Process Safety Applications for Emerging Issues in the Gas Industry

Dr. M. Sam Mannan, PE, CSP, DHC

Regents Professor and Director
Holder of T. Michael O'Connor Chair I
Mary Kay O'Connor Process Safety Center
Artie McFerrin Department of Chemical Engineering
Texas A&M University System
College Station, Texas 77843-3122, USA
mannan@tamu.edu, +1 (979) 862-3985
http://psc.tamu.edu

MARY KAY O'CONNOR PROCESS SAFETY CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

Outline

- Gas Exploration Hazards: Well Integrity and Blowout Modeling
- Transportation Hazards of Natural Gas
- LNG Hazards as Transportation Fuels
- LNG Hazard Assessment and Mitigation
- Changes in LNG Terminals

1. Gas Exploration Hazards: Well Integrity and Blowout Modeling

Well Integrity and Blowout Modeling

Compromised Well Integrity

Cement
Casing
Packers
Valves (*e.g.*, GLV, Shoetrack)
BOP

Safety aspects:
-Dangerous operating conditions
-Fire/Explosion
-Increased probability of an incident
-Protective barriers are compromised

Environmental aspects:
-Oil/gas spill
-Toxicity and exposure
-Wildlife impact

Worst Case: **Blowout**

Single Phase
Multiphase
Flow-rate
Decay rate

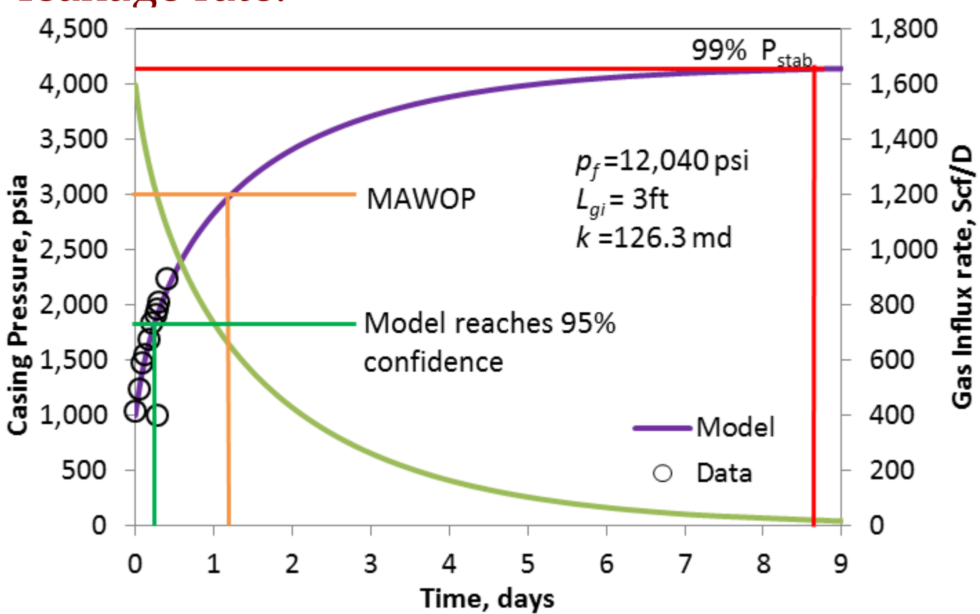
Consequence Modeling:
Gas dispersion
Plume modeling
Fire/Explosion

