SAND2014-xxxx

SAND2014-19517C

Exceptional service in the national interest

Sandia National Laboratories

LNG Use and Safety Concerns
(LNG export facility, refueling stations, marine/barge/ferry/rail/truck transport)

Tom Blanchat, Mike Hightower, Anay Luketa
Sandia National Laboratories

NARUC Commissioner Joint Meeting with LNG Working Group (CLOSED)

November 2014

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Introduction

- Review LNG transportation options/opportunities/scales of quantity
- Review hazards/consequences of:
  - pool fires
  - unignited dispersion events
  - ignited dispersion events
  - Boiling Liquid Expanding Vapor Explosion (BLEVE) events
- Strengths and weakness in knowledge base.

Relative Scale	gallons
LNG Ship	~6,000,000 - 66,000,000
Barge	~1,000,000 – 3,000,000
Refueling Station	~10,000 - 50,000
Rail - Tanker	~20,000 - 30,000
Rail - Tender	~20,000 - 30,000
Road - Trailer	~10,000
Isotainer	~10,000

DOE LNG Damage Program
Based on GAO Research Priorities

Research Priorities (High to Low)	Original Efforts (2000-2004)	Expanded Efforts (2007-2012)	Future Needs ?
Large fire phenomena		x	
Large scale spill testing		x	
Cascading damage testing		x	
Comprehensive modeling: interaction of physical processes		x	
Risk tolerability assessments	x		
Vulnerability of cargo tanks (hole sizes in large ships)	x		
Mitigation techniques		x	
Effects of water coming in as LNG flows out		x	
Impact of wind, environmental conditions, and waves		Did not address	?
Fireballs, Explosions, Boiling Liquid Expanding Vapor Explosion (BLEVE) during small scale transport			?

Hazards Depend on the Size and Location of LNG Transportation and Distribution

Sandia National Laboratories

Large Import and Storage Terminal

Ship Imports into Boston

Offshore Deep Water Regasification Port

10,000 gal Import Isotainer

10,000-50,000 gal Refueling Storage

10,000 gal Road Trailer

Emerging LNG Uses in Road Transportation

- Domestic natural gas LNG liquefaction capacity for highway applications, buses, tractor trailer rigs, etc. has doubled in the past 5 years

- UPS is establishing a fleet of 900 LNG-fueled tractor trailers rigs.

- Many commercial LNG fueling stations are being developed throughout the U.S. using domestic produced LNG.

- Pictured below – Los Angeles, CA – 15,000 gal LNG storage tanks (4)

LNG Locomotive Fuel and Rail Transport

Programs to evaluate LNG as a locomotive fuel are expanding throughout the rail industry, led by such stakeholders as GE Transportation, Electro-Motive Diesel, BNSF, Union Pacific, CN, Clean Energy Fuels, Chart Industries, Westport Innovations, Waste Management, Gaz Métro, and many others.

CN's current LNG development program, which began in 2012, uses two EMD 3,000hp SD40-2s equipped with modified 16-645E3 engines. The engines have been converted to LNG using available kits.

A 27,000-gallon LNG tender.

Europe's first LNG rail car prototype (~20,000 gal capacity) to be completed by the end of 2014.

LNG Marine Transport Options: Smaller-Scale Systems Are Likely

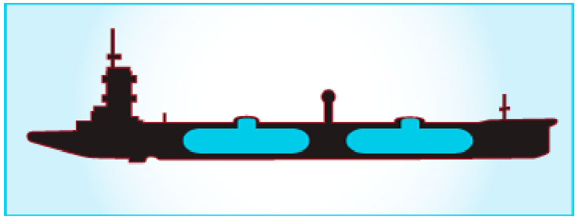
- 300 LNG ships in operation, 80 currently on order
  - 90% > 125,000 m^3 capacity
  - 5% > 50, 000 and < 125,000 m^3 capacity
  - 5% < 50,000 m^3 capacity

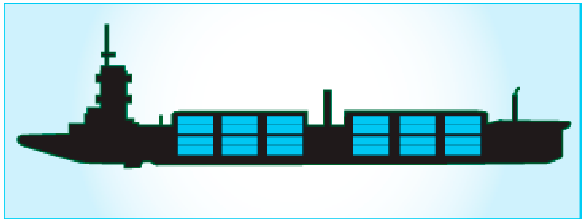
- LNG ships carry different volumes of natural gas with different hazards
  - 250,000 m^3 = 66,000,000 gallons = 5.4 BCF
  - 125,000 m^3 = 33,000,000 gallons = 2.7 BCF
  - 25,000 m^3 = 6,000,000 gallons = 0.5 BCF

Smaller LNG ships, LNG barges, and LNG isotainer vessels are likely in many smaller ports and intercoastal waterways, as natural gas applications expand.

LNG Marine Transport Options
Emerging Smaller-scale Systems

- Emerging LNG Articulated Tug/Barges
  - Bulk systems
    - 13 ,000 m^3 = 3,000,000 gallons = 0.25 BCF
    - 300 feet long
  - Isotainer systems
    - 144 - 10,000 gallons isotainers
    - Similar articulated tug and barge design, sizes, etc.

