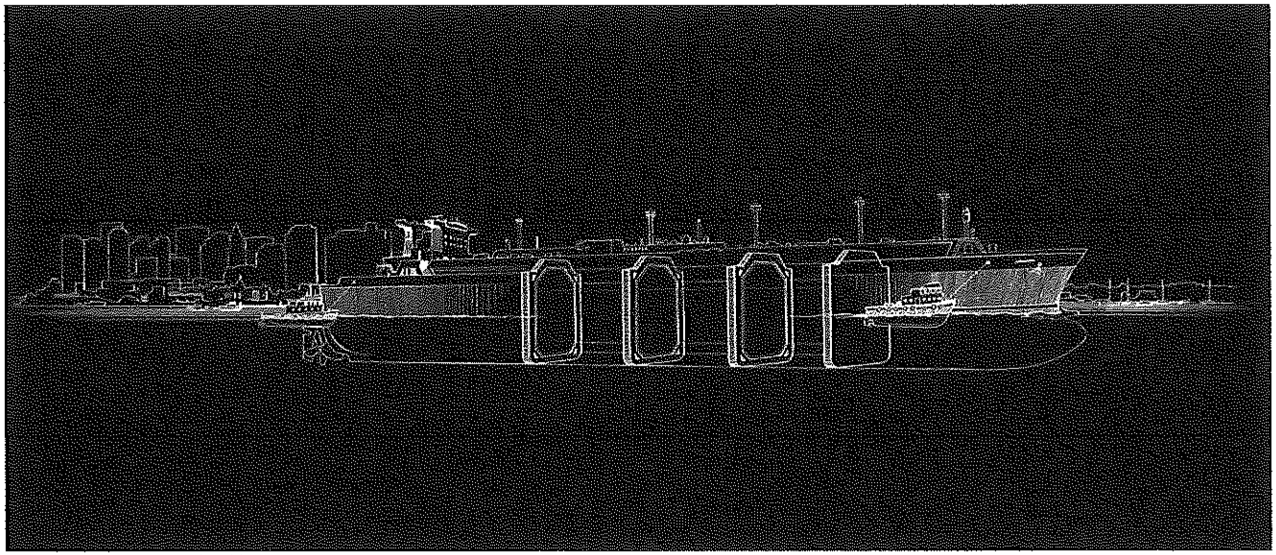
LNG tankers have been controversial ever since they started steaming through Boston Harbor to port in Everett in 1971, but became even more so after 9/11. If terrorists caused even 10 percent of the typical LNG tanker's payload to spill and ignite, the resulting fire could be calamitous, according to a 2004 report by Sandia National Laboratories for the U.S. Department of Energy. The study didn't publicly estimate casualties for Boston; in fact, no study has since 1977, when the Federal Energy Regulatory Commission estimated that up to 3,000 would die. Today, when the city's population of 610,000 swells to more than one million on workdays, the number could be higher. It's not hard to imagine why Boston remains the country's only major city with an LNG terminal.

The tankers were such cause for concern after 9/11, Mayor Thomas Menino asked a federal judge to ban them from the city. The effort failed, and the LNG debate faded — until this past February, when shipments started arriving from Yemen, a known terrorist haven and site of the 2000 attack on the USS *Cole*. "This is serious stuff," Menino says. "I take it very seriously, and my public-safety officials take it very seriously. We don't have the equipment to put down an explosion of an LNG tank. They say, 'Well, it will never happen.' Well, 9/11 hadn't happened either. We live in a different era."

For nearly a decade, Menino has been urging the federal government to develop more natural-gas pipelines and offshore LNG terminals for New England — an expensive solution to what has been, so far, a hypothetical problem. Executives of Distrigas, a subsidiary of French conglomerate GDF Suez, which owns the Everett terminal, counter that security is better than ever, and point to their industry's sterling safety record: There hasn't been a serious incident since an LNG storage tank exploded in Cleveland in 1944, destroying 79 homes and two factories, and killing 130 people.

Still, even ships coming from countries more stable than Yemen are scrutinized. The *Neptune*, for instance, had sailed from Trinidad. Just before dawn it reached Everett safely, like the nearly 1,000 ships before it.

Yet some LNG experts, like University of Arkansas chemical engineering professor Jerry Havens, point out that something need go wrong only once. "Moving this much flammable fuel through a populated area should be considered...low risk, low probability, but high consequence," he says.



Illustrations by Joe McKendry

LNG 101

What is LNG?

Natural gas that's been turned to liquid by chilling it to negative 260 degrees Fahrenheit. As a liquid, the gas occupies 600 times less space, making it easier to ship. In addition to coal and oil, natural gas is one of the world's most prized fossil fuels and is found in large deposits in North America, the Middle East, and Southeast Asia.

Why is natural gas important?

Besides firing up your stove, natural gas heats about half the homes in Massachusetts and generates 40 percent of New England's electricity.

Why do we import LNG?

North America has plenty of natural gas, but not enough New England pipeline. The LNG that comes into Everett provides 20 percent of the region's annual supply — double on the coldest days, when demand spikes. The Mystic power station, next to the Everett terminal, runs on LNG and fuels 30 percent of Greater Boston's power supply.

Where do the shipments originate?

Yemen, Egypt, and Trinidad. Distrigas declined to give exact numbers, but Frank Katulak, president and COO, says he'll get about 60 shipments a year: 10 from Yemen, 5 to 7 from Egypt, and the rest from Trinidad.

Why is Boston the only major city with an LNG terminal?

Because nobody else wants one. When the Everett terminal was built in 1971, many viewed it as a step toward the future — an important energy source at the hub of a region. Since then, environmental and security concerns have scared off other cities, including Providence and Long Beach, California. Offshore LNG facilities are more palatable to many critics (we have two terminals off the New England coast), but they're not as convenient as land-based terminals because they can't directly fuel power plants.

Why do we import from Yemen now?

Until February, Distrigas received all its shipments from Trinidad, but relatively low U.S. natural-gas prices caused some Trinidadian suppliers to seek out customers willing to pay more, Katulak says. To replace inventory, in 2005 Distrigas signed a 20-year deal to begin importing LNG from Yemen.

Who's on the ships from Yemen?

Distrigas is using the same ships and crews it's always used, and has hired no Yemeni nationals, Katulak says. Some critics have warned about the possibility of stowaways. Former U.S. counterterrorism chief Richard Clarke asserted in his 2004 book, *Against All Enemies*, that Al Qaeda stowaways had infiltrated Boston via LNG tankers from Algeria, a claim the FBI disputes. Katulak rejects the stowaway concern, arguing that it would be extremely difficult for someone to hide undetected on a ship for 18 days. Today, even Clarke is less concerned than before about stowaways. "There are easier ways" to get into the country, he says.

Shouldn't the 1977 risk-assessment study be updated?

Yes. Boston Deputy Fire Chief Jay Fleming has been agitating for this type of update for years. Menino says the Department of Homeland Security in February promised him an assessment of how to get LNG out of the harbor, but has yet to deliver a report. The DHS declined to comment.

How would the city respond to an LNG fire?

The worst kind of fire would be an event so large and unprecedented, it's near impossible to prepare for. The Massachusetts Firefighting Academy in Stow has an LNG training program, but it focuses on fighting fires from smaller-scale leaks, such as from pipelines or transport trucks. Pool fires (see page 91) are just too big. "We're not training for that type of an incident," says State Fire Marshal Stephen Coan, "and I don't think that you can train for that type of an incident" on a large scale. Still, Boston city officials, Distrigas, and the Coast Guard say they regularly collaborate on joint emergency drills.

What does Menino want?

The mayor wants tankers to stop coming, which would happen only if the region found other ways to get natural gas: via offshore facilities, for instance, or more pipeline, says Donald McGough, director of the city's Office of

Emergency Preparedness. City officials have said each shipment costs $25,000 in public-safety measures.

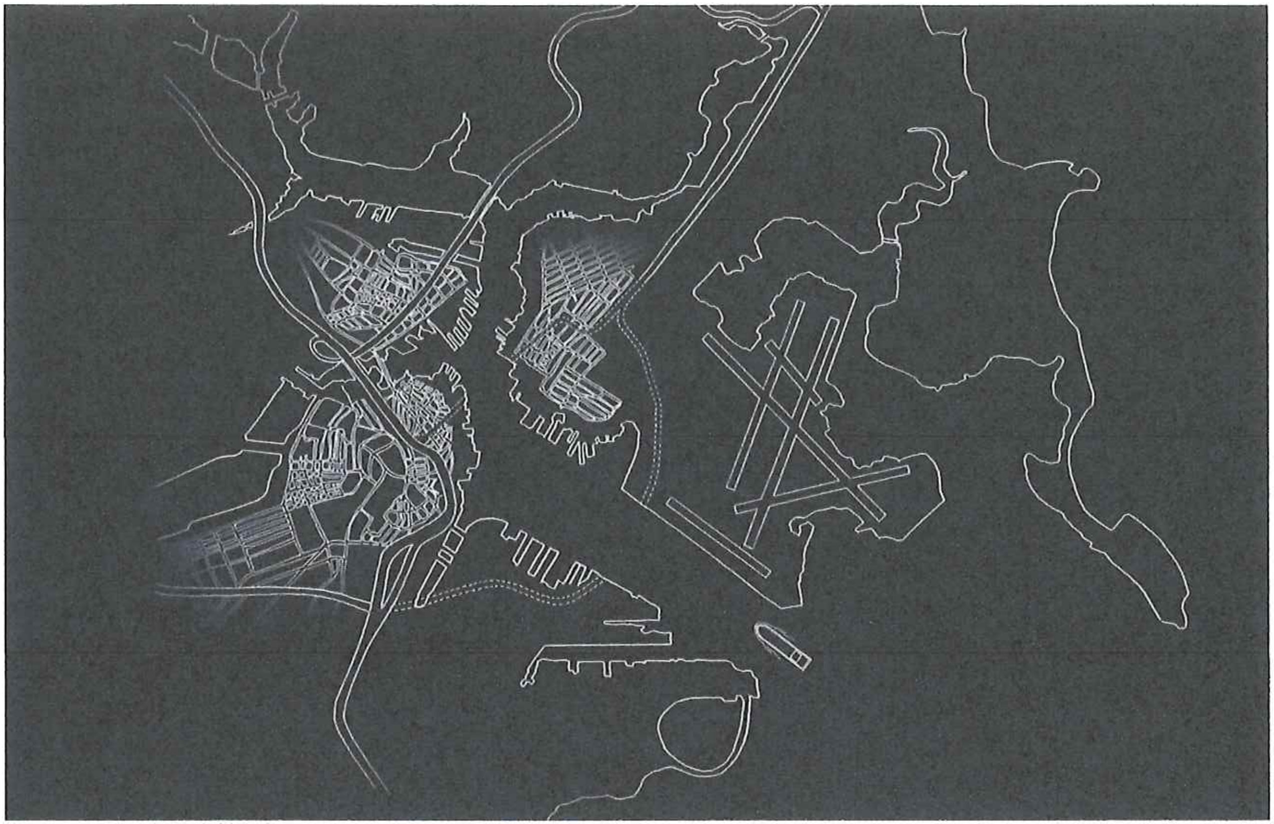


Illustration by Joe McKendry

THE ROUTE

Every LNG tanker cruises past the piers and bridges of downtown and Charlestown before docking in Everett. Here are some of the security measures taken along the way:

Four days out

The LNG tanker is required to alert the Coast Guard of its approach and provide a manifest. The Coast Guard runs background checks on the crew. (Distrigas performs its own background checks before its ships sail.) The tanker must contact the Coast Guard again at 48, 24, 12, and 5 hours outside Boston Harbor.

Six to twelve miles out

Two Coast Guard officers board the tanker for safety checks and to watch for vessels that get within 500 yards. The Coast Guard also sends in teams of 12 to 24 officers for random security sweeps, though they're more likely to spot check ships from Yemen.

Five miles out

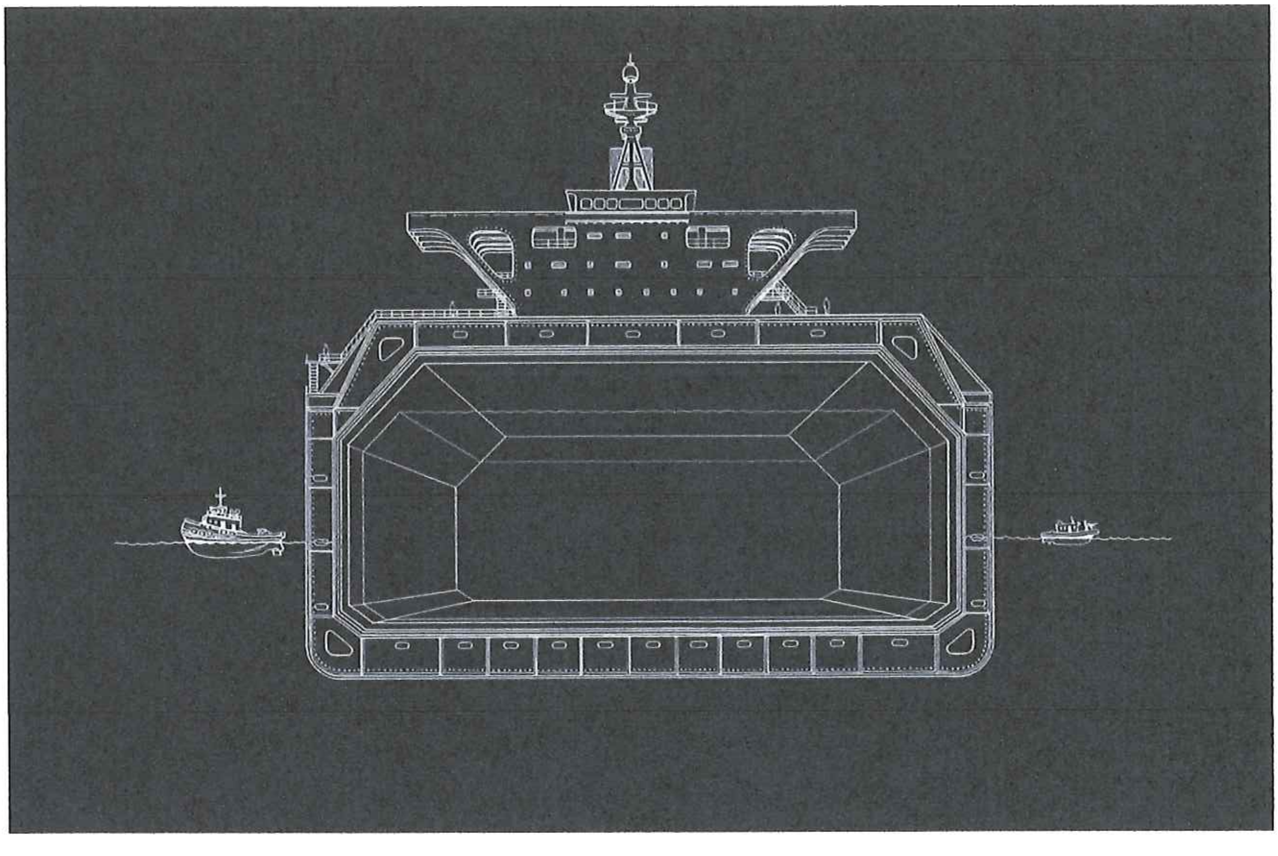
A member of the Boston Harbor Pilot Association meets and boards the tanker. After safety and information protocols are performed, the pilot directs the ship toward the harbor at about 10 knots, or 12 miles per hour.