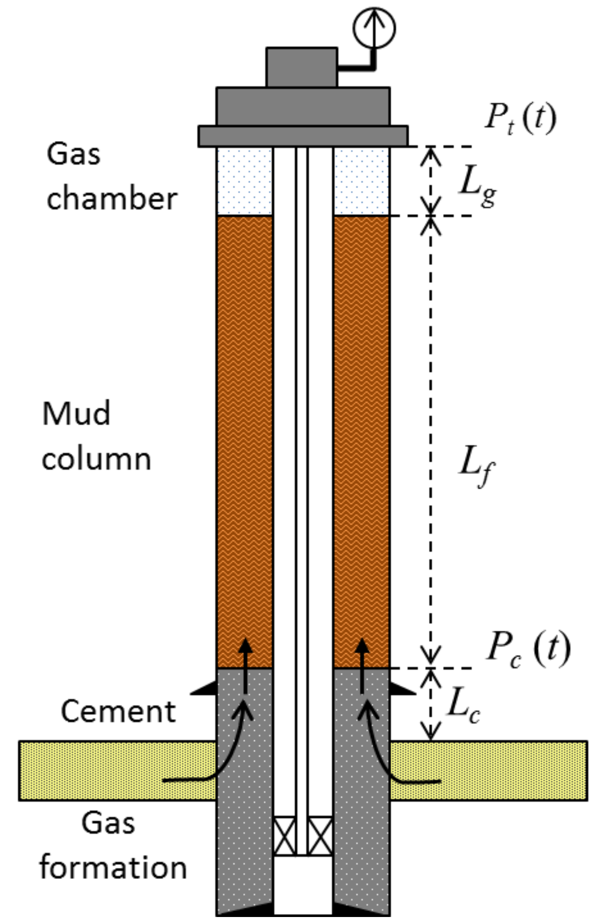
Well Integrity and Blowout Modeling

- Research Focused on Two areas:
  - Well Integrity Modeling
    - Improve understanding and modeling of the phenomena during well integrity issues
    - Develop models that facilitate or improve the design of safer operating and testing procedures
  - Blowout Modeling
    - Quantify, from science-based governing equations, the flow rate, either single or multiphase flow, and decay of flow rate from an uncontrolled blowout.

Well Integrity – Sustained Casing Pressure

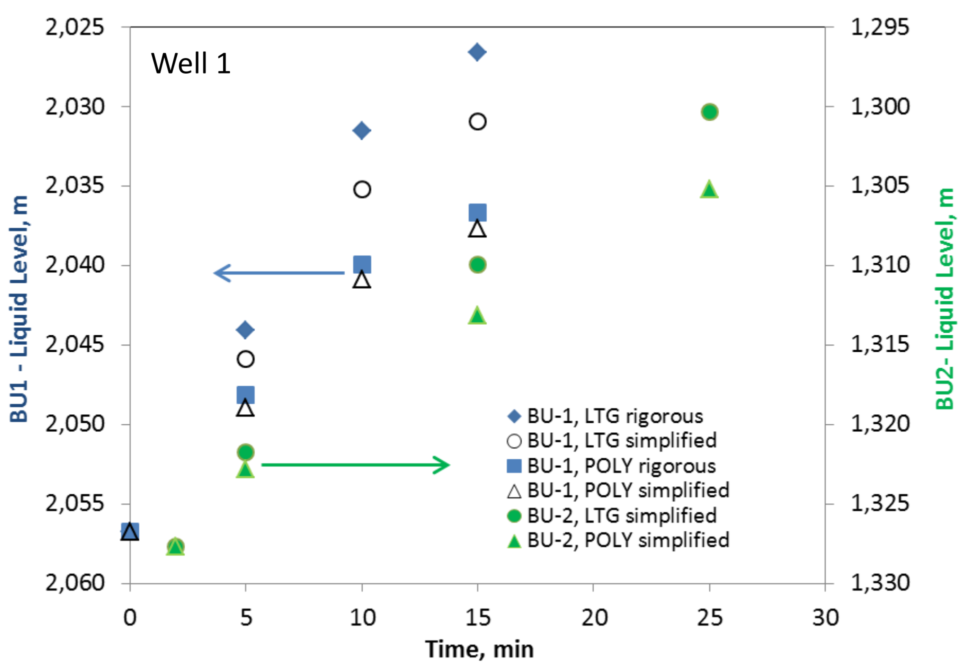
- Sustained Casing Pressure (SCP) Model: Predicts the behavior of gas migrating through an annulus in wells and that serves as a tool to determine the permeability of damaged cement.
- Analytic model for gas buildup, Inherently safer testing Quantitative estimation of cement permeability and leakage rate.