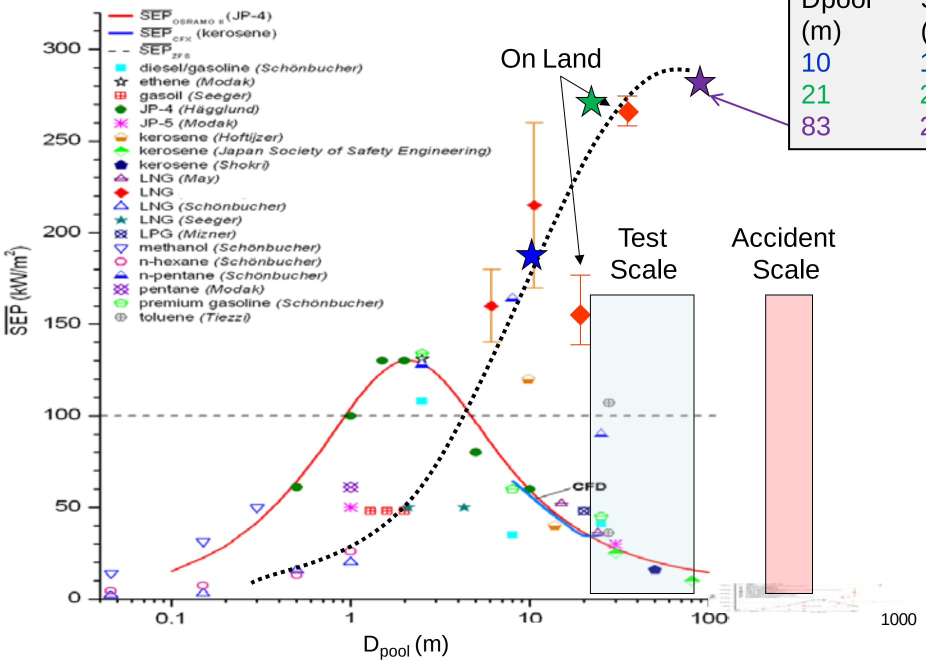




Large LNG Pool Fire Surface Emissive Power Data

Sandia National Laboratories

Data from large scale tests allows for validation of predictive models.



Dpool (m)	SEP (kW/m²)
10	190
21	277
83	286

Test 1 – 23 m dia, 20,000 gal spill, 2,000 gpm

Test 2 – 56 m dia, 65,000 gal spill, 30,000 gpm

Expected Damage for Various Thermal Radiation Levels

Damage	Thermal Radiation Flux Level (kW/m^2)
1. Will cause pain in 15 – 20 seconds and injury (seconds-degree burns) after 30 seconds.	**5**
2. Significant chance of fatality for extended exposure; high chance of injury after exposures of less than 30 seconds. Buildings made of flammable materials may suffer minor damage after prolonged exposure	12.5
3. Extended exposure results in fatality; there is a chance of fatality for instantaneous exposure. Buildings that are not fire resistant will suffer damage after short exposures. Fire-resistant structures and metal may suffer damage after prolonged exposure	21.0
4. Significant chance of fatality for people with instantaneous exposure. Flammable structures ignite spontaneously. Fire-resistant structures suffer damage after short duration. Metal fatigue after short to medium exposure	37.5

Thermal Hazards for Large Spills from Standard LNG Carriers

HOLE SIZE (m^2)	TANKS BREACH	DISCHARGE COEFF.	BURN RATE (m/s)	SURFACE EMISSIVE POWER (kW/m^2)	TRANS-MISSIV-ITY	POOL DIA. (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	0.8	209	20	250	784
5	3	.6	3×10^{-4}	220	0.8	572	8.1	630	2118
5*	1	.6	3×10^{-4}	220	0.8	330	8.1	391	**1305**
5	1	.9	3×10^{-4}	220	0.8	405	5.4	478	1579
5	1	.3	3×10^{-4}	220	0.8	233	16	263	911
5	1	.6	2×10^{-4}	220	0.8	395	8.1	454	1538
5	1	.6	8×10^{-4}	220	0.8	202	8.1	253	810
5	1	.6	3×10^{-4}	220	0.5	330	8.1	297	958
5	1	.6	3×10^{-4}	175	0.8	330	8.1	314	1156
12	1	.6	3×10^{-4}	220	0.8	512	3.4	602	1920

*Nominal case: Expected outcomes of a potential breach and thermal hazards based on credible threats, best available experimental data, and nominal environmental conditions for standard LNG ships (130,000 m^3)