Entering Boston Harbor

When the ship enters the North Channel, that's the point of no return. Until then, the harbor pilot can decide to stop, no questions asked. From here, though, the pilot has committed. As the ship passes through the harbor, it hugs the East Boston shoreline, where the channel is deeper. The Coast Guard allows LNG tankers to enter only on clear days.

Pleasure Bay

As the ship slows, four tugboats lash themselves to its sides. (The tugs can haul the tanker and help it maneuver in case of emergency.) Here, the tanker enters the security zone, and law enforcement appears. No unauthorized vessels are allowed within 500 yards. At least five small boats — the Coast Guard, city and state police, and Massachusetts Environmental Police among them — escort the tanker. One or more choppers hovers above.



HOW DANGEROUS IS IT? THE REALITY

Can LNG catch fire inside the tanker?

LNG itself is not flammable. You could light a match, drop it into a vat of the stuff, and be perfectly fine. Yet if LNG, which is extremely cold, spills out onto the relatively warm ground or water, it immediately starts to evaporate. That forms a vapor, which is flammable, but only under certain conditions (see "The Fire"). LNG tankers are built with double hulls, each made of one-inch-thick steel. By contrast, the USS Cole had a single hull of half-inch-thick steel.

Would it be easy to blow up a tanker?

Successfully attacking an LNG tanker would be very difficult, experts say, but it's hard to say exactly how difficult. For most ships passing through Boston, an attacker coming from outside the ship would first have to breach the security zone, then cause a leak by blasting through about 30 feet of the ship. Sandia considered all conceivable means and methods of attack for its 2004 report, though that part remains classified. "We got drawings of the ships and did very high-definition structural calculations of the damage you would get from those types of credible threats," says Mike Hightower, one of the study's authors. "We [considered] things like an attack, a hijacking, an insider threat where a member of the crew...brought some explosives onboard. We looked at a range of weapons, and we looked at things people could make into weapons: small aircrafts, small boats."

Do LNG accidents happen often?

There hasn't been a major LNG incident since the 1944 storage-tank explosion in Cleveland. And a shipwreck doesn't automatically mean disaster: A tanker once hit a rock outcropping head-on in the Strait of Gibraltar and had to be towed to port, yet lost not a drop of LNG.

EXPERTS SAY...

LNG ships carry four to six tanks. If about half of a single 6.6-million-gallon tank spilled from a 54-square-foot hole and the vapors ignited, the fire would "cause significant damage to structures, equipment, and machinery" within a 1,280-foot radius and leave second-degree burns on people more than three-quarters of a mile away, according to Sandia's study, which measured impact on open water. In a city, variables such as buildings would affect the fire's path and intensity. Sandia's worst-case scenario measured the result of LNG spilling simultaneously from three tanks, which "would set structures aflame out to 2,067 feet and burn people as far as [1.3 miles] away," says study coauthor Mike Hightower. Sandia is now studying scenarios in which tanks are breached successively. Results are expected this summer.

THE FIRE

1. LNG immediately begins to evaporate when it spills. A vapor cloud forms and grows, and you hope there's no spark. Even with a spark, only the cloud's edges, where 5 to 15 percent of the air is LNG, can ignite. Yet if that part catches fire, the whole thing burns.

2. In an attack, a spark would probably be present as the LNG began to spill, so a fire would start right away. Because the LNG hits the water faster than it all can evaporate, it would form a pool on top of the water. As more spilled, the pool — and the fire — would grow.

3. The LNG would continue feeding the blaze (imagine the fire being attached to the pool) until all the fuel evaporated and burned off, which could take anywhere from three to forty minutes. By then, anything within reach could have ignited and set off other fires.

Exhibit 13

http://www.thecuttingedgenews.com:80/index.php?article=531

The LNG Threat

Liquefied Natural Gas Tankers Remain Giant Terror Targets

Cindy Hurst June 16th 2008

Cutting Edge Contributor

Can Liquefied Natural Gas (LNG) be used as a lethal weapon of mass destruction? That question lies at the heart of the debate about increasing use of this important energy resource.

The answers are not reassuring. Nor are the questions.

Certainly, security measures currently in place make LNG terminals and ships extremely hard targets for terrorists. However, it would be imprudent to believe that terrorists are either incapable or unwilling to attack such targets. It would be equally imprudent to assume that these targets are impenetrable. A number of known vulnerabilities exist within the LNG industry. These vulnerabilities lie in the human factor. In other words, LNG ships and tankers are structurally sound. The potential for problems lies within the people who are somehow involved in the industry.

Inadequate vetting of crews

LNG shipments often originate from politically unstable and unfriendly countries and regions. Some of the locations in which LNG originates include Qatar, Nigeria, Algeria and Egypt. "It's the location of the ports, and where the LNG is loaded, and who gets on the vessel [that is important]," said William Doyle, Deputy General Counsel of the Marine Engineers' Beneficial Association (MEBA). Many ships operate under grossly unregulated "open registry" or "flags of convenience" registries and often originate from ports with poor security systems in place.

Due to a lack of any meaningful international regulatory oversight, it would be possible for someone to work under a different identity on board one of these tankers and avoid detection. Under the current system, no completely trustworthy and uniform system is in place for vetting foreign mariners. Background checks are conducted on Americans by the Coast Guard and the Transportation Security Administration (TSA). However, these same background checks are not performed on foreign crews. The Coast Guard does, on the other hand, require crew lists from all vessels entering U.S. ports. Unfortunately, no method is in place to ensure these crews are who they claim to be. Although this is an issue of security for all cargo ships, it is even more critical for ships carrying potentially dangerous cargo, such as LNG.

In a testimony to Congress, Ron Davis, President of MEBA, listed a number of differences between U.S. and foreign mariners, saying, "U.S. merchant marines receive their credentials to work from the Coast Guard. Foreign mariners do not. U.S. mariners undergo extensive background checks through the FBI. Foreign mariners do not. U.S. mariners are vetted through the national driver record database. Foreign seafarers are not. U.S. mariners will be subject to terrorism background checks through the TSA. Foreign Seafarers are not.

Finally, U.S. merchant mariners are U.S. citizens or persons lawfully admitted for permanent residency. The mariners who crew these ships are not." As a result, it is impossible to be certain that a mariner is who he claims to be or that he is not a security risk. Davis said that there are practically no Americans employed on LNG ships today. At the top of MEBA's list of threats to an LNG tanker is the possibility that a knowledgeable crewmember could deliberately sabotage the vessel. According to Davis, "The most vulnerable (thing) that you have on the ship is the crew. It is the crew that controls the ship. One or two engineers down in the engine room can take control of the ship, can control the steering of the ship, can control the speed of the ship, can have the ship going 20 knots up the Houston ship channel or in the New York Harbor or in places of confined areas. They can ram the ship anywhere they want." Davis stated that terrorists might one day intentionally ram an LNG ship into a strategic target such as one fully loaded with a highly flammable, explosive material onboard. Or, as William Doyle said, two or three terrorists infiltrating an LNG tanker could cause serious damage by one taking control of the ship and the other(s) detonating an onboard explosion as the tanker enters a busy harbor. Terrorists could attack an LNG tanker as well as they could any cargo ship. In a 2004 edition of *Jane's Terrorism and Security Monitor*, *Jane's* reported that the type of attack widely envisaged, based on analyses of compromised terrorist preparations, would include "an explosion onboard a cargo ship laden with fuel oil and ammonium nitrate fertilizer, in effect turning the vessel into a waterborne fireball."

Should a terrorist somehow manage to get onboard a LNG tanker and cause an explosion, it might be possible to cause a boiling-liquid-expanding-vapor-explosion (BLEVE). A BLEVE might be possible in some instances if the LNG is heated to above its boiling point while still contained within the tank. This rapid heating could cause a percentage of the LNG within the tank to "flash" into a vapor state almost instantaneously. This would cause pressure in the tank to rapidly build up. While LNG tanks do have massive pressure relief valves in place, if these valves were to fail in their ability to release the gas quickly enough or altogether, the pressure in the tank might create a type of explosion that would send dangerous debris flying. Most experts agree that LNG tankers are built to prevent such an event from occurring. One expert polled during the GAO study, Dr. Robin Pitblado from Det Norske Veritas, however, pointed out that a BLEVE might be possible on a Moss spherical tank because these tanks are constructed such that pressure could build up within them.

Skepticism exists within the industry regarding Pitblado's claim. Captain Scott Conway who has served eight years onboard LNG tankers and who is intimately familiar with the construction of the Moss spherical tanker, views Pitblado's scenario as unrealistic, questioning his conclusions by asking, "Where is the BLEVE going to occur in this tank? Where are you going to direct the flames back at this tank to heat up the liquid? How are you going to build up the pressure so that it overcomes the safety release? When you can explain this all logically as per the ship's construction, then we'll talk seriously."

Inadequate U.S. security measures for facilities

During a hearing in the United States House of Representatives on 21 March 2007, Jim Wells of the GAO raised doubt that the Coast Guard can marshal the resources needed to meet its responsibilities. While it took 40 years to build the fleet of LNG carriers to 200 tankers worldwide, it will take less than four more years for that number to grow to 300. This rapid growth rate coupled with the anticipated growth rate of LNG imports into the U.S. presents a real security challenge. The U.S. faces today potential lack of security measures and resources to protect these new assets.

Shortage of qualified mariners & U.S. officers

The rapid growth of LNG does not affect only the ability to safeguard each ship; it also affects the quality of mariners working onboard these vessels. Due to the nature of LNG, highly skilled and trustworthy individuals are required to ensure its safe transport. Currently, LNG tankers have crews consisting of mostly foreigners. Yea Byeon-Deok, professor and LNG initiative coordinator of the International Association of Maritime Universities said, during a conference in Australia, "Many substandard vessels have begun to appear as demand for LNG increases, while there is a chronic shortage of experienced crew."

Because of sudden rapid growth in the industry, many experts question whether or not there will be enough qualified mariners to crew these vessels. Nearly 1,500 senior officers and 750 senior engineers will be required to man the 100 new LNG ships. Approximately 80 percent of these ships will be fitted with steam turbines, requiring engineers with steam experience, which, according to one report, is a "vanishing resource." The fact that many senior LNG officers are due to retire soon, and new, highly skilled mariners will be required to replace them exacerbates the situation. It will be tough enough just to replace those who are retiring, increasing existing shortages of crew members and officers to crisis proportions.

The Society of International Gas Tanker and Terminal Operators LTD (SIGTTO) has recognized the acute shortage. "A short-term answer for an LNG vessel operator is to 'poach' its crew from another such operator but, clearly, the long-term answer is training, training, and further training. SIGTTO members, as much as anyone, wish for the quite unique safety record of LNG shipping to be preserved. The influx of new personnel into the industry is of concern, especially if there is a temptation by a minority of operators to 'cut corners' and put officers into positions of responsibility on a LNG carrier before they have been properly trained."

The U.S. Maritime Administrator has been striving to increase the number of U.S. mariners employed on these tankers. U.S. officers go through a rigid qualifications process to ensure they become highly skilled. Meanwhile, the U.S. has no control over the quality of foreign officers. According to H. Keith Lesnik, Director of the Office of Deepwater Port Licensing, officials are pushing to bring more U.S. officers onboard LNG tankers. So far, four shipping companies have agreed to do this. Under the Deep Water Port Act, the Administrator has to allow these ships access to the port facilities, whether they have U.S. mariners onboard or not. In an effort to try to influence companies not wishing to comply with the manning request, the Maritime Administrator offers priority processing to companies agreeing to the manning requirement. The priority allows these ships to be moved to the front of the line for the license application process.

No U.S.-Flagged LNG Vessels

Up until 2001, there were U.S.-flagged LNG tankers. Since 2001, however, not a single U.S.-flagged LNG tanker exists.

The reason for this is purely economic. It is more costly to register a ship in the U.S. than in a foreign country because a U.S.-flagged vessel is required to employ Americans, which is more expensive, and also to pay higher taxes and fees. Additionally, running a U.S.-flagged vessel entails more stringent requirements because the vessel then falls under the U.S. Code of Regulations. These U.S. regulations require more rigid crew training and more stringent licensing standards on crew documents. All of these factors drive up the costs of running the ships. The real benefit for a ship to carry a U.S. flag would be so that it can carry cargo from state to state within the U.S. and it can carry U.S. military cargo from U.S. bases to overseas bases. Neither of these advantages serves as a motivator to LNG trading companies because neither is necessary in an LNG operation. The flag flown has no bearing on the ship's operator. Registering a ship is a fairly easy process. The International Transport Worker's Federation lists 28 countries as flag-of-convenience (FOC) countries. Registering a ship in an FOC country generally requires much less paperwork than do countries that have national registers. In some cases, such as Panama, registration can be done in just a few hours by fax.

The implications are that since requirements are much less stringent, security precautions and fleet training are most likely lacking.

Hijacking

A 2004 study conducted by the European Conference of Ministers of Transport jointly with the Organization for Economic Cooperation and Development (OECD), describes two scenarios involving terrorists striking at sea. In the first scenario, called the Trojan Horse scenario, terrorists develop legitimate trading identities that would allow them to ship and misuse "dangerous consignments." In the second scenario, the hijacking scenario, terrorists seize control of an entire vessel and its cargo to use it in a mass assault. According to *Jane's Terrorism and Security Monitor*, the intelligence community fears that preparations for a major seaborne assault might already be in an advanced stage. In March 2003, during the night, about a dozen heavily armed men boarded the chemical tanker Dewi Madrim off the coast of Sumatra. The hijackers proceeded to take over the ship. Experts believed that this might have been a training exercise because the pirates navigated the ship for an hour through the Strait of Malacca then kidnapped the captain and first mate without demanding a ransom. Some experts believed that the hijackers could have been terrorists practicing operation of a large vessel in the crowded shipping lanes.