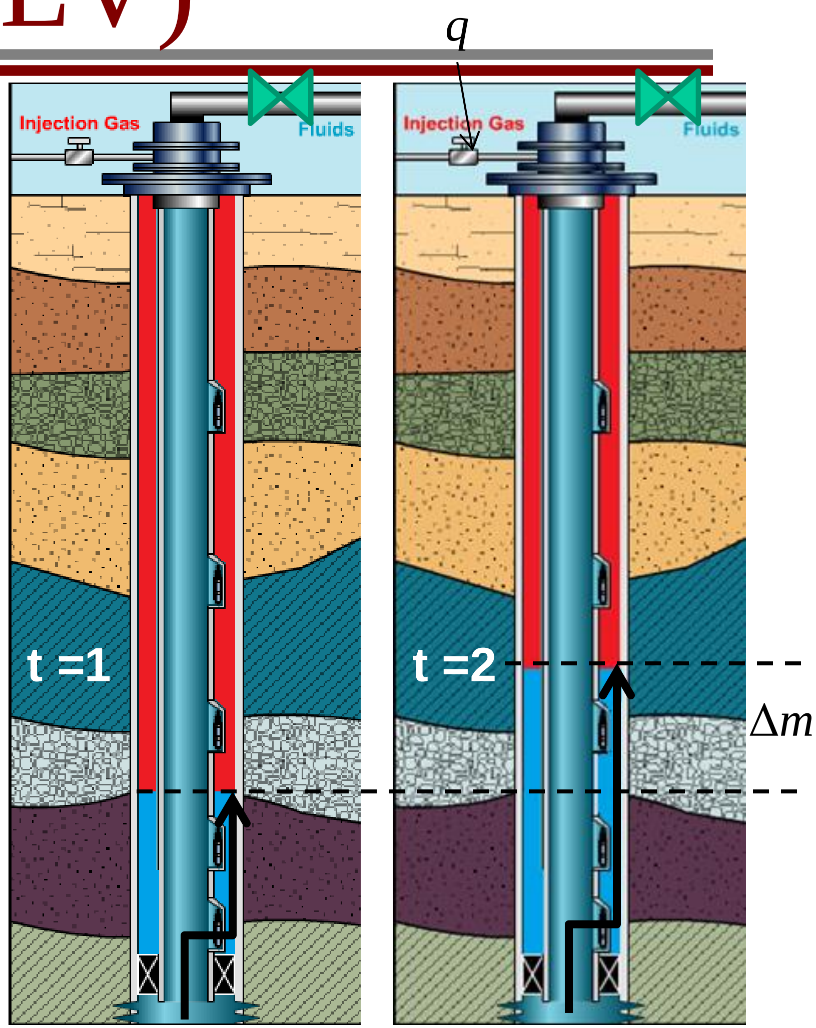




Well Integrity – Faulty Gas-Lift Valve (GLV)

- GLV leakage model: Methodology for Determining a GLV's integrity that avoids retrieving the valve and relies on examining the annular transient-pressure response. Presents an alternative to using Acoustic Well Sounding.

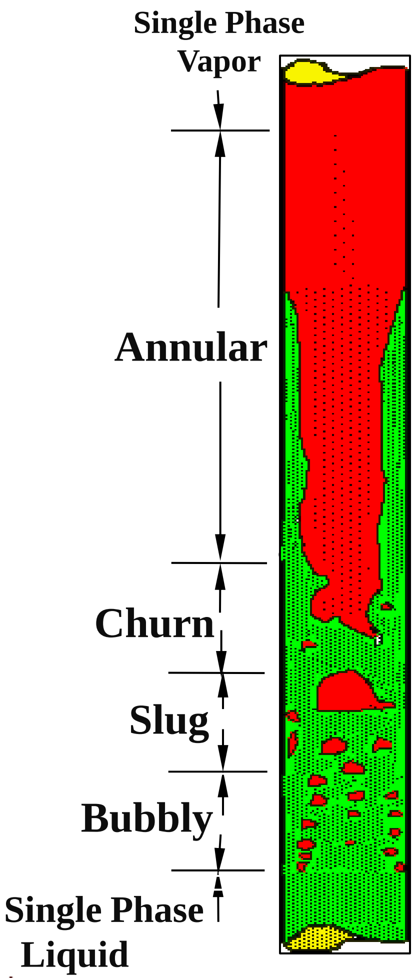




MARY KAY O'CONNOR PROCESS SAFETY CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