Small LNG Pool Fire Characteristics

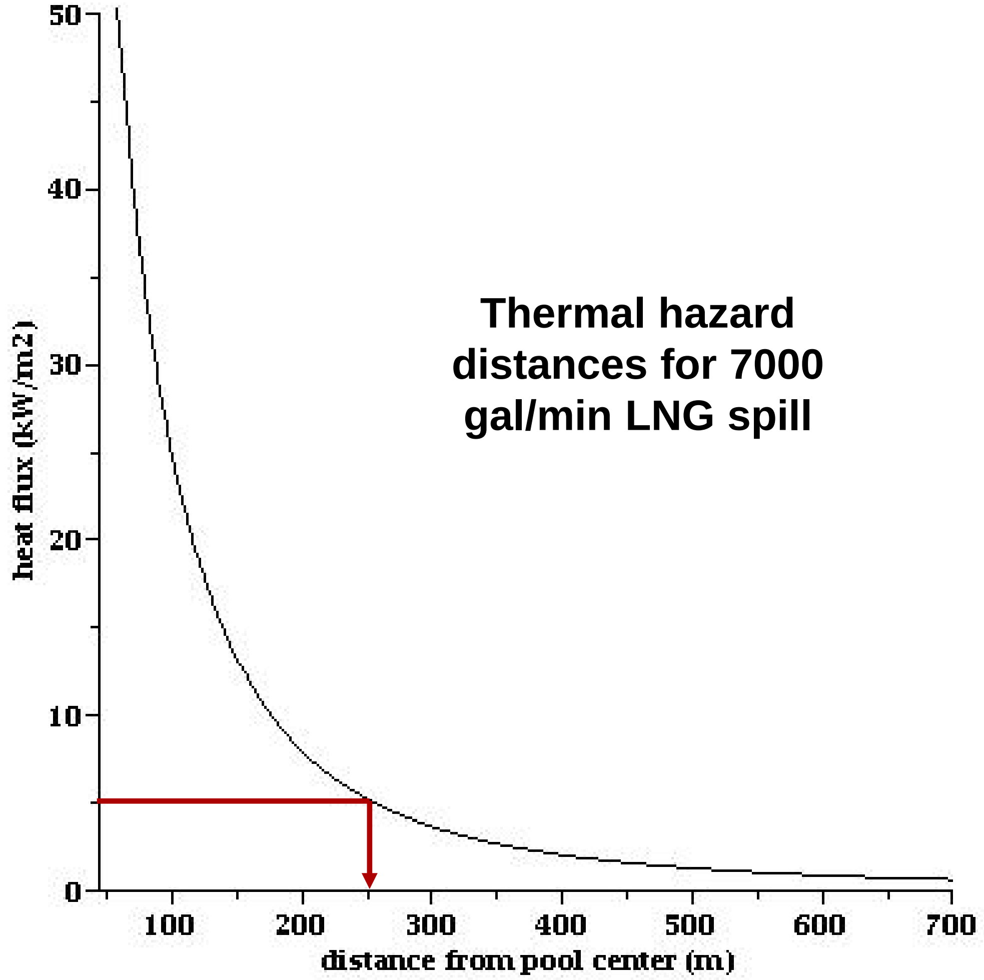
- Tall fires, no smoke, fire smaller than pool size
- Surface emissive power is less
  - Small ~190 kW/m^2
  - Large ~290 kW/m^2
- **Significantly smaller fire and dispersion hazard distances**
- No spill residues left after a fire or dispersion

Sandia 2005 LNG Pool Fire Test

10 m dia, 300 gal/min LNG spill

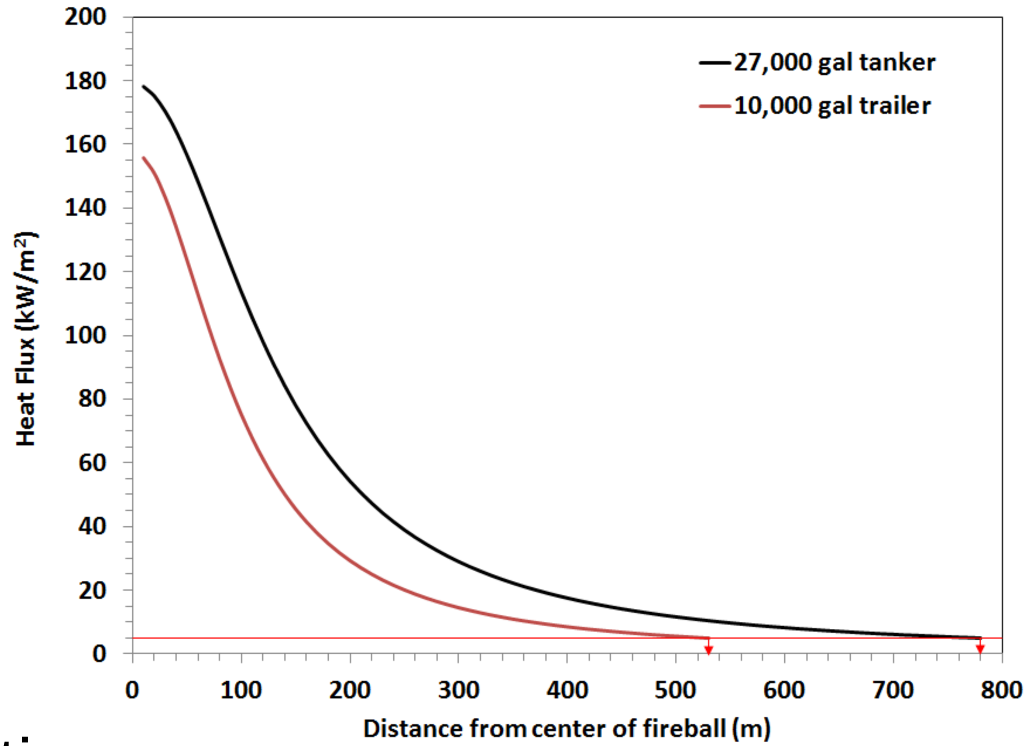
Thermal Hazards from Small LNG Transportation Spills – 10,000-20,000 gal

- Hazard distances from small LNG spill - 300 gal/min (1.1 m^3/min)
  - 10 m diameter
  - ~15 m to 37.5 kW/m^2
  - ~60 m to 5 kW/m^2
- Hazard distances for possible isotainer or LNG trailer spill - 7000 gal/min (27 m^3/min)
  - 43 m diameter
  - ~70 m to 37.5 kW/m^2
  - ~250 m to 5 kW/m^2



Fireballs

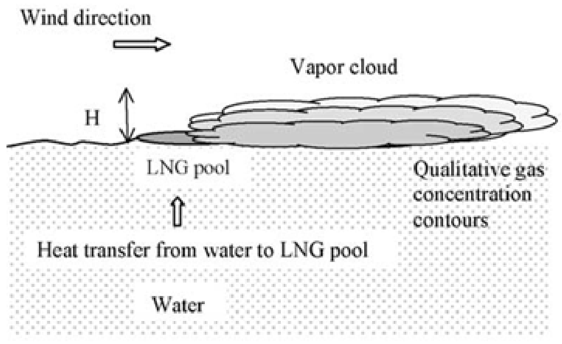
- Fireballs form when a rich compact vapor cloud is ignited. The hot spot rises, creating a vortex that rapidly incorporates the rest of the fuel.
- They burn in seconds releasing a large amount of radiant energy.