According to an ABC News investigative report, fears in shipping and security circles were increasing with the notion that these armed terrorists, or ven pirates, could take control of a vessel carrying LNG and transform it into a floating bomb. Admiral Kevin Eldridge, who was the commander of the U.S. Coast Guard's 11th District in California, stated that an attack by ship on U.S. shores was "likely enough for us to put a lot of effort into the planning of it." Eldridge continued, "There aren't enough ships [and] there aren't enough planes for us to set up a picket line, so that we know what's coming." He continued, "We're pushing our borders out. Frankly, if we have a vessel in our port that has a problem, it's too late." According to Captain Conway, physically it would be extremely difficult for pirates to successfully scale the 50-foot hull of an LNG vessel. However, according to Anne Korin, co-director of the Institute for the Analysis of Global Security (IAGS), acts of pirates hijacking a ship have been facilitated by planting an insider within the ship.

Stepped up and more realistic security measures on LNG terminals and ships must address the vulnerabilities--and soon.

Cindy Hurst is a political-military research analyst with the Foreign Military Studies Office. She is also a Lieutenant Commander in the United States Navy Reserve. This article was adapted from a report for the Institute for the Analysis of Global Security www.iags.org.

Exhibit 14

http://in.news.yahoo.com/060620/137/65814.html

LNG demand growth risks fall in shipping standards

June 20, 2006
Y! India News
By Paul Marriott

DARWIN (Reuters) - Growing global demand for liquefied natural gas (LNG) and tight supply of specialized tankers and crew create the risk of dangerous lapses in standards and security, a shipping expert said on Tuesday. "Nobody knows what would happen if a significant accident occured on a large LNG carrier," Yea Byeon-Deok, professor and LNG initiative coordinator of the International Association of Maritime Universities, told a conference in Australia.

"All we can say is that a 100,000 tonnes tanker has four times the energy potential of the atomic bomb used to hit Hiroshima," he said.

"Many sub-standard vessels have begun to appear as demand for LNG increases, while there is a chronic shortage of experienced crew."

LNG demand is expected to more than double in the next 10 years due to growing use in China, India and the United States, alongside traditional users Japan and Korea, and the inauguration of major new export projects in Australia, Qatar and Nigeria.

Yea said diversifying sources of both demand and supply had blown apart an oligopoly of suppliers, ship-builders and operators, increasing competition but also placing emphasis on price and reducing investment in safety and training.

He said global orders had been placed for 143 new tankers through to the end of the decade, 102 of which would be larger than 100,000 tonnes and 36 of which would be over 200,000 tonnes, but that orders and sizes were increasing all the time.

New orders implied a need for 3,575 officers over the next three years, Yea said, of which 60 percent would need to be at "senior" or experienced level.

But he warned that recruitment and training were falling dangerously short of requirements to staff complicated vessels which could make dramatic targets for potential terror attacks.

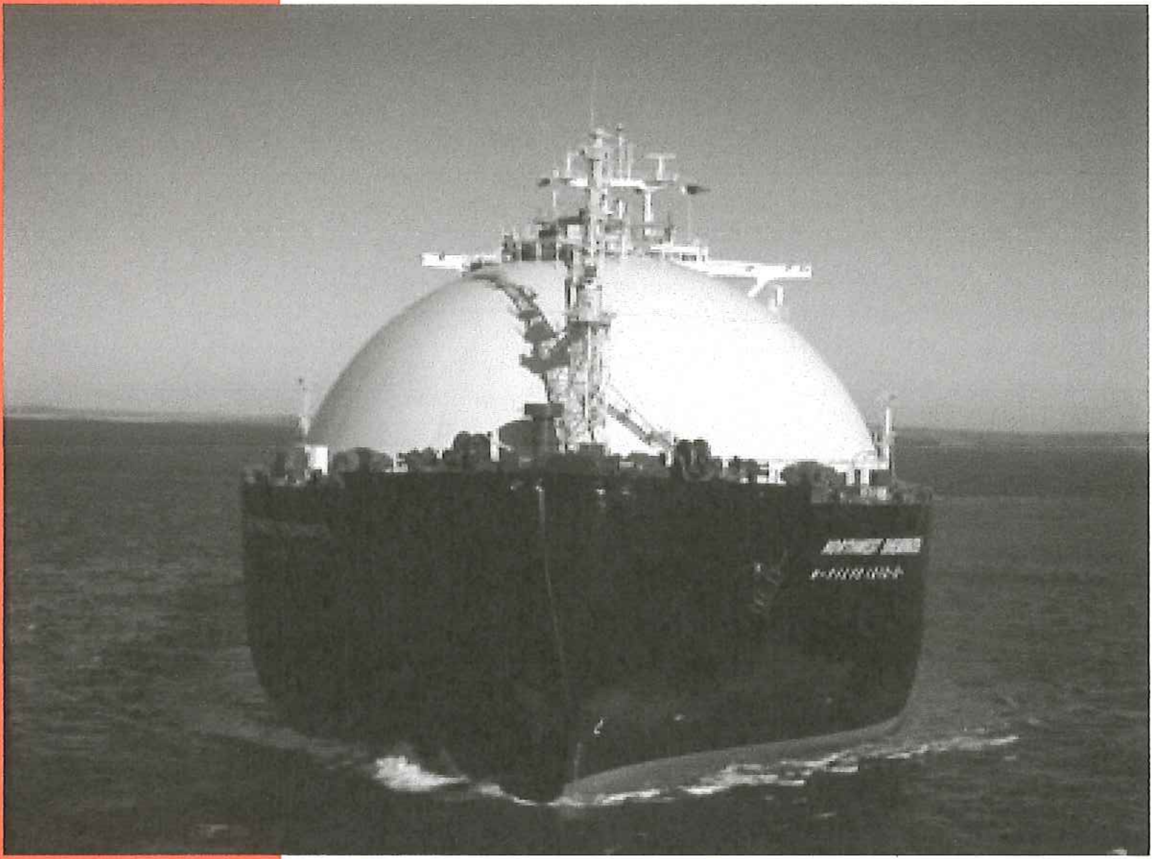
Yea pointed to the growth in "flag of convenience" ships which fly alternative flags to the country of ownership, potentially allowing them to avoid taxes and quality control and labour regulations, as evidence of deteriorating standards.

Asian shipyards are operating near full capacity after an order boom in 2003-2005 gave them enough business to keep busy for years, with China emulating Korea and Japan in creating a ship-building industry to support its growing energy imports.

LNG, regasified from liquid tanks at the receiving point and piped to consumers, is used to fuel industries, power plants and households directly.

Exhibit 15

The Terrorist Threat to Liquefied Natural Gas: Fact or Fiction?



by LCDR Cindy Hurst

February 2008
Institute for the Analysis of Global Security (IAGS)

The Institute for the Analysis of Global Security (IAGS) is a Washington based non-profit public educational organization dedicated to research and public debate on issues related to energy security. IAGS seeks to promote public awareness to the strong impact energy has on the world economy and security and to the myriad of technological and policy solutions that could help nations strengthen their energy security.

WWW.IAGS.ORG

Cindy Hurst is a political-military research analyst with the Foreign Military Studies Office. She is also a Lieutenant Commander in the United States Navy Reserve.

On 14 February 2007, the Saudi Arabian arm of al-Qaeda put out a call to all religious militants to attack oil and natural gas sources around the world. Through such attacks, according to the call, al-Qaeda hopes to "strangle" the U.S. economy.[1] Such proclamations give fodder to those who highlight the possibilities that liquefied natural gas (LNG) could be used as a lethal weapon of mass destruction. Industry officials on the other hand point out the improved security measures in place as a result of 9/11. While the U.S. continues to pursue LNG as a way to diversify its natural gas resources in order to meet anticipated future shortfalls and increase energy security, opponents and proponents of LNG have been locked in a bitter debate with no solid conclusion. Proponents are correct in that both safety and security measures currently in place make LNG terminals and ships extremely hard targets for terrorists. However, it would be imprudent to believe that terrorists are either incapable or unwilling to attack such targets. It would be equally imprudent to assume that these targets are impenetrable. If anything, in today's environment, insiders will always remain a potential threat.

Dangerous Assumptions

On 1 February 2007, the media reported on a study by former White House counterterrorism chief Richard A. Clarke who worked as a consultant to a firm proposing an LNG terminal in eastern Baltimore County. Clarke is said to have released a two-page summary of his report on the proposed Sparrows Point LNG terminal in the Baltimore area. In it, he stated that the terminal would be located sufficiently far from homes and schools and would therefore pose "no threat." Clarke, according to media reports, went on to justify his findings by saying that terrorists "want to kill people. They want to kill hundreds of people."[2] Therefore, since the proposed terminal would be located 1.2 to 1.3 miles from the Dundalk neighborhood of Turners Station, according to Clarke, it would not be a sufficiently attractive target for terrorists. Additionally, he said that the facility would not be close enough to Washington to be a "symbolic target."[3] However, recent studies run counter to Clarke's alleged conclusion. One of the best ways to study al-Qaeda, or any other terrorist group, is through an analysis of historical trends. In early 2007, Rand Corporation released a lengthy analytical report on terrorist targeting preferences for the Department of Homeland Security. The paper focused on 14 terrorist attacks in which al-Qaeda was believed to have been somehow involved, either through association, sponsorship or direction. According to the study, 10 out of the 14 attacks analyzed had either a medium or high casualty potential. In other words, these attacks were meant to kill people—a lot of people. However, the other four attacks had a low casualty potential. The study further showed a desire to damage the economy, with 10 of the 14 attacks indicating a medium or high potential to damage the economy and the other four with a low

"Once ignited, as is very likely when the spill is initiated by a chemical explosion, the floating LNG pool will burn vigorously…Like the attack on the World Trade Center in New York City, there exists no relevant industrial experience with fires of this scale from which to project measures for securing public safety."

Professor James Fay, Massachusetts Institute of Technology

potential. Based simply on the Rand study, Clarke's statement that the proposed terminal location would pose "no threat," is a dangerous assumption which leaves no room for error because al-Qaeda and its associates, through propagations distributed via the Internet, have already expressed an interest in crippling the U.S. economy. To further compound the argument against Clarke's conclusion, energy experts expect LNG imports into the U.S. to increase dramatically through 2030. This shift could potentially make LNG an even more desirable target as the U.S. becomes increasingly dependent on LNG to satisfy its growing natural gas consumption habits.

Maritime terrorism has been a core part of al-Qaeda and its affiliates' historical strategy

The final argument against Clarke's claim, and perhaps the most compelling one, lies within a study released by the Government Accountability Office (GAO) in February 2007 on the public-safety consequences of a terrorist attack on LNG.[4] In its analysis, the GAO scrutinized six completed studies on the potential hazards of an LNG spill. The GAO then drew a series of conclusions from the studies and polled a panel of 19 experts to see whether or not they agreed with the findings. Not all experts agreed on the heat/hazard zone of an LNG spill. One quarter of the experts polled during the study believed that one to 1.25 miles was not a sufficiently conservative estimate to describe the heat hazard zone of an LNG related fire. If the experts who disagreed with this distance happen to be correct, it would put members of the general population located at the questionable threshold of 1.2 or 1.3 miles away from the site in a risky location.

Probability and Motivation of a Terrorist Attack

Few groups are capable of implementing an attack on LNG. However, an attack on LNG would fit well with al-Qaeda's tactics, techniques and procedures. al-Qaeda is a radical Sunni Muslim organization with approximately 50,000 members located at various bases of operations in 45 countries. In addition to its own members, al-Qaeda's network includes groups operating in up to 65 countries. al-Qaeda's objective is to serve as a "defensive jihad" fighting against anyone or anything it perceives as attacking Muslims across the world. As a result, the group's aim is to overthrow non-Islamic (or insufficiently Islamic) regimes that seem to oppress their Muslim citizens. In 32 incidents traced back to al-Qaeda, there were 3,464 deaths and 8,864 injuries. Although there has never been an attack against either an LNG terminal or tanker, maritime terrorism has been a core part of al-Qaeda and its affiliates' historical strategy. In 2000, suicide bombers rammed the *USS Cole* in Yemen, killing 17 sailors. In 2002, terrorists rammed the *Limburg*, a French oil tanker carrying 400,000 barrels of crude oil.

There have reportedly been indications of terrorists planning to hit LNG tankers. In November 2002, the capture of Abd al-Rahim al-Nashiri, al-Qaeda's operational commander in the Gulf region, brought to light the idea that terrorists were already planning to go after such targets. Nashiri, allegedly a specialist in maritime operations, had already played a key role in the attack on the *USS Cole* and the *Limburg*. According to a Western counterterrorism official during an interrogation, Nashiri indicated that al-Qaeda had information on the vulnerability of supertankers to suicide attacks and the economic impacts they would have. The official informed *The Daily Star* that al-Qaeda had a naval manual describing "the best places on the vessels to hit, how to employ limpet mines, fire rockets or rocket-propelled grenades from high-speed craft, and turn LNG tankers into floating bombs. They (terrorists) are also shown how to use fast craft packed with explosives and the use of trawlers, or ships like that, that can be turned into bombs and detonated beside bigger ships or in ports, where petroleum or gas storage areas could go up as well. They (manuals) even talk of using underwater scooters for suicide attacks."[5]

al-Qaeda had a naval manual describing how to turn LNG tankers into floating bombs

According to Dan Verton in his book *Black Ice: The Invisible Threat of Cyberterrorism* (2003), "al-Qaeda cells now operate with the assistance of large databases containing details of potential targets in the U.S. They use the Internet to collect intelligence on those targets, especially critical economic nodes, and modern software enables them to study structural weaknesses in facilities as well as predict the cascading failure effect of attacking certain systems."[6] al-Qaeda is a "goal-driven organization." This means that they take action toward an end goal of affecting the "future state of the world." al-Qaeda's ultimate goal is to establish "an Islamic caliphate," which will ultimately extend across the global Islamic community. The biggest obstacle to accomplishing this is the U.S. Therefore, in order to try to achieve this goal, al-Qaeda must first bring down the U.S.[7] With America's growing appetite for natural gas, LNG could potentially become one of al-Qaeda's targets.