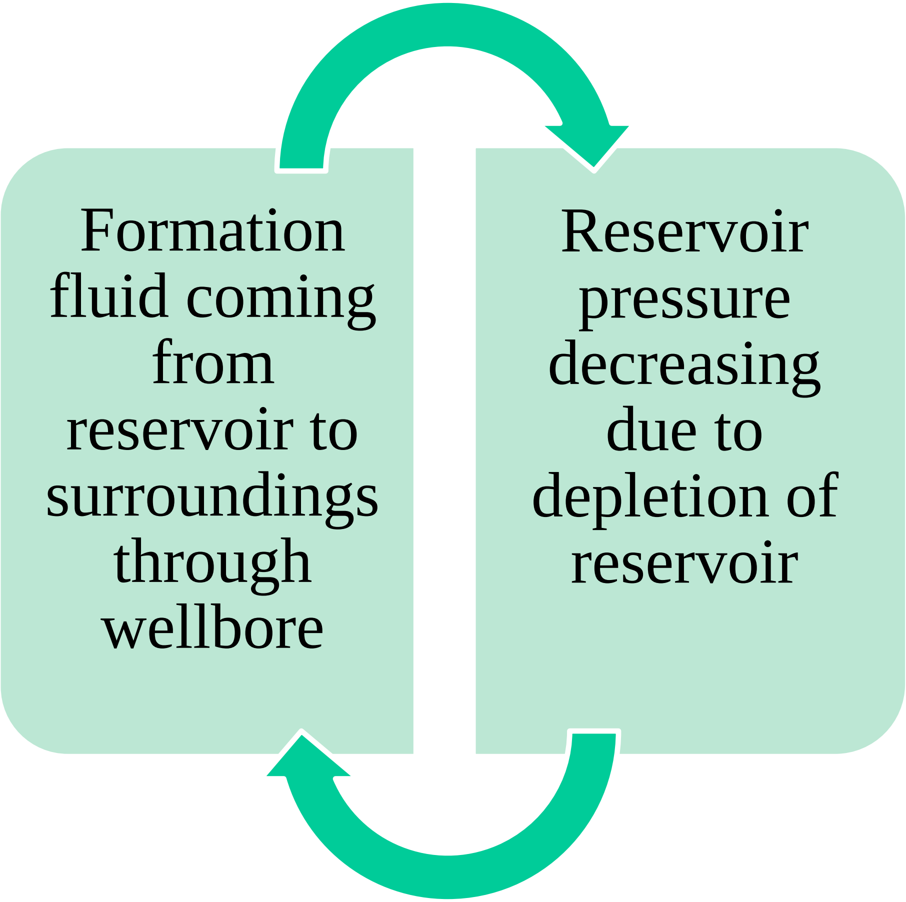
Blowout Modeling – Overview

- Establishes a mathematical model based on the basic physical phenomena, such as heat transfer and transient fluid flow dynamics.
- The analytical model can be used to estimate blowout rate and production loss for different types of blowout
  - Single phase oil blowout
  - Single phase gas blowout
  - Multiphase fluid blowout
- Both onshore and offshore wells are considered in the blowout modeling



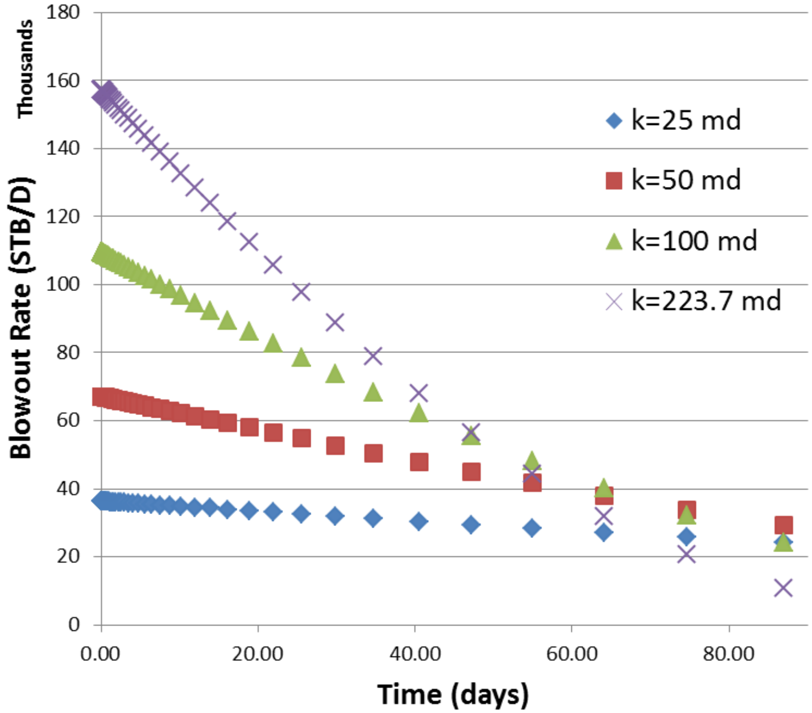
Blowout Modeling – Methodology

- Reservoir
  - Material balance
- Wellbore
  - Mass balance
  - Momentum balance
  - Energy balance
- Interactions
  - Analytic equations