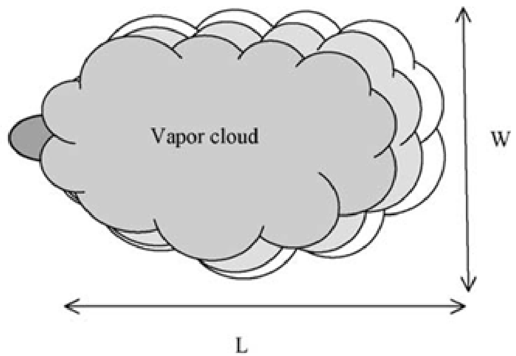
Fireball from accidental ignition of Falcon5 LNG test in 1987 [1]

[1] Ronald P. Koopman Ph.D. P.E.
Formerly Liquefied Gaseous Fuels Program Leader
Lawrence Livermore National Laboratory

LNG Vapor Cloud Shape in Wind



Side View



Bottom View

- Cloud travels at ~wind speed (before becoming buoyant and dispersing)
- Clouds persist for 10s of minutes
- L/W ratio of cloud on order 5 for wind speeds >4 mph
- Cloud height <10 m (L/H ratio on order of 100)
- Unconfined burn speed - relatively slowly, on the order of 1 m/s (3 ft/s)

LFL - lower flammability limit, lowest value where LNG can be ignited (5% methane in air)

LNG dispersion tests on water

Experiment	Spill volume (m^3)	Spill rate (m^3/min)	Pool radius (m)	Downwind distance to LFL (m) (max)
ESSO [46–47]	0.73–10.2	18.9	7–14	442
Shell [51]	27–193	2.7–19.3	NA (jettisoned)	2250[a] (visual)
Maplin Sands [52–55]	5–20	1.5–4	~10	190 ± 20
Avocet (LLNL) [56]	4.2–4.52	4	6.82–7.22	220
Burro (LLNL) [22–23]	24–39	11.3–18.4	~5	420
Coyote (LLNL) [16–21]	8–28	14–19	Not reported	310
Falcon (LLNL)[b] [57]	20.6–66.4	8.7–30.3	Not reported	380

[a] Total extent of the cloud (maximum LFL distance not measured). Thus, maximum distance to LFL is less than this value.
[b] Vapors were partially contained within a vapor fence.

Potential Dispersion Hazards for Large Spills from Standard LNG Carriers

Sandia National Laboratories

HOLE SIZE (m^2)	TANKS BREACHED	POOL DIAMETER (m)	SPILL DURATION (min)	DISTANCE TO LFL (m)
Accidental Events				
2	1	256	20	1710
Intentional Events				
5	1	405	8.1	2450
5	3	701	8.1	3614

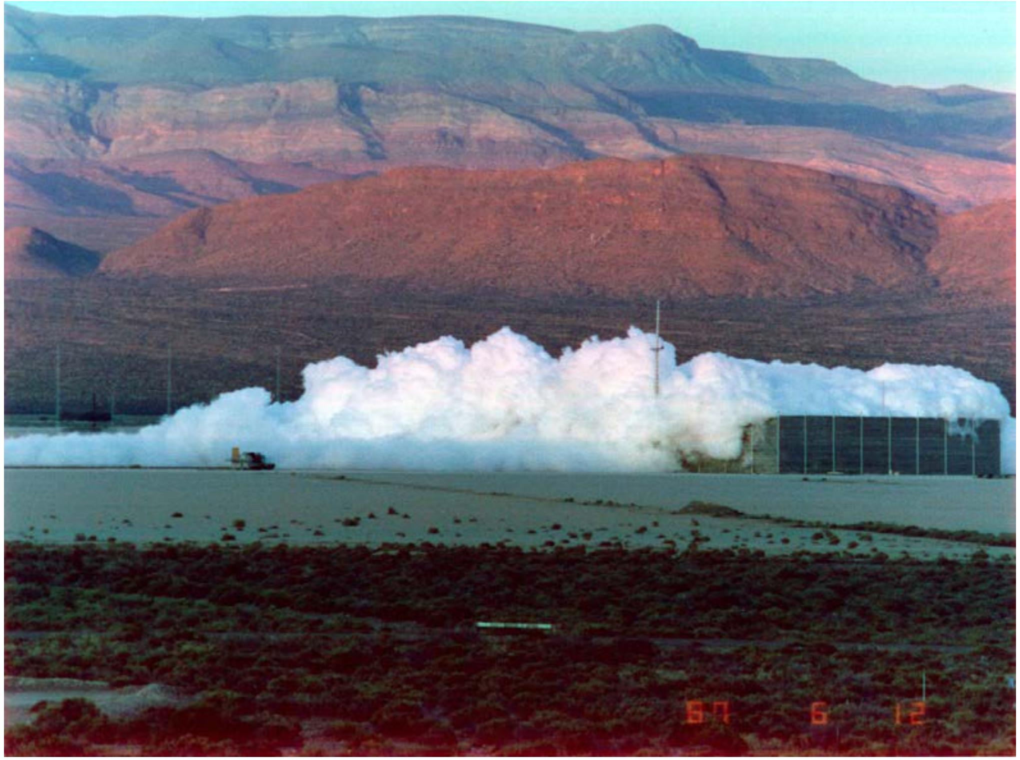
LFL - lower flammability limit, lowest value where LNG can be ignited (5% methane in air)