The 2007 Rand study, entitled *Exploring Terrorist Targeting Preferences*, not unexpectedly, lists capability and motive as the two variables that can best predict the probability that al-Qaeda, or one of its affiliates, will select a target. It would be impossible for an attack to occur with only one variable. In other words, al-Qaeda must first have a motive. Once a motive is established, the group must then possess the capability to carry out its selected mission. Without capability, the attack cannot occur, at least not successfully. Capability includes financial backing, technology, flexibility in movement, physical access to target or target area, ability to penetrate security of a target or target area, ability to conduct reconnaissance and planning, external links to sources of information/weapons/technology, and sophistication of media.

The Rand study broke down al-Qaeda's motivational factors into four plausible groups. These four factors are *coerce*, *damage*, *rally* and *franchise* operations.

Coerce: al-Qaeda's desire is to "coerce" the U.S. and its Western allies toward a specific goal by causing pain, most likely through casualties. A successful attack on LNG has the potential to be deadly.

Damage: al-Qaeda's desire is to reduce the ability of the U.S. to intervene in the Islamic world. This would likely be accomplished by somehow damaging the economy. Under the damage hypothesis, al-Qaeda has already repeatedly demonstrated the desire to try to cripple the U.S. economy through both its propagations (i.e.: its call to attack oil and gas sources to "strangle the U.S. economy") and through a pattern of historical terrorist acts, both successful and unsuccessful, many of which affected the economy to some degree. While the bombing of the World Trade Center was clearly motivated by a desire to take as many lives as possible, it also had a strong impact on the economy.[8] An attack on LNG would also have an impact on the economy. The extent of that impact would depend upon the extent of the damage, coupled with the human-emotion factor, discussed a little later.

Rally: al-Qaeda's desire is to rally support in the Muslim world. Under the rally hypothesis, hard targets symbolize

U.S. strength and are the most difficult targets to penetrate. Three of the 14 terrorist attacks analyzed by Rand were hard targets. "By striking and destroying them, al-Qaeda has been able to underscore its credentials as a meaningful force, establishing a benchmark of power that it has then used to build morale among existing members and attract new recruits."[9] Indeed, al-Qaeda tends to hit soft targets more frequently than hard targets. However, it has already proven it is willing to hit hard targets. With the numerous security measures implemented in every LNG shipment, LNG terminals and tankers are extremely hard targets. The added publicity surrounding LNG terminals in the U.S. could potentially draw increased appeal to them as targets for terrorist groups hoping to send out a strong message on their strength and potential, which could lure more support.

Franchise: al-Qaeda might not possess the means or capability to carry out a particular terrorist act and, therefore, a like-minded terrorist group might assume the task instead. Under the franchise hypothesis, since 9/11 and the global war on terrorism (GWOT), the U.S. has managed to destroy much of al-Qaeda's infrastructure in Afghanistan. However, some analysts believe that rather than destroying bin Laden's movement, the GWOT has actually "given rise to new, less predictable organizations composed of dozens of like-minded extremists." If al-Qaeda is unable to execute an attack on LNG, perhaps a lesser known extremist group would step in unexpectedly.

The Rand study found that the majority of terrorist acts committed fell under at least two categories of the above hypotheses. For example, the 1993 bombing of the World Trade Center, in which a car bomb was detonated in the underground parking garage, killing six people, and injuring 1,042, falls under the categories of *coercion* and *damage*. This attack was meant to cause mass casualties while also impacting the economy. 9/11 falls under three categories – coerce, damage and rally. It caused mass casualties, impacted the economy and rallied support in the Muslim world. A well executed attack on the U.S. LNG infrastructure would fall under three categories or even potentially under all four categories.

The most controversial LNG terminal in the U.S. is the Suez Energy North America's Everett LNG terminal in Everett, Massachusetts. The location of this terminal makes it an ideal candidate for a terrorist attack under the *coerce* hypothesis. Almost weekly, LNG tankers have to pass within several hundred yards of the crowded Boston waterfront, past the end of the Logan International Airport runway and under a busy bridge. Immediately after 9/11, Richard Clarke, who was then the White House counterterrorism chief, prompted the U.S. Coast Guard to close Boston Harbor to all LNG tankers. LNG shipments resumed several weeks later after a federal judge ruled there was no evidence of a credible threat.[10] However, these LNG operations started back up under much heavier security.

The rest of the world does not seem to share the same security and safety concerns as Americans regarding LNG. This could be a potential problem. Acting on these concerns, the U.S. has strict security measures in place. Meanwhile, in other areas of the world security is severely lacking, leaving massive tankers floating as easy targets. An attack could occur anywhere. One key location would be in Southeast Asia. Since 9/11, analysts have often pointed to the vulnerabilities of the Strait of Malacca. The Strait of Malacca is approximately 600 miles long, but only 1.5 miles at its narrowest point. Furthermore, it is the busiest chokepoint in the world. In 2006, more than 65,600 ships sailed through it.[11] An attack on an LNG tanker in the narrowest part of the strait would put a serious delay on the traffic traversing through. This could have a significant impact on the world's economy, which is heavily dependent on commerce traversing the strait. At least a dozen LNG tankers pass through the Strait every day.[12] Catherine Zara Raymond, of the Jamestown Foundation, described a number of potential scenarios that could occur in Southeast Asia involving maritime terrorism.[13] Citing concern by Singapore's Foreign Minister George Yeo in a speech to the ASEAN Regional Forum in July 2005, Raymond suggested that terrorists could highjack an LNG tanker and blow it up in Singapore harbor. Yeo described the potential impact of such a scenario as severe. According to Raymond, terrorists would most likely try to create an explosion onboard an LNG tanker by ramming a smaller vessel into the LNG tanker. This could rupture the hull and cause the gas to escape. However, experts point out that the fire would likely be contained at the site where of the leak, burning the fuel off as it escapes and therefore might not be as deadly, as would be the case if a vapor cloud were allowed to form and then ignited.

When assessing the probability of a terrorist attack against LNG infrastructure based on the Rand Study, it is important to remember that these are simply a series of hypotheses based on an intense analytical study of previous terrorist attacks not related to LNG. It is not a scientific study but it might provide some indication of the probability of a terrorist attack against LNG. The fact that LNG fits well into each hypothesis would seem to increase its potential as a target.

Vulnerabilities

A number of known vulnerabilities exist within the LNG industry. These vulnerabilities lie in the human factor. In other words, LNG ships and tankers are structurally sound. The only potential for problems lie within the people who are somehow involved in the industry.

Inadequate vetting of crews: LNG shipments often originate from politically unstable and unfriendly countries and regions. Some of the locations in which LNG originates include Qatar, Nigeria, Algeria and Egypt. "It's the location of the ports and where the LNG is loaded and who gets on the vessel" that is important, said William Doyle, Deputy General Counsel of the Marine Engineers' Beneficial Association (MEBA).[14] Many ships operate under grossly unregulated "open registry" or "flags of convenience" registries and often originate from ports with poor security systems in place. Due to a lack of any meaningful international regulatory oversight, it would be possible for someone to work under a different identity on board one of these tankers and avoid detection. Under the current system, no uniform, completely trustworthy system is in place for vetting foreign mariners.[15] Background checks are conducted on Americans by the Coast Guard and the Transportation Security Administration (TSA). However, these same background checks are not performed on foreign crews. The Coast Guard does, on the other hand, require crew lists from all vessels entering U.S. ports. Unfortunately, no method is in place to ensure these crews are who they claim to be. Although this is an issue of security for all cargo ships, it is even more critical for ships carrying potentially dangerous cargo, such as LNG.

In a testimony to Congress, Ron Davis, President of MEBA, listed a number of differences between U.S. and foreign mariners, saying, "U.S. merchant marines receive their credentials to work from the Coast Guard. Foreign mariners do not. U.S. mariners undergo extensive background checks through the FBI. Foreign mariners do not. U.S. mariners are vetted through the national driver record database. Foreign seafarers are not. U.S. mariners will be subject to terrorism background checks through the TSA. Foreign Seafarers are not. Finally, U.S. merchant mariners are U.S. citizens or persons lawfully admitted for permanent residency. The mariners who crew these ships are not."[16] As a result, it is impossible to be certain that a mariner is who he claims to be or that he is not a security risk. Davis said that there were practically no Americans employed on LNG ships today. At the top of MEBA's list of threats to an LNG tanker is the possibility that a knowledgeable crewmember could deliberately sabotage the vessel. According to Davis, "The most vulnerable (thing) that you have on the ship is the crew. It is the crew that controls the ship... One or two engineers down in the engine room can take control of the ship, can control the steering of the ship, can control the speed of the ship, can have the ship going 20 knots up the Houston ship channel or in the New York Harbor or in places of confined areas. They can ram the ship anywhere they want." Davis stated that terrorists might one day intentionally ram an LNG ship into a strategic target such as one fully loaded with a highly flammable, explosive material onboard.[17] Or, as William Doyle said, two or three terrorists infiltrating an LNG tanker could cause serious damage by one taking control of the ship and the other(s) detonating an onboard explosion as the tanker enters a busy harbor.[18]

Terrorists could attack an LNG tanker as well as they could any cargo ship. In a 2004 edition of *Jane's Terrorism and Security Monitor*, Jane's reported that the type of attack widely envisaged, based on analyses of compromised terrorist preparations, would include "an explosion onboard a cargo ship laden with fuel oil and ammonium nitrate fertilizer, in effect turning the vessel into a waterborne fireball." [19] Should a terrorist somehow manage to get onboard a LNG tanker and cause an explosion, it might be possible to cause a boiling-liquid-expanding-vapor-explosion (BLEVE). A BLEVE might be possible in some instances if the LNG is heated to above its boiling point while still contained within the tank. This rapid heating could cause a percentage of the LNG within the tank to "flash" into a vapor state almost instantaneously. This would cause pressure in the tank to rapidly build up. While LNG tanks do have massive pressure relief valves in place, if these valves were to fail in their ability to release the gas quickly enough or altogether, the pressure in the tank might create a type of explosion that would send dangerous debris flying. Most experts agree that LNG tankers are built to prevent such an event from occurring. One expert polled during the GAO study, Dr. Robin Pitblado from Det Norske Veritas, however, pointed out that a BLEVE might be possible on a Moss spherical tank because these tanks are constructed such that pressure could build up within them.[20] Skepticism exists within the industry regarding Pitblado's claim. Captain Scott Conway who has served eight years onboard LNG tankers and who is intimately familiar with the construction of the Moss spherical tanker, views Pitblado's scenario as unrealistic, questioning his conclusions by asking, "Where is the BLEVE going to occur in this tank? Where are you going to direct the flames back at this tank to heat up the liquid? How are you going to build up the pressure so that it overcomes the safety release? When you can explain this all logically as per the ship's construction, then we'll talk seriously."

Source: Moss Maritime Website

Inadequate security measures for U.S. facilities: During a hearing in the United States House of Representatives on 21 March 2007, Jim Wells of the GAO raised doubt that the Coast Guard can marshal the resources needed to meet its responsibilities[21] While it took 40 years to build the fleet of LNG carriers to 200 tankers worldwide, it will take less than four more years for that number to grow to 300. This rapid growth rate coupled with the anticipated growth rate of LNG imports into the U.S. presents a real security challenge. The U.S. faces today potential lack of security measures and resources to protect these new assets.

Shortage of qualified mariners & U.S. officers: The rapid growth of LNG does not affect only the ability to safeguard each ship; it also affects the quality of mariners working onboard these vessels. Due to the nature of LNG, highly skilled and trustworthy individuals are required to ensure its safe transport. Currently, LNG tankers have crews consisting of mostly foreigners. Yea Byeon-Deok, professor and LNG initiative coordinator of the International Association of Maritime Universities said, during a conference in Australia, "Many sub-standard vessels have begun to appear as demand for LNG increases, while there is a chronic shortage of experienced crew."[22] Because of sudden rapid growth in the industry, many experts question whether or not there will be enough qualified mariners to crew these vessels. Nearly 1,500 senior officers and 750 senior engineers will be required to man the 100 new LNG ships. Approximately 80 percent of these ships will be fitted with steam turbines, which require engineers with steam experience, which, according to one report, is a "vanishing resource." [23] The fact that many senior LNG officers are due to retire soon, and new, highly skilled mariners will be required to replace them exacerbates the situation. It will be tough enough just to replace crew and officers who are retiring, making these shortages of crew members and officers reach crisis proportions.[24]

The Society of International Gas Tanker and Terminal Operators LTD (SIGTTO) has recognized the acute shortage. "A short-term answer for an LNG vessel operator is to 'poach' its crew from another such operator but, clearly, the long-term answer is training, training, and further training. SIGTTO members, as much as anyone, wish for the quite unique safety record of LNG shipping to be preserved. The influx of new personnel into the industry is of concern, especially if there is a temptation by a minority of operators to 'cut corners' and put officers into positions of responsibility on a LNG carrier before they have been properly trained."[25]

The U.S. Maritime Administrator has been striving to increase the number of U.S. mariners employed on these tankers. U.S. officers go through a rigid qualifications process to ensure they become highly skilled. Meanwhile, the U.S. has no control over the quality of foreign officers. According to H. Keith Lesnik, Director of the Office of Deepwater Port Licensing, officials are pushing to bring more U.S. officers onboard LNG tankers. So far, four shipping companies have already agreed to do this. Under the Deep Water Port Act, the Administrator has to allow these ships access to the port facilities, whether they have U.S. mariners onboard or not. In an effort to try to influence companies not wishing to comply with the manning request, the Maritime Administrator offers priority processing to companies agreeing to the manning requirement. The priority allows these ships to be moved to the front of the line for the license application process.

No U.S.-Flagged LNG Vessels: Up until 2001, there were U.S.-flagged LNG tankers. Since 2001, however, not a single U.S.-flagged LNG tanker exists.

The reason for this is purely economic. It is more costly to register a ship in the U.S. than in a foreign country because a U.S.-flagged vessel is required to employ Americans, which is more expensive, and also pay higher taxes and fees. Additionally, running a U.S.-flagged vessel entails much more stringent requirements because it falls under the U.S. Code of Regulations. These U.S. regulations require more rigid crew training and more stringent licensing standards on crew documents. All these factors drive up the costs of running the ships. The real benefit for a ship to carry a U.S. flag would be so that it can carry cargo from state to state within the U.S. and it can carry U.S. military cargo from U.S. bases to overseas bases. Neither of these advantages serves as a motivator to LNG trading companies because neither is necessary in an LNG operation. The flag flown has no bearing on the ship's operator. Registering a ship is a fairly easy process. The International Transport Worker's Federation lists 28 countries as flag-of-convenience (FOC) countries. Registering a ship in an FOC country generally requires much less paperwork than do countries that have national registers. In some cases, such as Panama, registration can be done in just a few hours by fax. [26] The implications are that since requirements are much less stringent, security precautions and fleet training are most likely lacking.