Dispersion distance limited by closest ignition source

Potential Fire Hazard Distances for Transportation Small Spill/Dispersion

- Hazard distances from small LNG spill - 300 gal/min (1.1 m^3/min)
  - Max. LFL dispersion distance ~75m

- Hazard distances for possible isotainer or LNG trailer spill
  - 10,000-20,000 gal spill
  - Max. LFL dispersion distance ~300m



Falcon LNG Vapor Barrier Experiments [1]
Nevada Test Site, 1987

[1] Ronald P. Koopman Ph.D. P.E.
Formerly Liquefied Gaseous Fuels Program Leader
Lawrence Livermore National Laboratory

Flame speed ~1 m/s (walking speed)

Explosions from Combustion of Flammable LNG Fuel–Air Mixtures

- **Deflagrations (a relatively 1 m/s slow burn) are the more probable mode of combustion in accident situations since detonations (flame front at shock wave speeds, 2500 m/s) are very difficult to achieve.**

- **Deflagrations in open air produce little overpressure.**

- **Weak ignition of vapor clouds in an unconfined and unobstructed environment is highly unlikely to result in a deflagration to detonation (DDT), but is more likely with confinement and the presence of obstacles.**

- **DDT can produce damaging overpressures (100s of psi).**

- **Boiling Liquid Expanding Vapor Explosion (BLEVE) Accidents can produce damaging overpressures and thermal radiation hazards from fireballs.**

SKIKDA
DDT

REPORT OF THE U.S. GOVERNMENT TEAM SITE INSPECTION OF THE SONATRACH SKIKDA LNG PLANT IN SKIKDA, ALGERIA MARCH 12-16, 2004

- Large and sudden cold hydrocarbon leak in gas or liquid form.
- Leak was **semi-confined** by process equipment and structures.
- Gas (**10s of gals**) was sucked into boiler, boiler exploded and ignited remaining spill.
- Estimated fuel required to produce that damage **~6000 gallons of LNG or LPG**.

Sandia National Laboratories

SKIKDA DDT

Explosion of the boiler combustion chamber alone could not yield the global damage.

Boiling Liquid Expanding Vapor Explosion (BLEVE) Accidents

- Historical analysis of MHIDAS accident database (2004)
  - 12,179 accidents, 1% (9 accidents) involved LNG road transport.[1]
  - 4 - no LNG release nor fire, 3 - LNG release was controlled, no fire, 1- LNG 1 – LNG was not affected, **1 – LNG load (12,000 gal) involved in fire**.

- Database showed 60 BLEVEs, but no BLEVEs (by definition) from LNG, but…
- 2002 LNG road tanker accident and explosion (Tivissa, Catalonia).

[1]E. Planas-Cuchi et al. / Journal of Loss Prevention in the Process Industries 17 (2004) 315–321

Boiling Liquid Expanding Vapor Explosion (BLEVE) Accidents

- Violent explosion ~20 min. into fire resulting in overpressure, fireball, and missile ejection (large truck/tanker pieces thrown 80-260 m.
- Driver died, 2 persons 200 m away burned by fireball (150 m dia., 12 s).
- Pressure at failure estimated to be ~8 bar (energy release 75 kg $TNT_{\text{energy equivalent}}$)
- Not a BLEVE using Reid (1976) definition, likely BLEVE using CCPS (1994).



Tank rear (thrown 80 m) **Tank center** **Tank front (thrown 125 m)**

Conclusions and Recommendations

- Large scale experimental data from **pool fires** and **dispersion tests** were used to validate computational fluid dynamics models/codes.
  - **Allows good prediction of thermal hazard distances and improved understanding of consequences.**

- Explosion potential from release and dispersion LNG in unconfined or low congested/clutter environments is essentially zero.

- Explosion potential from release and dispersion LNG in confined environments is high (as with any flammable fuel).

- There is relatively sparse data to understand explosion potential and consequences from LNG release and dispersion in environments that could yield DDT
  - **Further work must be done before prediction can be made whether DDT will occur for any given spill scenario.**

- LNG tank BLEVE is possible in some transportation scenarios.

USCG Request for Guidance on Safety of LPG Spills over Water

- Safety standards exist for LNG spills on water, however not so much so for LPG spills on water
- Some studies of marine LPG safety use hazard analysis approaches derived from LNG safety and guidance
  - While LNG and LPG are both often transported as cryogenic gases, they have somewhat different fire and dispersion values
  - Currently limited guidance on accidental or intentional breach evaluation, spill analysis, and fire, dispersion, or explosion hazard analyses
- The expected growth in marine transport of LPG suggests that standardized hazards assessments and modeling are needed to ensure the safety of the public for local operations and conditions