Hijacking: A 2004 study conducted by the European Conference of Ministers of Transport jointly with the Organization for Economic Cooperation and Development (OECD), describes two scenarios involving terrorists striking at sea. In the first scenario, called the Trojan Horse scenario, terrorists develop legitimate trading identities that would allow them to ship and misuse "dangerous consignments." In the second scenario, the hijacking scenario, terrorists seize control of an entire vessel and its cargo to use it in a mass assault. According to *Janes Terrorism and Security Monitor,* the intelligence community feared that preparations for a major seaborne assault might already be in an advanced stage.[27] In March 2003, during the night, about a dozen heavily armed men boarded the chemical tanker *Dewi Madrim* off the coast of Sumatra. The hijackers proceeded to take over the ship. Experts believed that this might have been a training exercise because the pirates navigated the ship for an hour through the Strait of Malacca then kidnapped the captain and first mate without demanding a ransom. Some experts believed that the hijackers could have been terrorists practicing operation of a large vessel in the crowded shipping lanes. [28] According to an ABC News investigative report, fears in shipping and security circles were increasing with the notion that these armed terrorists, or ven pirates, could take control of a vessel carrying LNG and transform it into a floating bomb. Admiral Kevin Eldridge, who was the commander of the U.S. Coast Guard's 11th District in California, stated that an attack by ship on U.S. shores was "likely enough for us to put a lot of effort into the planning of it." Eldridge continued, "There aren't enough ships (and) there aren't enough planes for us to set up a picket line, so that we know what's coming." He continued, "We're pushing our borders out. Frankly, if we have a vessel in our port that has a problem, it's too late." [29] According to Captain Conway, physically it would be extremely difficult for pirates to successfully scale the 50-foot hull of an LNG vessel. However, according to Anne Korin, co-director of the Institute for the Analysis of Global Security (IAGS), acts of pirates hijacking a ship have been facilitated by planting an insider within the ship.

LNG: A Growing Economic Target?

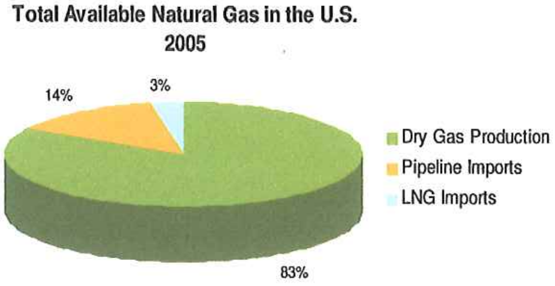
During the 21 March 2007 hearing, Congressman Bennie G. Thompson, of the second district of Mississippi, observed that although it is important to consider the dangers of LNG, it is equally important to try to assess the economic impacts that an LNG incident might incur. "...Terrorists would just as well like to keep a port out of business for a week or two and that would be an absolutely significant incident... So, I think part of our challenge is how we look at all the consequences associated with the handling of LNG. Clearly, we want to know the hazards initially, but we also want to look at economic conditions that relate to it."[30]

The variables that would affect the economic impact are too numerous to make such a predetermined calculation possible. Additionally, as time passes and the role of LNG grows worldwide, the potential impact of a terrorist attack on these tankers or terminals increases. According to the Energy Information Administration (EIA), LNG imports comprised only three percent of overall natural gas consumption in the U.S. in 2005. Energy analysts expect LNG imports into the U.S. to increase by 8.7 percent annually through 2030. Conversely, natural gas piped in from Canada, which is the number one source of imported natural gas to the U.S., is expected to decrease by 4.6 percent. At this rate, by 2030, approximately 17 percent of all natural gas required to meet U.S. consumption needs, will be supplied via LNG imports.

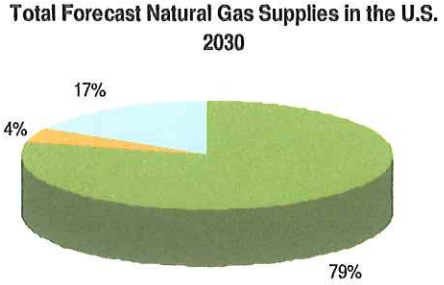
The 17 percent figure is merely an estimated EIA projection based on analysis of numerous trends and variables. The EIA came up with both a low and high LNG estimate forecast through 2030. Variables that contribute to the calculation of a "low LNG" estimate include obstacles, such the denial of construction on a proposed LNG terminal. A proposed LNG terminal in Mobile Bay, Alabama, for example, did not come to fruition due to its lack of citizen and local government support. Another variable is the discovery of new natural gas fields, which would increase the availability of natural gas imports via pipeline and potentially decrease the need for building new LNG terminals. Examples of variables that would contribute to a high LNG estimate include a shift in Canada's natural gas export to a different end-user, possible environmental factors putting a halt to certain domestic natural gas production, and the successful permitting and construction of LNG terminals in the U.S. As of March 2006, there were five LNG terminals operating in North America. These five terminals had a peak send-out capacity of 5.24 billion cubic feet per day. There were, however, 17 proposed LNG import terminals in North America that government regulators had already approved. If these terminals proceed through construction as planned, they will have the capacity to send out an estimated 24.2 billion cubic feet per day. In addition to these 17 approved terminals, various energy companies are proposing some 25 other LNG projects in Canada, the U.S. and Mexico. These 25 projects will have a send-out capacity of 27.75 billion cubic feet per day.[31] To offer a point of comparison, in 2006 the U.S. consumed an average of approximately 60 billion cubic feet of natural gas per day.

The EIA estimated that by 2030, LNG could make up as little as seven percent or as much as 33 percent of the total natural gas consumed in the U.S. [32] Should the use of LNG in the U.S. follow the trend that would lead to the "high LNG" scenario, or 33 percent, then it would be reasonable to say that the probability of a terrorist attack against LNG, for economic purposes, would increase due to its greater potential economic impact. In order to stress the importance of this, the author will take the high LNG scenario.

Some of the variables required to calculate the economic impact of an LNG disaster include time of year, weather conditions, location of storage unit(s) affected, natural gas prices, location of incident and perhaps most challenging, the human emotional factor. Emotion, whether positive or negative, can sway the stock market and affect global pricing of energy and the economy. It is impossible to measure anticipated human emotion. A small scale LNG leak could cause natural gas prices to spike temporarily before returning to normal. A large-scale leak or attack that leads to human-casualties could cause prices to spike severely and not return back to their original rates. Despite the unknown outcomes of human emotion, it is critical and cannot be omitted from any potential calculation.


Total Available Natural Gas in the U.S. 2005

So far, in non-terrorist related incidents, with pipelines making up a majority of natural gas transport, impacts have been easily reversed. In the case of the 2004 Skikda disaster in which an LNG related explosion killed 27 people in Algeria, state-owned Sonatrach was able to regain its footing, although there were a number of hurdles to overcome. Two days after the explosion occurred, the media reported that Algeria had lost nearly 25 percent of its export capacity. However, European customers said they were not expecting the outage to cause them problems.[33] Several days later, on 27 January, a Sonatrach official told World Gas Intelligence, "For our customers in Spain and Italy, filling supply gaps will not be a problem, as we can make up for the shortfall using the (Maghreb and Transmed) pipelines to Spain and Italy. Gaz de France, however, will be difficult." [34] LNG from Skikda accounted for approximately eight percent of France's total imports. According to a spokeswoman for Gaz de France, the company was looking at all measures it could take to offset the lost volume. [35] Finally, Gaz de France was able to turn to overland transport networks already in place from northern Europe to make up for the potential shortfall. Gaz de France maintains a diverse portfolio of suppliers from Norway, Algeria, Russia, the Netherlands, the United Kingdom, Nigeria and Egypt. [36] Shortly after the Skikda blast, stock prices shot up due to a fear factor in the market. These fears were compounded by the uncertainty over how much LNG production had been affected by the blast. Some people reportedly felt that the news had affected the winter 2004 prices at the Northern Border Stock Price (NBP). These prices did settle back fairly quickly, though.


Total Forecast Natural Gas Supplies in the U.S. 2030

In areas such as the East Coast, where the Everett terminal is located outside of Boston Harbor, LNG is critical to the energy makeup of the region. The Everett terminal is the only terminal in the U.S. that operates at 100 percent capacity 365 days a year. It represents approximately 25 to 30 percent of the base load natural gas brought into the

New England market everyday. This is due to demand outweighing available piped-in sources of natural gas. The other four remaining terminals operate at anywhere from 45 to 65 percent.[37] Therefore, an attack either on a tanker within the Boston Harbor or the Everett terminal itself would likely have a much greater economic impact.

As piped-in natural gas supplies become less abundant and U.S. consumption rates increase, were an LNG disaster to occur in the U.S., it would have an immediate impact. Natural gas serves over 64 million customers and provides around 24 percent of all energy consumed. Not only is this energy essential for home heating, it is also increasingly used toward power generation and serves as a major feedstock for the chemical industry. Every one of these sectors could be subject to price hikes, shortened productivity and even increased dependence on foreign trade, etc.

LNG holds appeal of increasing a nation's energy security because of its fungible nature, however it could also be damaging to energy security because of the vulnerability of the extensive infrastructure required to process it. Should terrorists somehow manage to damage or destroy this infrastructure, or the ports that lead to the processing plants, it would be detrimental to those regions which have become highly dependent on LNG.

Conclusions

The natural gas industry has an excellent safety record. However, the 9/11 attacks have changed the threat profile. If the U.S. is to continue increasing its appetite for natural gas, it will inevitably increase its imports of LNG because Canada cannot provide enough natural gas to meet U.S. future requirements. The key question, however, is whether or not the benefits outweigh the risks and even how big the risks truly are. The most inherent problem with LNG is that despite scientists, scholars, officials and academicians conducting various high-profile studies on the safety implications of LNG, too many unknown variables and unanswered questions still exist. Experts don't agree fully on safety boundaries. Empirical data demonstrating what would happen if there were to be an attack are virtually non-existent. Because of this uncertainty, members of the public remain adamantly opposed to bringing LNG with its foreign ships and crews into their "backyards," perhaps rightly so. More studies are needed to bring about sound conclusions and ensure the greatest possible degree of public safety, as well as to ensure the security of an important commodity.

Building a terminal offshore will certainly mitigate a possible attack, as will enhanced security measures. However, despite the myriad security measures in place, it would be difficult to thwart people willing to die to carry out an attack. Attacks such as 9/11 and the bombing of the *USS Cole* serve as reminders that "events" many industry officials consider improbable are still possible. In fact, some people would say that in hindsight, turning passenger airliners, fully loaded with fuel, into missiles and flying them into the World Trade Center and the Pentagon is indeed probable. While discussing a topic unrelated to LNG, Andrew Kohut, director of the Pew Research Center for the People and the Press, said, "I attended a lot of meetings, and one in February of 2001 with security experts on scenarios for asymmetric warfare, and there were only a minority of people there who thought that the United States could be endangered, seriously threatened by a non-nation state, actor or group."[38] Seven months later, the improbable became reality.

People within the LNG industry argue vehemently about the safety of LNG.

William Cooper, Executive Director for the Center of LNG said, "The added security features for the tankers coming into port are such that a successful attack on an LNG tanker is slim to none." Captain Scott Conway argues that LNG tankers are the safest tankers in the shipping industry. "There's no way I'd bring my wife or child on an oil tanker, for example. However, we didn't hesitate to bring our families on the LNG ships. That is how safe the ships were. They're very well made." After witnessing various experiments done on LNG and working closely with the liquid, Conway also views it as "an extremely safe, non-toxic, non-explosive cargo." [39] Despite these views, the debate continues, and as long as the uncertainties surrounding the safety of LNG remain unanswered, officials must continue to strive for maximum safety measures. The U.S. and other consumers of LNG should learn to manage and understand these risks in order to reach a solution that will best mitigate any possible incident. Anne Korin summed it up by saying, "We don't know what would happen because there hasn't been such an attack yet." The goal should be to place a large enough buffer between tankers (and terminals) "from any dense urban areas so as to minimize appeal of the target, which lies in its potential to provide a mass casualty incident." Finally, when it comes to LNG as an economic target, the best measure to mitigate this possibility is simply to ensure that appropriate measures are taken to keep dependency on LNG at a reasonable level.

NOTES

[1] "al Qaeda Calls For Attacks on U.S. Oil Sources," *Xinhuanet*, February 15, 2007.

[2] Laura Barnhardt, "Gas Plant Called No Terror Risk," *Baltimore Sun,* February 1, 2007.

[3] Ibid.

[4] "Maritime Security: Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification," United States Government Accountability Office, February 2007.

[5] Ed Blanche, "Tanker Terror: Gulf's Oil Routes Under Threat," *Jihad Watch,* April 22, 2004, http://www.jihadwatch.org/archives/001677.php, (April 26, 2007).

[6] Gabriel Weimann, "How Modern Terrorism Uses the Internet," United States Institute of Peace, March 2004, Special Report No. 116.

[7] Martin C. Libicki, Peter Chalk and Melanie Sisson, *Exploring Terrorist Targeting Preferences*, Rand Corporation, 2007, p. 5.

[8] According to the New York City Comptroller's Office in a preliminary report on, the economic impact of the attack on the World Trade Center was between $90 and $105 billion. Of this, $45 billion was attributed to capital losses while the rest was attributed to "continuing economic cost, including cleanup/rescue/security; business interruption; and lost rents and wages. Jobs displaced fell at over 100,000. "2003-04 Budget Analysis: Review of Economic and Revenue Forecasts," New York State Office of the State Comptroller, Office of Budget and Policy Analysis, March 2003, http://www.osc.state.ny.us/press/releases/mar03/revrept.pdf, (March 5, 2007).

[9] Martin C. Libicki, Peter Chalk and Melanie Sisson, "Exploring Terrorist Targeting Preferences," 63.

[10] Mark Clayton, "LNG: A Prized Energy Source, or Potent Terror Target?" *The Christian Science Monitor*, April 6, 2004.

[11] "Malaysia Urges Malacca Strait Users to Fund Littoral States," *People's Daily Online*, March 14, 2007, http://english.people.com.cn/200703/14/eng20070314_357246.html, April 26, 2007.

[12] Zachary Abuza, "Terrorism in Southeast Asia: Keeping Al-Qaeda at Bay," Jamestown Foundation, 6 May 2004, http://www.jamestown.org/terrorism/news/article.php?articleid=236669, April 25, 2007.