Relative Flammability Limits for Methane and Propane Chemicals

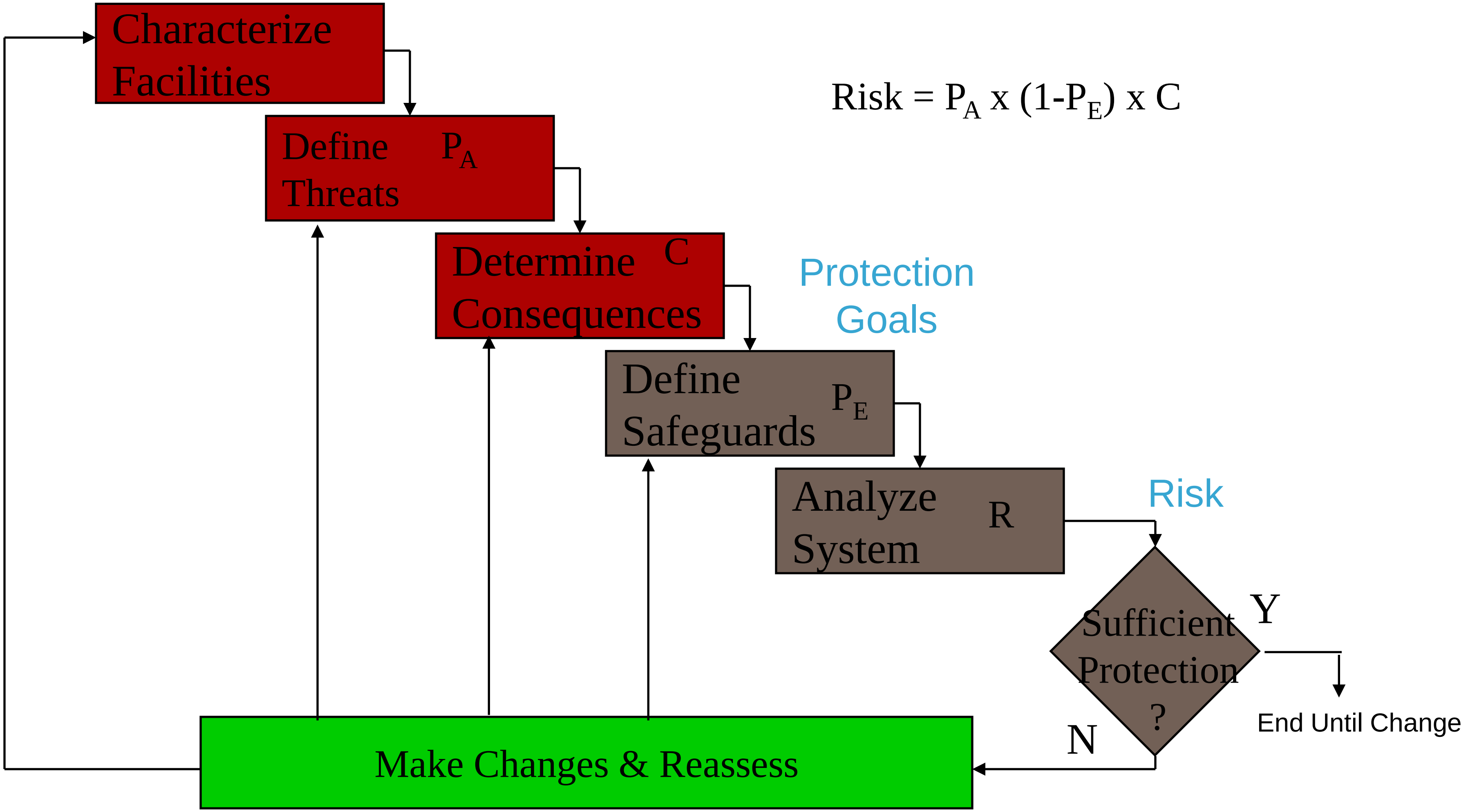
FUEL	LOWER FLAMMABILITY LIMIT (LFL) % by volume in air	UPPER FLAMMABILITY LIMIT (UFL) % by volume in air
Methane	5.5	14.0
Butane	1.6	8.4
Propane	2.1	9.6
Ethanol	3.3	19.0
Gasoline (100 Octane)	1.4	7.8
Isopropyl alcohol	2.0	12.7
Ethyl ether	1.9	36.0
Xylene	0.9	7.0
Toluene	1.0	7.1
Hydrogen	4.0	75.0
Acetylene	2.5	85.0

Methane heating value – 1000 btu/ft^3 – 24,000 btu/lb
Propane heating value – 2572 btu/ft^3 - 21,500 btu/lb

Sandia asked by the USCG to Create a Risk-based Hazards Analysis Approach for LPG spills – similar to LNG Approach

Sandia National Laboratories

$$Risk = P_A \times (1-P_E) \times C$$



Sandia LPG Spill Safety Analysis and Risk Management Guidance for the USCG

- Utilize best available LPG fire and dispersion data, ship data, and models
- Provide process for site-specific hazards evaluations – ship, location, etc.
- Provide direction on analytical tools and risk management considerations
- Identify "scale" of hazards for range of accidental and intentional events
- Utilize LNG safety guidance format to present hazard issues – nominal hazard issues, general hazard zones, etc.

Backup Slides

Note to self: The introductory slide should describe what will be discussed in the presentation………and attempt to meet the below requests.

Thoughts for this slide…the following presentation will

1. **Review transportation options/opportunities/scales of quantity**
2. **Review hazards/consequences of pool fires/unignited dispersion events**
3. **Discuss potential for explosions and consequences**
4. **Wrap up – strengths and weakness in knowledge base.**

Commissioner request: (Westbrook and Pickett). Address the following:

(1) The myths re: the safety of the new LNG applications; distinguish the myths from any legitimate concerns;

(2) what should the regulators know about the safety of LNG that we may not know.; and

(3) Would treatment of an event at a smaller scale LNG facility be the same/similar/different than a larger scale facility (importing/exporting facility).

In essence, equip the Commissioners & Staff to respond to arguments we may hear regarding the expanded use of LNG.

Christopher Freitas request:

1. **Does SNL have research findings that you can reference to address the questions raised?**
2. **Showcases SNL expertise.**

Relative Flammability Limits for Various Chemicals

Sandia National Laboratories

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

Methane vapor is relatively hard to ignite and very difficult to detonate unless spilled in a confined area with a very large detonation source - LNG vapor is even more difficult to ignite and detonate because it is very cold

Asphyxiation Issues with LNG and Natural Gas

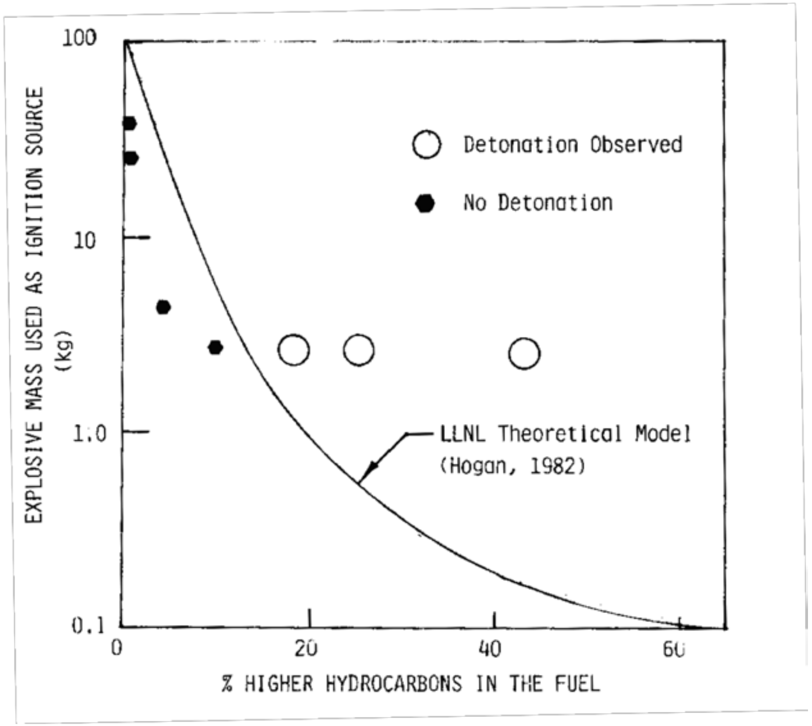
% O_2 AT SEA LEVEL	OXYGEN PARTIAL PRESSURE (mmHg)	PHYSIOLOGICAL EFFECTS
20.9	159	Normal
19	144	Some adverse physiological effects, but they are unnoticeable.
16	121	Impaired thinking and attention. Reduced coordination.
14	106	Abnormal fatigue upon exertion. Emotionally upset. Faulty coordination. Poor 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.

Asphyxiation requires about a 50% methane concentration in air, and therefore thermal impacts from a fire are more likely and a bigger concern

Explosions from Combustion of Flammable Fuel–Air Mixtures

- The amount of explosion overpressure is determined by flame speed and the amount of vapor within the flammability limits.
- In order for a vapor cloud explosion to occur, the LNG vapor must be sufficiently mixed with air to form a mixture within the flammability limits.
- Detonation of pure methane–air mixtures is very difficult since methane is a low reactivity fuel, but with the addition of higher reactivity fuels the difficulty decreases. LNG is composed principally of methane (85–95%), but may contain ethane up to 15%, and propane up to 5%, depending upon the source.
- The addition of small amounts of ethane and/or propane (10%) can reduce the required ignition charge for detonation by almost a factor of 10.
- Differential boil-off from an LNG pool can cause the vapor cloud to have a different composition than the liquid, and to have varying composition within the cloud. Due to limited mixing, the entire vapor cloud will not have a composition within the explosion limits of the constituent fuels of LNG in air.

Vapor cloud explosions and detonations [1]



Detonation threshold NWC data with LLNL model for stoichometric fuel-air mixtures

- Unconfined ordinary LNG vapor clouds burn but do not detonate
- At higher hydrocarbon levels of 40% or more detonations can occur in unconfined clouds
- Detonations can always occur when vapor clouds are confined by walls, buildings, equipment racks or terrain

[1] Ronald P. Koopman Ph.D. P.E.
Formerly Liquefied Gaseous Fuels Program Leader
Lawrence Livermore National Laboratory

Explosions from Combustion of Flammable Fuel–Air Mixtures

- There have been several reviews on explosions of hydrocarbon–air mixtures [89–100].
- Weak ignition of vapor clouds in an unconfined and unobstructed environment is highly unlikely to result in a deflagration to detonation (DDT) even for more sensitive fuel–air mixtures, but is more likely with confinement and the presence of obstacles (Moen 97).
- Understanding of how confinement, temperature, pressure, and mixture composition influence the initiation source and distance to DDT is not complete, and that further work must be done before prediction can be made whether DDT will occur for any given spill scenario (Nettleton 91) .

[89] J.H.S. Lee, I.O. Moen, The mechanism of transition from deflagration to detonation in vapor cloud explosions, Prog. Energy Combust. Sci. 6 (1980) 359–389.

[90] I.O. Moen, Transition to detonation in fuel-air explosive clouds, J. Hazard. Mater. 33 (1993) 159–192.

[91] M.A. Nettleton, Recent work on gaseous detonations, Shock Waves 12 (2002) 3–12.

[92] D.C. Bull, J.A. Martin, Explosion of unconfined clouds of natural gas, American Gas Association, Transmission Conference, Missouri, USA 16–18th May, AGA Operating Section Proceedings, Paper 77-T-40, 1977.