[13] Catherine Zara Raymond, "Maritime Terrorism in Southeast Asia: Potential Scenarios," Jamestown Foundation, *Terrorism Monitor,* April 6, 2006, Volume 4, Issue 7, http://www.jamestown.org/terrorism/news/article.php?issue_id=3679, April 25, 2007

[14] William Doyle and David Tubman, telephone interview, May 3, 2007.

[15] Testimony of the Marine Engineers' Beneficial (MEBA), Docket # 05-LNG-1, before the California Resources Agency, Secretary of State Office Auditorium, Sacramento, California, 1-2 Jun 2005, in cooperation with the California Energy Commission, posted at http://www.energy.ca.gov/lng_docket/documents/2005-06-01_workshop/comments/marine_eng_beneficial_assoc.pdf April 12, 2007.

[16] "Securing LNG Tankers to Protect the Homeland," United States House of Representatives, Committee on Homeland Security, 21 March 2007 http://hsc.house.gov/hearings/index.asp?ID=25

[17] Ibid

[18] William Doyle and David Tubman, May 3, 2007.

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[19] Thomas Orsz g-Land, "Less Convenient Maritime Flags," *Jane's Terrorism & Security Monitor*, June 7, 2004.

[20] "Maritime Security: Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification," 16.

[21] "Securing LNG Tankers to Protect the Homeland," United States House of Representatives, Committee on Homeland Security, a hearing on March 12, 2007.

[22] "Warning on LNG Shipping Standards," *Oil and Gas News Worldwide*, May 7, 2007

[23] "Serious LNG Crew Shortage Looms," Summary from *Oil and Gas Journal*, April 4, 2005, http://www.ogj.com/display_article/224811/94/ARCHI/none/none/Qatar,-India,-Egypt-advance-plans;-US-gulf-terminals-break-ground/, May 13, 2007.

[24] Ibid.

[25] SIGTTO News, September 2005, p.5.

[26] Paul Martin, "Flags of Convenience," CBC News Online, March 17, 2006, http://www.cbc.ca/news/background/martin_paul/flagsofconvenience.html, May 10, 2007.

[27] Thomas Orsz g-Land, June 7, 2004.

[28] Ibid.

[29] Charles Glass, "Officials Fear Terror on High Seas," *ABC News*, September 10, 2003 http://abcnews.go.com/WNT/story?id=129447 April 20, 2007.

[30] "Securing LNG Tankers to Protect the Homeland," United States House of Representatives, Committee on Homeland Security, a hearing on March 21, 2007.

[31] "North America LNG Import Terminals," Natural Gas Intelligence, March 2006, http://intelligencepress.com/features/lng/, March 6, 2007.

[32] *Annual Energy Outlook: 2007*, Energy Information Administration, February 2007.

[33] Lies Sahar, "Fatal Blast at Algerian LNG Plant Cuts Export Capacity by 25%," *Platt's Oilgram News*, January 21, 2004, p.1.

[34] "Sonatrach Manages, Just," *World Gas Intelligence*, January 27, 2004.

[35] "Algerian LNG Blast Kills 27, slashes exports," *Platts International Gas Report*, January 30, 2004, p.3.

[36] "Security of Supply: The Skikda Example," Gaz de France website.

[37] William Cooper, Telephone Interview, March 22, 2007.

[38] "Congress and the War," The Diane Rehm Show on National Public Radio Broadcast, April 30, 2007.

[39] Scott Conway, personal interview, May 21, 2007.

Exhibit 16

http://www.thememoryhole.org/energy/lng_security_distrigas.htm

THE MEMORY HOLE

rescuing knowledge. freeing information

Pulled Document:

LNG Security at Distrigas Facility

>>> The document below was unearthed through a state freedom of information request in Maine. The requesters asked the Governor's office for all documents pertaining to liquefied natural gas facilities. They received 29 documents [here]. Among them was this security review of the Distrigas Facility in Everett, Massachusetts. It used to be posted here, but that page now contains the following message:

> Not available. Removed per request of Department of Homeland Security 9/15/04

Thanks to reader CM, we were able to recover it from Google's cache. (*Note*: Although the document, as transcribed, refers to "Distigas," the actual name of the corporation is "Distrigas.")

REPORT OF FINDINGS
LNG SECURITY PROCEDURES
DISTIGAS NATURAL GAS STORAGE FACILITY
MYSTIC RIVER, EVERETT, MASSACHUSETTS

TABLE OF CONTENTS

REPORT OF FINDINGS
LNG SECURITY PROCEDURES
DISTIGAS NATURAL GAS STORAGE FACILITY
MYSTIC RIVER, EVERETT, MASSACHUSETTS

CONFIDENTIAL Draft

BACKGROUND

Liquefied Natural Gas, (LNG) is a product that is typically created by using a three-step manufacturing process. First, subterranean gaseous-form natural gas is cooled into a liquid state through a complex cryogenic process. The liquid gas is then taken to a facility at temperatures that are as low as 260 degrees Fahrenheit and at atmospheric pressure, where a process known as re-gasification is completed. The gaseous product is then transported via pipeline and sold to the market. The volatility of natural gas in the cooled liquid form is much lower than in its gaseous state and it requires 1/600 the storage space. Tankers transporting LNG maintain the freezing temperature of the product through insulation, not refrigeration. The tankers are double hulled and are specially designed with redundant monitoring systems. LNG has been transported across the oceans for over 40 years with over 40,000 safe voyages covering 60 million miles with no reported significant accidents or safety problems in port or at sea. All of the tankers that deliver LNG to the Distigas Facility in Everett, Massachusetts originate in Trinidad.

After September 11, 2001 and the terrorist attacks in New York City, Washington D.C. and Pennsylvania, the risks involved with the transportation of Liquefied Natural Gas (LNG) caused the United States Coast Guard to modify its transportation plan of LNG to the Distigas Facility. The Captain of the Port of Boston, who is responsible for the safe maritime transportation of the product within his jurisdiction, mandated the modifications.

DISTIGAS TRANSPORTATION STRATEGY

INBOUND: The Distigas Facility in Everett, Massachusetts is located a short distance up the Mystic River from Boston Harbor, just under the Tobin Bridge. The proximity to a major metropolitan area as well as a major highway has influenced the strategy used by the agencies involved in the transportation security.

The United States Coast Guard (USCG) is the lead agency and controls the transport of a vessel in Boston Harbor. Upon notification of a delivery, the USCG notifies all the other agencies via an operational order, which delineates the time of delivery and also sequence of security activities. Each agency then notifies and deploys appropriate assets. The Massachusetts State Police Criminal Investigative Division deploys two undercover officers well in advance of the tanker's arrival to observe the docking site. These officers stay in position for 24 - 26 hours. In addition, eleven members of the Massachusetts State Police Dive Team inspect the wharf as well as a large section of the bottom of the river each time the tanker is to dock. The underwater inspection is done after the above - mentioned surveillance is set up. A Unified Command Post is set up at the USCG Station, Boston Group, several hours before the arrival of the tanker. The Command Post is made up of high-ranking members of the following agencies, USCG, Mass. SP, Boston PD, Environmental Police, and Boston Fire Department.

When the tanker reaches waters approximately two miles from the Harbor, five USCG vessels meet it and establish a 500-yard perimeter or "bubble" around it. The two forward vessels are equipped to ram an offending vessel if needed but are charged with herding suspect vessels away from the hull of the tanker. The two aft USCG vessels are equipped with heavy weaponry and are charged with dismantling a suspect vessel if the forward USCG vessels fail to stop the advance. The fifth USCG vessel is the command vessel (OTC) from where all decisions regarding the security of the transport are made. This vessel is free to move wherever it needs to but generally stays aft of the transport tanker.

Another security "bubble" or perimeter is established at the 1000-yard mark, from the transport tanker. This 1000-yard bubble is comprised of, four Mass. State Police boats (two forward and two aft), one Boston PD boat to the port side, and one Environmental Police boat on the starboard side. These vessels will approach a suspect vessel and attempt to "chase" it from the area. These vessels operate under existing rules of engagement with respect to the use of deadly force previously established by their respective agencies.

In addition to water assets, the Massachusetts State Police has the responsibility to shut down traffic on the Tobin Bridge while the tanker is in close proximity to it. A State Police Helicopter hovers and provides observation from the time the tanker is met outside the Harbor until it is docked. Boston Police Department has the responsibility of closing all adjacent roads and wharfs that lead to the Harbor. There are police units stationed at each of these access points from the time the tanker enters the Harbor to the time it docks, approximately two hours. Boston Police Department estimates that it ties up 20 - 30 members per trip

(Inbound/Outbound).

Boston Fire Department devotes one person to the Unified Command Post but stays at normal operating levels. If there is an incident, Boston Fire has a mutual aid pact with the adjacent towns. The fire departments involved would call for every available asset and would use water and foam to put out the fire.

WHILE DOCKED Security measures fall to the Distigas Facility private security firm the Everett Fire Department as well as the Everett Police Department. Five members of the Everett Police Department maintain a visible presence while the tanker is in port and unloading. The typical offload takes 24 hours or so.

OUTBOUND On the outbound trip, the USCG OTC boat (aft) and one State Police boat (foreword) maintain the 1000-yard perimeter while three USCG boats maintain the 500- yard reaction zone. Additionally, traffic on the Tobin Bridge is reduced to center lanes only, but not stopped. Access points are controlled by Boston Police Department, similar to the inbound passage.

DISTIGAS FACILITY

According to Mark Swordinski, the Manager of the Distigas Facility, the tanker is most vulnerable during the transit through Boston Harbor. The potential for harm is the greatest at that stage due to the fact that a tanker holds 33 million gallons of product, is nearly 1000 feet long and is traveling in a channel that is approximately 1200 feet from shore to shore. Once the product is on the grounds of the facility, it is stored in two vertical towers with a total storage capacity of 42 million gallons. The facility has a maximum production capacity of 1 billion cubic feet of gas per day. The site sits on 35 acres and is surrounded by other industrial facilities, with no security buffer between.

The Distigas Facility pays $3.0 million dollars a year in taxes to the Town of Everett, in addition to the expenses mentioned below.

PHYSICAL SECURITY: The Distigas Facility has perimeter security fencing that surrounds the entire facility and is monitored by video cameras. The facility is going to implement a closed circuit TV system in the next few months to enhance the remote surveillance of the fence line. Entry and exit into the faclity is limited to fixed positions and each access point is protected with crash rated vehicle barriers as well as jersey barriers. The facility is also installing scanning technology at each point of entry that will be mounted in the ground that will be integrated with the gate. The scanner is so sophisticated that it has the ability to detect changes in a vehicle's appearance over time and will prevent access if certain parameters are met. The two storage tanks are situated in a secure location on top of a berm and are monitored by video cameras. According to Mr. Swordinski, the most important system for an LNG facility is an intrusion detection system that will sound an alarm in the event that there is a fence line breach. The Distigas Facility is currently looking to install one of these systems. The facility uses the Federal Code of Regulations as a guide for physical security needs but added that they go way above what is required by either the CFR or the USCG M.T. S.A. regulations. Since September 11, the Distigas Facility has spent $1.5 million in physical security upgrades.

SECURITY PERSONNEL: The Distigas Facility contracts for security services from GUARDSMARK, a private firm. The base line compliment is 9 full time guards and one full time supervisor. Neither the supervisor, nor the guard force is armed at any time. The security force mans the entry points and completes regular security checks pursuant to CFR regulations. When a tanker is docked, the security element increases to 12 full time guards and one supervisor as well as five armed Everett Police Officers. These personnel remain on site until the tanker leaves. In addition, The Facility has direct radio communications with the Police Department. The Distigas contract with GUARDSMARK is $1.2 million a year. The Distigas Facility has paid the Everett Police Department $1.0 million since Sept. 11, 2001 for the five officers detailed per tanker.

FIRE SUPPRESSION: The Distigas Facility has a dual loop fire control system installed at the dock, which has a 6000-pound dry chemical storage capability as well as 3000 gallon a minute salt water pumping capacity. The Facility also has fire suppression equipment in close proximity to the storage towers. In addition, while a ship is at the dock unloading, a fire truck and crew of four is detailed from the Everett Fire Department until the tanker leaves. The Distigas Facility has paid $750,000 since Sept. 11 for the services of the Everett Fire Department.

SUMMARY OF DISTIGAS SECURITY EXPENSES

Physical Security Upgrades Post 9/11	$1.5 Million
Private Security - Guardsmark	$1.0 Million / r
Everett Police Department Post 9/11	$1.0 Million
Everett Fire Department Post 9/11	$750,000

TRANSPORT SECURITY COSTS / SUSPICIOUS ACTIVITY

The Distigas Facility has received 102 inbound deliveries since 10/29/O1, making the total trips 204. The Facility expects to increase the trips to 68 inbound per calendar year, 1 trip every six days, starting very soon due to an increased demand for the product.

To date, the Massachusetts State Police Criminal Division has logged 40 - 50 reports of suspicious persons and/or incidents. These situations include foreign nationals taking pictures of the tanker, security detail and the Tobin Bridge. Foreign nationals have also been seen taking pictures of the container yard, which is at the mouth of Boston Harbor. The State Police only handles complaints that it receives directly and they have no information of additional complaints reported to USCG, the FBI or Boston Police Department.

Although it fluctuates, the financial impact on the Massachusetts State Police has been astronomical. The overtime costs associated with the trips since October 2001 is 1.2 million dollars. This figure does not include operational costs associated with the State Police assets involved. Specifically, the average number of overtime hours per LNG delivery = 231.14 hours at an average cost of $11,960.55 per trip (these figures are for the Massachusetts State Police only // average OT rate for FY 03 04 is $52.50 per hour). Boston Police Department uses existing personnel for their part to defray some of the costs, however specific figures are unavailable at this time.

Distigas is currently negotiating with the State of Massachusetts regarding compensation for State Police assets used for security. Distigas has agreed in principle to compensate the State for a percentage of these services.

PUBLIC SAFETY THREAT DISTIGAS FACILITY

After September 11, Lloyds of London, Shipping Division, inspected the tankers used to transport LNG to the Distigas Facility at the request of the Federal Government in the interest of assessing the realistic threat of a hull breach. Distigas has been told, as a result of this inspection, that to cause the hull a catastrophic failure, the equivalent force caused from an anti-ship missile would be required. An RPG or shoulder fired rocket may be successful in breaching the exterior hull, but it would not be successful in igniting any product. An anti-ship missile is so large that it would have to be moved on a trailer. In the event of a hull breach, the product will burn at an incredibly high temperature.