[93] D.C. Bull, et al., A study of spherical detonation in mixtures of methane and oxygen diluted by nitrogen, J. Phys. D. Appl. Phys. 9 (14) (1976) 1992–2000.

[94] M.C. Parnarouskis et al., Vapor cloud explosion study. Six. Congr. Int. Gaz. Natl. Liq., vol. 2, Sess 3, paper 12, 1980.

[95] C.D. Lind, J.C. Witson, Explosion hazards associated with spills of large quantities of hazardous materials phase II, Report No. CG-D-85-77, 1977.

[96] R. Vander Molen, J.A. Nicholls, Blast wave initiation energy for detonation of methane-ethane-air mixture, Comb. Sci. Technol. 21 (1979) 75–78.

[97] I.O. Moen, et al., Flame acceleration due to turbulence produced by obstacles, Comb. Flame 39 (1980) 21–32.

[98] A.J. Harrison, J.A. Eyre, The effect of obstacle arrays on the combustion of large premixed gas/air clouds, Comb. Sci. Technol. 52 (1987) 121–137.

[99] D. Bradley, T.M. Cresswell, J.S. Puttock, Flame acceleration due to flame-induced instabilities in large-scale explosions, Comb. Flame 124 (2001) 551–559.

[100] S.R. Tieszen, D.W. Stamps, C.K. Westbrook, W.J. Pitz, Gaseous hydrocarbon–air detonations, Comb. Flame 84 (1991) 376–390.

BLEVE Definitions

- Boiling liquid expanding vapor explosions were defined by Walls (1979), one of those who first proposed the acronym BLEVE , as ‘‘a failure of a major container into two or more pieces occurring at a moment when the container is at a temperature above its boiling point at normal atmospheric pressure’’.
- Reid (1976) defined BLEVEs as ‘‘the sudden loss of containment of a liquid that is at a superheated temperature for atmospheric conditions’’; this definition has been widely accepted for years.
- More recently, less restrictive definitions have been proposed and are being accepted by diverse authors; for example, (CCPS, 1994) ‘‘an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at normal atmospheric pressure’’.

SNL/USDOE Field Work Proposal – LNG Spill and Dispersion Safety Study

- Designed to look a the issues of large LNG spills and associated dispersion events that could occur in populated or structurally congested/cluttered areas, where an ignition source could lead to a deflagration to detonation transition of the dispersed vapor cloud.
- If initiated, the resulting high overpressure could cause significant personnel injuries and structural damage.
- While this type of event is unlikely to occur in open areas, like marine transportation environments, emerging LNG transportation on railroads and roadways in populated and often confined transportation corridors may be susceptible to these types of high overpressure hazards from an accident and spill.
- This research will attempt to quantify the likelihood, severity, and factors that control an LNG spill detonation.
- The data and understanding developed will be used to suggest transportation and operational safety guidelines and strategies to reduce the probability and consequences of such events
- Proposed 2 year study, ~$2M cost

SNL/USDOE Field Work Proposal – LNG Spill and Dispersion Safety Study

Proposal Milestones

Duration	Milestone Tasks
3 months	Develop initial design of experiments plan, including identification of instrumentation needs, safety and ESH, LNG procurement and storage, and preliminary test plan and schedule. Initiate dispersion and detonation modeling development.
6 months	Construct and instrument dispersion test site and place all test equipment. Use dispersion and detonation modeling tools to help design test setup and testing matrix.
4 months	Conduct preliminary LNG dispersion and detonation tests with varying spill rates and geometries to establish detonation boundaries and validation of dispersion and detonation modeling tools.
8 months	Complete dispersion and detonation testing and modeling, focusing on performance prediction and assessing and quantifying estimated hazards and consequence mitigation strategies.
3 months	Prepare and submit final report on testing and modeling results, and present recommendations on hazards estimates and mitigation options and approaches for various types of LNG spill scenarios.

LNG Risk Based Safety: Modeling and Consequence Analysis
By John L. Woodward, Robin Pitbaldo

6.4.3 Pool Fire Radiation Exclusion Zone

The U.S. regulation 49CFR193.2057 Subpart B entitled "Thermal Radiation Protection" specifies that *thermal exclusion zones* must be calculated for impounding areas (diked areas, sumps, and associated trenches) around all LNG containers and LNG transfer systems. These exclusion zones are based on defined design spill scenarios and must be large enough so that the thermal radiation from an LNG fire does not exceed a specified limit for protecting offsite people and property. Those limits are listed in Table 6.2.

Table 6.2 Thermal hazard criteria in NFPA 59A Standard

Thermal Radiation Flux Limits to Property Lines and Occupancies		
Thermal Radiation Flux		Exposure
kW/m^2	$BTU/(hr \cdot ft^2)$	
5	1,600	For ignition of a design spill, a property line limit for building upon.[a]
5	1,600	For a fire in an impounding area, the nearest point outside the property line that, at the time of the plant siting, is used for outdoor assembly by groups of 0 or more persons.
9	3,000	For a fire in an impounding area, the nearest point of a structure outside the property line that is in existence at the time of plant siting that is used for assembly, education, health care, detention and correction, or residential occupancies.
30	10,000	For a fire over an impoundment area, the nearest property line that can be built upon.[b,c]

[a]See NFPA 59A Section 5.2.3.5 for the definition of a design spill.
[b]See NFPA 59A Section 5.2.2.1 for the requirements for impoundment areas.
[c]See NFPA 101, Life Safety Code, or NFPA 5000, Building Construction and Safety Code, for definitions of occupancies.