Representatives from the Boston Fire Department, Massachusetts State Police as well as the United States Coast Guard were asked their impressions with respect to the realistic threat to public safety. All three of the agencies had an understanding that the likelihood of a hull breach was unlikely, however; they did report that the threat from fire is their primary concern. They advised that LNG burns at an extremely high temperature and if left unchecked will cause the hull of the tanker or the structure of Tobin Bridge, to melt. If an impact large enough to puncture the hull were possible, the impression is that the product would pour out in liquid form, most likely freezing everything around it. If a secondary ignition source was present , however, the LNG could ignite and would burn.

They advised further that if the product were in its gaseous form and/or a large amount of fumes were present with an ignition source an explosion could result. A member of the State Police Dive Team told me that they have been advised by Federal Explosive Ordinates Officials that the amount of explosive necessary to rupture the hull of the ship from an underwater detonation would be approximately the size of a small passenger car.

A fire of the size that is possible from the 33 million gallons of product on board a tanker would be a significant risk to the metropolitan area around the Harbor. Of greater concern, according to the representatives that we spoke to, is the possibility that the hull could be ruptured and then the tanker would sink to the seafloor. The commercial flow of traffic through the Harbor would be obstructed which would have a devastating financial impact. In addition, the environmental impact from such a sinking as well as the logistical challenge of removing the hull would be immense. Boston Fire Department reported that they are trying to upgrade their fire boat to increase their pumping capacity. The Department feels that their current capacity is not adequate.

SECURITY EFFECTIVENESS

Several members of the Massachusetts State Police were asked about their comfort level with the current security protocols in regard to the effectiveness of threat mitigation. The opinion voiced was that it is impossible to know specifically what deterrent effect the protocols have had. However, what can be said conclusively is that there have been no incidents of terrorism or other mishaps since the protocols were put in place. When asked about the effectiveness of the two undercover officers who provide surveillance of the wharf, a representative stated that no one dared to pull the officers off the detail.

When asked about emergency evacuation procedures and plans, the collective understanding was that emergency evacuation of the greater metropolitan area would be conducted pursuant to existing plans. The lead agency would be M.E.M.A. and each agency has an established role in the overall plan developed by M.E.M.A.

From the perspective of the Distigas Facility, according to Mark Swordinski, the current transportation security protocol is prudent and effective with the exception of the shutdown of access points to Boston Harbor by Boston Police Department and the shutdown of the Tobin Bridge. Mr. Swordinski feels that these measures are an unnecessary inconvenience to the public. With respect to the access points, Mr. Swordinski feels that the relative size of required explosive is so large that normal law enforcement operations would probably notice it and, therefore, the shut down of the Harbor access points is unnecessary. Additionally, Mr. Swordinski does not see the utility of shutting down the Tobin Bridge.

Mr. Swordinski reported that since September 11, 2001, there have been NO suspicious incidents or persons located at their facility. Mr Swordinski feels that the facility is secure.

FAIRWINDS PROJECT DESCRIPTION HARPSWELL

The "Fairwinds" proposal calls for a re-gasification facility with an initial terminal design capable of processing 500 million cubic feet of gas per day. The facility would sit on approximately 70 acres of land and LNG tankers would arrive every four to nine days. LNG would be stored in two towers, each tower would be 120 feet tall and 240 feet in diameter. The facility would be one of five re-gasification facilities in the United States, the closest being in Everett, Massachusetts. The terminal will be designed to receive tankers that can carry up to 200,000 cubic meters of product. The Fairwinds Project would be a direct competitor to Distigas, as they would be supplying the same market.

The economic impact projected for the immediate area as a result of the $350 million dollar Fairwinds project is as follows:

CONSTRUCTION PHASE

900 construction jobs during the three years of construction
$500,000 / yr into a community investment fund
$6 million dollars / yr lease and property tax payments

OPERATION PHASE

50 high skilled jobs to support operation

50 acres of shore land donated to the Town of Harpswell for recreational use, $3.0 million allocated for this purpose.
$12 - 13 million / yr in corporate, personal income and sales tax
$3 5 million / yr direct and indirect spending
490 indirect jobs

PROJECT TIMELINE:

Sept. 18 -Dec. 16: Information dissemination and public meetings
Mid-December: Town Vote on project approval
2004-2005: Federal and State permitting process
2006-2009: Project construction
2009: Project startup

FACILITY COMPARISON

Acreage
Distigas 35
Fairwinds 70*
Storage capacity
Distigas 42 million gallons
Fairwinds
Storage tanks
Distigas 2
Fairwinds 2*
Daily production capacity
Distigas 1 billion cubic feet
Fairwinds 500 million cubic feet*
Full time employees needed for operation
Distigas 49
Fairwinds 50*
On site security - non-delivery
Distigas 10 (1 supervisor)
Fairwinds n/a
On site security - delivery
Distigas 12 (1 supervisor) plus 5 armed Everett Police
Fairwinds
Delivery Schedule
Distigas 1/seven days
Fairwinds 1 / four to nine days
Municipal Expenses
Distigas $3.0 million taxes/yr
Fairwinds $8.0 million lease fee / yr
* Indicates current projection from Fairwinds Publication*

PUBLIC SAFETY AGENCY IMPACT - FAIRWINDS

UNITED STATES COAST GUARD: The specific transportation security plan needed for the proposed site in Harpswell, and the subsequent state and local public safety agency involvement, will depend on the United States Coast Guard's recommendations. Lt. Ron Pigeon of the United States Coast Guard Marine Security Office, Portland, Maine said that specific decisions have not been made yet with respect to the operational plan. Lt. Pigeon did say that the 500 yard and 1000 yard perimeters are being heavily considered, as are other devices like protective booms at the facility. Lt. Pigeon said that it is impossible to assess the potential financial impact to state agencies at this point due to the fact that the composition of the perimeters has not been - established. Due to the locality and route of travel, it is possible that many fewer boats will be needed to maintain the perimeters than is seen in the Massachusetts model. In addition, the need for air assets may be reduced due to the locality involved in the projected site and the need for divers to check the site is still being considered.

Lt. Pigeon said that specific plans would not be developed until the site location is definite, schedule in place and travel routes established. Lt. Pigeon stated that according to what he has heard, the delivery schedule being proposed is nearly constant with a delivery coming every four days. Lt. Pigeon is not aware of what fire suppression infra structure exists in the Harpswell area but added that Federal Law would require the Facility to maintain this capability at an adequate level regardless of the Town.

When asked what state resources would be used to assist the USCG in the establishment of the safety perimeters during a transport, Lt. Pigeon stated that no decisions have been made, but added that the USCG is in the process of coming to an agreement with the Maine State Marine Patrol to provide law enforcement services in maritime security zones. Lt. Pigeon added that the proposed delivery schedule would require a long-term commitment on any agency with a part in the plan. Lt. Pigeon can he reached at the M. S-0. office in Portland at 780-3092.

MAINE MARINE PATROL: Major John Fetterman, of the Maine State Marine Patrol, is familiar with the Fairwinds proposal and has tried to assess the potential impact on the Marine Patrol. The impact is hard at this stage to assess with any degree of accuracy due to the fact that the USCG has not made any firm decisions regarding several issues. However, the Marine Patrol currently provides law enforcement services in security zones in an informal agreement with the USCG. It is from a review of these current operations that a preliminary assessment is possible.

According to Major Fetterman a formal memorandum of understanding between the two agencies has been proposed and is in the final stages of being adopted. The MOU is significant in that it provides a mechanism for the USCG to re-imburse the Maine Marine Patrol for services that it provides at the request of the USCG. In addition, the Marine Patrol would operate under USCG rules of engagement while operating in the security zones, at the request of the USCG. This MOU became possible due to a recent law change at the state level and is the first type agreement in the United States.

If the MOU were approved, it stands to reason that the Maine Marine Patrol will have a substantial role in the security apparatus needed for each tanker transport. In addition, Major Fetterman indicated that the USCG does not have ample resources for this type of operation currently in Maine and has been the norm with past operations, will ask that the Maine Marine Patrol to assist. Major Fetterman indicates that he feels that the rate of deliveries to the Fairwinds Facility would require a full time crew of Marine

Patrol personnel at the site. Major Fetterman felt that the Marine Patrol would need an increase of 12 men to handle the additional responsibilities. In addition, Major Fetterman indicated that the Marine Patrol would need three additional vessels added to the current fleet. The estimated cost on these three 27 foot Boston Whalers would be $1.0 million dollars. Major Fetterman indicated that his agency has always relied upon the Maine State Police Tactical Team to provide tactical services and he sees a role for the Tactical Team in this operation as well.

Major Fetterman is hopeful that the State of Maine will attempt an agreement with PhillipsConoco regarding re-imbursement for State assets / services.

MAINE STATE POLICE: Lt. Raymond A. Bessette, the Commander of the Maine State Police Dive Team, has indicated that if the Massachusetts model was adopted for the project in Harpswell, relative to dive operations, there would be a need for an increase in team membership. The current team is comprised of 7 State Police members and it costs approximately $5,000 to outfit each member. The number of divers on the team would have to be increased to support the delivery schedule. The size of increase needed will depend on site - specific information, such as current, dock position and size of security sweep area. This type of information will not be available until the site development process is further along.
Other entities of the Maine State Police such as the local Field Troop or the Tactical Team may be impacted but until an operation plan is developed, the extent of the impact is impossible to determine.

In addition, local agencies that provide environmental clean up/ monitoring, police, fire and emergency evacuation services would obviously be impacted as well and would have to assess the potential impact to their respective agencies.

FEDERAL REGULATIONS

Some of the relevant Federal Codes are summarized below:
The Code of Federal Regulations, Title 49, Volume 3, Part 193-Liquefied Natural Gas Facilities: Federal Safety Standards provides mandates with respect to facility construction, operation and safety procedures.

EMERGENCY PROCEDURES

Sec. 193.2509 Emergency Procedures deals with emergency procedures and it does mandate that the Facility:
l.) Respond to controllable emergencies, including notifying personnel and using equipment appropriate for handling the emergency.

Recognize an uncontrollable emergency and take action to minimize harm to the public and personnel, including prompt notification of appropriate local officials of the emergency and the possible need for evacuation of the public in the vicinity of the LNG plant.

Coordinate with appropriate local officials in preparation of an emergency evacuation plan, which sets forth the steps required to protect the public in the event of an emergency, including catastrophic failure of an LNG storage tank.

Cooperate with appropriate local officials in evacuations and emergencies requiring mutual assistance and keeping these officials advised of
i.) The LNG plant fire control equipment, its location, and the quantity of units located throughout the plant.
ii.) Potential hazards at the plant, including fires;
iii.) Communication and emergency control capabilities at the LNG plant

SECURITY PROVISIONS:

Sec. 193.2709 Security
Personnel having security duties must be qualified to perform their assigned duties by successful completion of the training required under Sec. 193.2715.

Sec. 193.2903 Security procedures.
Each operator shall prepare and follow one or more manuals of written procedures to provide security for each LNG plant. The procedures must be available at the plant in accordance with

Sec. 193.2017 and include at least:
(a) A description and schedule of security inspections and patrols performed in accordance with Sec. 193.2913;
(b) A list of security personnel positions or responsibilities utilized at the LNG plant;
(c) A brief description of the duties associated with each security personnel position or responsibility;
(d) Instructions for actions to be taken, including notification of other appropriate plant personnel and law enforcement officials, when there is any indication of an actual or attempted breach of security;
(e) Methods for determining which persons are allowed access to the LNG plant;
(f) Positive identification of all persons entering the plant and on the plant, including methods at least as effective as picture badges; and
(g) Liaison with local law enforcement officials to keep them informed about current security procedures under this section.

Sec. 193.2909 Security communications.

A means must be provided for:
(a) Prompt communications between personnel having supervisory security duties and law enforcement officials; and
(b) Direct communications between all on-duty personnel having security duties and all control rooms and control stations.

Sec. 193.2913 Security monitoring.
Each protective enclosure and the area around each facility listed in Sec. 193.2905(a) must be monitored for the presence of unauthorized persons. Monitoring must be by visual observation in accordance with the schedule in the security procedures under Sec. 193.2903(a) or by security warning systems that continuously transmit data to an attended location. At an LNG plant with less than 40,000 m3 (250,000 bbl) of storage capacity, only the protective enclosure must be monitored.

Sec. 193.2911 Security lighting.
Where security warning systems are not provided for security monitoring under Sec. 1932913, the area around the facilities listed under Sec. 193.2905(a) and each protective enclosure must be illuminated with a minimum in service lighting intensity of not less than 2.2 lux (0.2 ft) between sunset and sunrise.

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posted 06 Oct 2004

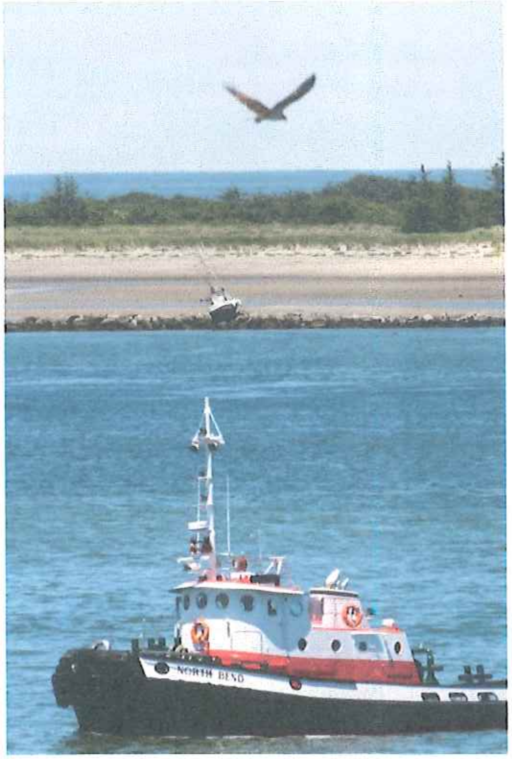
Exhibit 17

https://theworldlink.com/news/local/fishing-vessel-runs-aground-on-the-north-spit-after-losing/article_e90717d9-613b-5201-9823-bcec642599fa.html

Fishing Vessel runs aground on the North Spit after losing power

NICHOLAS A. JOHNSON - The World
Jun 21, 2018

The Princess Pacific tacks Thursday past the 28-foot commercial fishing vessel Kluane stranded on the North Spit since early Tuesday morning , The vessel lost power and drifted aground onto Cribs Jetty.
Photo by Ed Glazar – The World



COOS BAY — Around 5 a.m. Tuesday morning, a 28-foot commercial fishing vessel known as the Kluane lost power on its way out to sea and ran aground at low tide on the North Spit.

After the vessel lost power it drifted into a rocky area of the North Spit known as the Cribs Jetty. The tide going out caused the vessel to sustain significant hull damage and become stuck.

“The vessel apparently lost power and drifted up onto the rocks where it became lodged on the Cribs Jetty. The tide went out and it wasn’t able to get off of the rocks,” commanding officer at Coast Guard Station Coos Bay Kary Moss said.

A Coast Guard team from Astoria has already come down to clean up environmental concerns associated with the wreck.

“Sector Columbia River opened up a federal fund and contracted to have all of the diesel fuel, oils, and pollutants removed from the vessel so that there is no environmental hazard,” Moss said.

Shortly after the vessel became stuck the owner decided to wait until the next high tide to try and maneuver the boat free. However, the Coast Guard deemed that to be an unsafe operation.

“We asked him to get off the boat because we felt like it was an unsafe situation… He had a friend of his come and pick him up off the boat. We had a couple of our assets standing by in case we were needed,” Moss said.

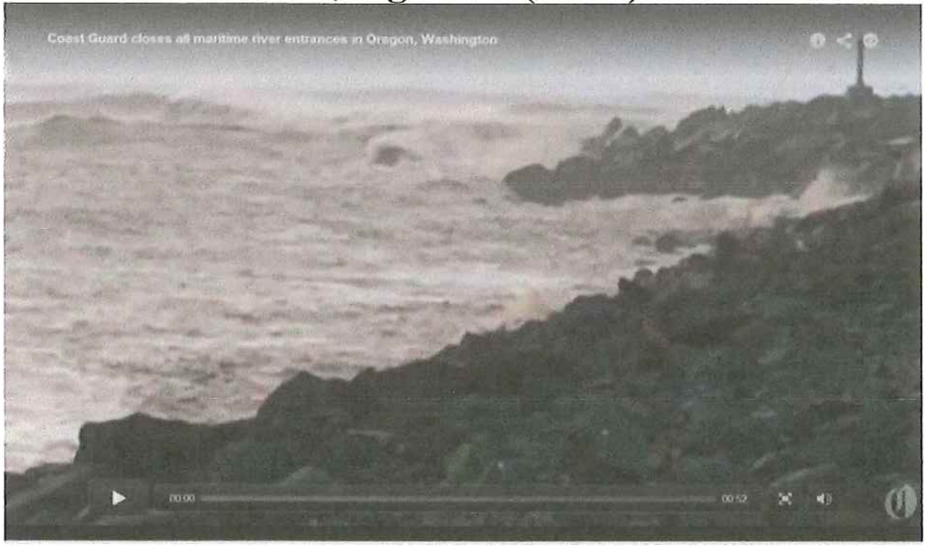
The Coast Guard does not remove vessels in these situations. It is up to the owner to have it removed.

“It’s up to the owner to submit an approved salvage plan to the captain of the port up in Columbia River, but I don’t know if that’s going to happen,” Moss said.

Exhibit 18

http://www.oregonlive.com/pacific-northwest-news/index.ssf/2015/12/coast_guard_closes_all_maritim.html

Coast Guard closes all maritime entrances in Oregon, Washington due to flood debris, high seas (video)



Coast Guard closes all maritime river entrances in Oregon, Washington. **Tillamook Bay was choked with storm runoff and debris this week. The color of the surf turned chocolate brown.**

By Stuart Tomlinson | The Oregonian/OregonLive
on December 11, 2015

The U.S. Coast Guard has shut down all maritime entrances in the Pacific Northwest due to high seas and the large amount of debris in the water from 5 days of heavy rain.

Officials said the Oregon ports closed to all traffic are the ports of Chetco River in Brookings; Coos Bay; the Umpqua River in Winchester Bay; the Siuslaw River in Florence; Yaquina Bay in Newport; Depoe Bay; Tillamook Bay in Garibaldi; and the Columbia River at Astoria.

The ports of Grays Harbor in Westport and the Quillayute River in LaPush are also closed.

"My job as a Captain of the Port is to ensure safety throughout the maritime infrastructure and part of that is to sometimes close the lanes of traffic that mariners use," said Capt. Dan Travers, commander Sector Columbia River and Captain of the Port for all ports in Oregon and Southwest Washington. "The storms that we all experienced over the last several days have made it dangerous for mariners to transit in and out of our many rivers due to severe sea conditions and debris."

On Wednesday at Tillamook Bay, the surf was chocolate brown and choked with floating debris. By Thursday, more powerful surf had pushed all that frothing debris back into the bay, replaced by high surf and blue water.

The Columbia River runs brown from silt and runoff after days of heavy rainfall in Astoria Friday. Heavy rains and flooding can cause excess debris to be washed into the river creating hazards to navigation for mariners in the area. *Petty Officer 3rd Class Jonathan Klingenberg*

"It's not rare at all to close the ports," said Coast Guard spokesman, Petty Officer 1st Class Levi Read. "The closures usually come with heavy sea conditions and the ships can't get out. The reason for this closure in addition to the heavy seas is because of the amount of the debris."

For updated river entrance observations and conditions visit the NOAA Western U.S. Bar Observation site.

Exhibit 19

https://theworldlink.com/lifestyles/food-and-cooking/dead-after-commercial-crabbing-vessel-capsizes-off-oregon/article_81b0bf8c-1e7c-51cb-a425-b25a96f39f45.html

3 dead after commercial crabbing vessel capsizes off Oregon

By GILLIAN FLACCUS Associated Press

Jan 10, 2019

A commercial crabbing boat capsized in rough waters off the Oregon Coast, killing the three men aboard. The U.S. Coast Guard said the vessel, the Mary B. II, overturned about 10 p.m. Tuesday as it crossed Yaquina Bay bar in Newport, Oregon. (Jan 10)

In this Jan 9, 2019 photo provided by the U.S. Coast Guard, a U.S. Coast Guard boat crew responds to three fishermen in the water after the commercial fishing vessel Mary B II capsized while crossing Yaquina Bay Bar off the coast of Newport, Ore. Authorities say three men were killed when their fishing boat capsized in rough waters off the Oregon coast. (U.S. Coast Guard via AP)

This Jan 9, 2019 photo provided by the Oregon State Police shows authorities in Newport, Ore examine the wreckage of the Mary B. II, a commercial crabbing vessel that capsized while crossing the Yaquina Bay Bar off the coast of Newport, Ore. Three crew members died in the accident. (Oregon State Police via AP)

PORTLAND, Ore. (AP) — A commercial crabbing boat capsized in rough waters off the Oregon coast, killing the three men aboard and sending a shock wave through a seafaring community already struggling from a monthlong delay to the annual crabbing season.

The U.S. Coast Guard said the vessel, the Mary B. II, overturned about 10 p.m. Tuesday as it crossed Yaquina Bay bar in Newport, Oregon. The bar is one of the most notorious off the Oregon coast, and authorities said crews faced 12- to 14-foot (3.6- to 4.2-meter) waves as they tried to rescue the fishermen.

The men had called for an escort across the bar and a responding Coast Guard boat was nearby when the crabbing boat capsized "without warning," the Coast Guard said Wednesday evening in a news release. The Coast Guard is investigating the incident.

James Lacey, 48, of South Toms River, New Jersey, was pulled from the ocean by helicopter and flown to a local hospital, where he was pronounced dead. The body of Joshua Porter, 50, of Toledo, Oregon, washed up on a beach early Wednesday.

The body of the boat's skipper, Stephen Biernacki, 50, of Barnegat Township, New Jersey, was found on the hull of the boat after it, too, washed up on a jetty.

The tragedy was nothing new for Newport, a working fishing port about 130 miles (210 kilometers) southwest of Portland on Oregon's central coast. The small town hosts a granite memorial at Yaquina Bay etched with more than 100 names of local fishermen lost at sea over the past century and shared tragedies are woven into the fabric of the community.

"It happens frequently enough that we actually have funds that help families during this time. We fundraise all year long, and we try to help them as much as we can," said Taunette Dixon, president of the nonprofit Newport Fishermen's Wives, which supports families who have lost a breadwinner to the waves.

But those in the industry said the loss hit particularly hard this year, when crabbers were rushing to sea to try to catch up after the annual Oregon Dungeness crab season was delayed more than a month. The season usually begins Dec. 1, but this year it only began last week because the crabs were too small and didn't have enough meat to harvest.

Then, a series of bad storms in the first week of the season prevented many crabbers from recovering their pots on Jan. 4, the first day they could do so, said Tim Novotny, spokesman for Oregon Dungeness Crab Commission.

"When they did get out, some of them had to stay out a little longer because of the weather. The difficulty is once you're out at sea, they can handle a lot of conditions. But the trouble is trying to get back across those bars," Novotny said.

A bar is an area near the coast where a river — in this case the Yaquina River — meets the sea. The force of the river water colliding with the ocean can create hazardous currents and swells, particularly during a storm. The Yaquina Bay bar is considered one of the more dangerous ones along the Oregon coast. On Wednesday, reports showed waves 16 feet (nearly 5 meters) tall there.

It's so treacherous that the dangers of crossing it with a fully loaded crab boat were the premise of a spin-off of the "The Deadliest Catch," a reality TV show about commercial fishermen that aired on the Discovery channel.

"The fishermen and their families know all too well, unfortunately . that that danger is real. They accept the challenge because they love what they do," Novotny said. "It's part of who they are and what they do."

The appeal also lies in the money that the succulent Dungeness crabs can bring.

Live Oregon Dungeness crabs are currently selling for anywhere between $5.99 a pound and $11.99 a pound, depending on location, and they are a staple of the holidays for many on the West Coast. The crabs are also fished in California and Washington.

Crabbing permits are capped at 424 vessels spread over six major ports running the length of the Oregon coast, from Astoria in the north to Brookings near the California border. Three-quarters of the harvest is brought in in the first eight weeks of the season, which usually runs from December to August.

The 10-year average haul for Dungeness crab in Oregon is 16 million pounds, but last year crabbers brought in 23 million pounds. That haul was worth more than $74 million at the docks and pumped $150 million into the state and local economy, Novotny said.

Follow Gillian Flaccus on Twitter at http://www.twitter.com/gflaccus https://www.cbsnews.com/news/dungeness-crab-fishing-boat-capsizes-yaquina-bay-3-dead-dungeon-cove-deadliest-catch/

Dungeness crab fishing boat capsizes in Oregon, killing 3

UPDATED ON: JANUARY 9, 2019 / 11:37 AM / CBS/AP

Newport, Ore. -- A commercial fishing boat capsized in rough waters off the Oregon coast, killing three men aboard. The U.S. Coast Guard said the vessel, the Mary B. II, overturned about 10 p.m. Tuesday as it crossed Yaquina Bay Bar in Newport, Oregon.

Authorities say crews faced 12- to 14-foot waves during the initial response as they tried to rescue the fishermen. The USCG Pacific Northwest posted an image of the rescue effort.
View image on Twitter

The perils of vessels catching crabs in the area are featured on the Discovery TV series "Deadliest Catch: Dungeon Cove." There were initial reports that the ship was featured in the show but a synopsis of episodes doesn't mention the boat.

The Coast Guard pulled one fisherman from the sea Tuesday, and the man later died. Authorities say a second body washed ashore after midnight and the third body was found on the hull of the boat.

Identities have not been released.

"We did everything we could. Unfortunately, it was just a tragic outcome and our hearts and thoughts are with the family and friends of the crew," said Petty Officer Levi Reed with the U.S. Coast Guard, according to CBS affiliate KPIC-TV.

Newport is about 130 miles southwest of Portland.

CBS affiliate KOIN-TV reports the coast will continue to see dangerous and choppy water through Wednesday night as wind gusts remain around 40 miles per hour for majority of the day.

Exhibit 20

http://thefacts.com/story.lasso?ewcd=f482d0ca682cb716

Coast Guard preparing for port shutdowns

By Hunter Sauls
The Facts

Published April 14, 2008

FREEPORT — It was evident as U.S. Coast Guard sailors prepped their 41-foot patrol boat that they've done it many times before.

Cruising out into the heart of Freeport's shipping arteries — the busy intersection of the Intracoastal Waterway and the jetty channel — the sailors are enjoying the calm before the storm. The first liquefied natural gas ship will soon cruise in and change life in the harbor for years to come.

Each time a ship crawls into the harbor, water-borne authorities like the Coast Guard will shut down all boat traffic in a 1,000-meter radius. Petty Officer Second Class Richard Ahlers said it probably will take up to three hours for the boat and its security perimeter to pass through in the first arrivals. As ship captains and Coast Guard sailors become more accustomed to the process, it will be quicker, he said.

"Once they start doing them more, it will take less time," Ahlers said.

Surfside Beach Mayor Jim Bedward said the village boat ramp, once it opens, will be closed as the ships pass. City Hall will get a 92-hour warning of the oncoming ships but will keep knowledge of the high-security vessels' arrival to themselves — for obvious reasons.

When the facility is at capacity, a ship will arrive every three to four days, Freeport LNG terminal manager Steven Arbelovsky said. But that kind of frequency is unlikely in the foreseeable future because LNG ships are going to greener pastures such as Asia, where the price of LNG is double what it is in the United States, Arbelovsky said.

"That's the way it looks right now," Arbelovsky said.

Regardless of the ships' timetables, Coast Guard sailors would appreciate every fisherman and recreational boater taking note of the new security zone around Freeport LNG. An invisible line now extends from a shoreline sign that reads "SECURITY ZONE KEEP OUT" to its counterpart on the other side of the site's channel entrance.

"There's the sign," Ahlers said as he pointed to the shore. Encroaching on the Freeport LNG waters could earn a hapless boater an unpleasant visit by armed sailors.

"This used to be a pretty popular fishing spot," Ahlers said as the patrol boat cruised past the towering blue pipes which will draw precious cargo into the site's tanks. "Not anymore."

Chief Warrant Officer Bee Perry, the commanding officer of the Coast Guard's Freeport Station, recognizes most boaters are just becoming aware of the new landscape on the water. He said his sailors have pulled over boaters on the wrong side of the invisible line and politely warned them of their error, giving them a map showing the locations of the area's three now-forbidden zones.

Petty Officer Second Class John Willis said he's looking forward to new blood at the Freeport Station, extra hands to carry the patrol load. He said they'll have heavier patrol shifts to watch the channel.

"We've been gearing up for this for some time," Willis said.

Hunter Sauls covers Freeport for The Facts. Contact him at (979) 237-0153.

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