Blowout Modeling – Examples

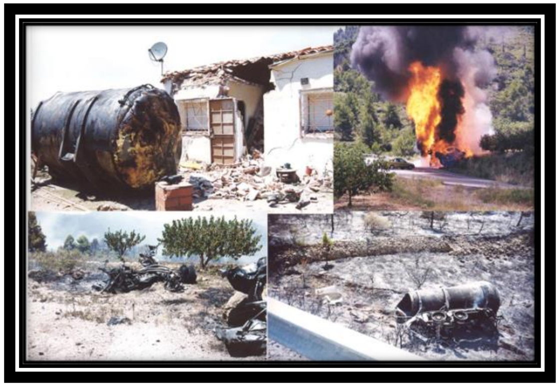
- Macondo Incident
  - Estimation of blowout rate and volume of oil spilled
  - Sensitivity analysis owing to uncertainties in reservoir



Permeability (md)	Production Loss (million STB)
25	2.57
50	3.98
100	5.13
223.7	5.71

2. Transportation Hazards of Natural Gas

Background



Images Retreived from Planas - Cuchi et al. (2004)

Ship Accident
June 29, 1979: The 125,000 - m3 *El Paso Paul Kayser* ran aground at 19 knots under full load in the Strait of Gibraltar.

Truck Accident- On June 22, 2002 at Catalonia, Spain- LNG truck accident possible had lead to a (BLEVE) . 1 Killed and 2 injured

Kleen Energy Power plant Accident

Feb 7, 2010 Middletown, Connecticut 6 killed,50 injured

❖ Liquefied to LNG or Compressed to CNG?

Natural Gas
Fixed Transportation Systems

Pipeline Components (Gathering, Transmission & Distribution Lines)

Compressor Stations

Metering Stations

Valves

Control Stations

Natural Gas
Portable Transportation Systems

Tanker truck

Railway Tanker

LNG/CNG carriers

Common Causes of Failure of Pipelines

- External Force
  - Encroachment
  - Weather-Related
- Corrosion
  - External Causes
  - Internal Causes
- Defective Pipe and Welds
- Equipment Malfunction and Operator Error
- Natural calamities like Hurricane and Earthquake pose direct risk to pipelines

Hazards of Fixed Transportation Systems

- Leaks leading to fire hazards
- Fire Hazards
  - Jet Fire
  - Flash Fire
  - Vapor Cloud Explosion (outdoor and enclosed)

Common Cause of failure of portable transportation systems

- Collisions- Ship-ship & ship- shore, vehicles in road transportation, collision of trains with obstacles or other trains.
- Grounding
- Intentional Terrorist Attacks
- Rupture in loading/offloading operations

Hazards of Portable Transportation Systems

Fire Hazards	• Flash Fire-ignition of portions of vapor cloud before dilution to LFL • Pool Fire- Flammable vapor cloud traces back to the pool burning vapor above liquid • Jet Fire - compressed or liquefied gas released as jet ignites to form jet fire.
Vapor cloud Explosion	• Vapor cloud formed in a confinement can produce damaging over pressures and hence explosion • Large fraction of heavier hydrocarbons increase likelihood
Rapid phase transition	• Physical explosion caused due to sudden boiling or phase change when LNG is spilled on water • Ranges from small pops to large blasts
Freeze Burns	• When LNG is in direct contact with skin , damage can occur in the form of pain and numbness.
Rollover	• The stratification of LNG into layers based on its varying densities due to the different components is called rollover. • Sudden increase in tank pressure can exceed the capacity of the pressure relief valves and may damage equipment
BLEVE	• an explosion caused by the rupture of a vessel containing a pressurized liquid above its boiling point

3. LNG Hazards as Transportation Fuels

LNG Transportation Hazards on Land

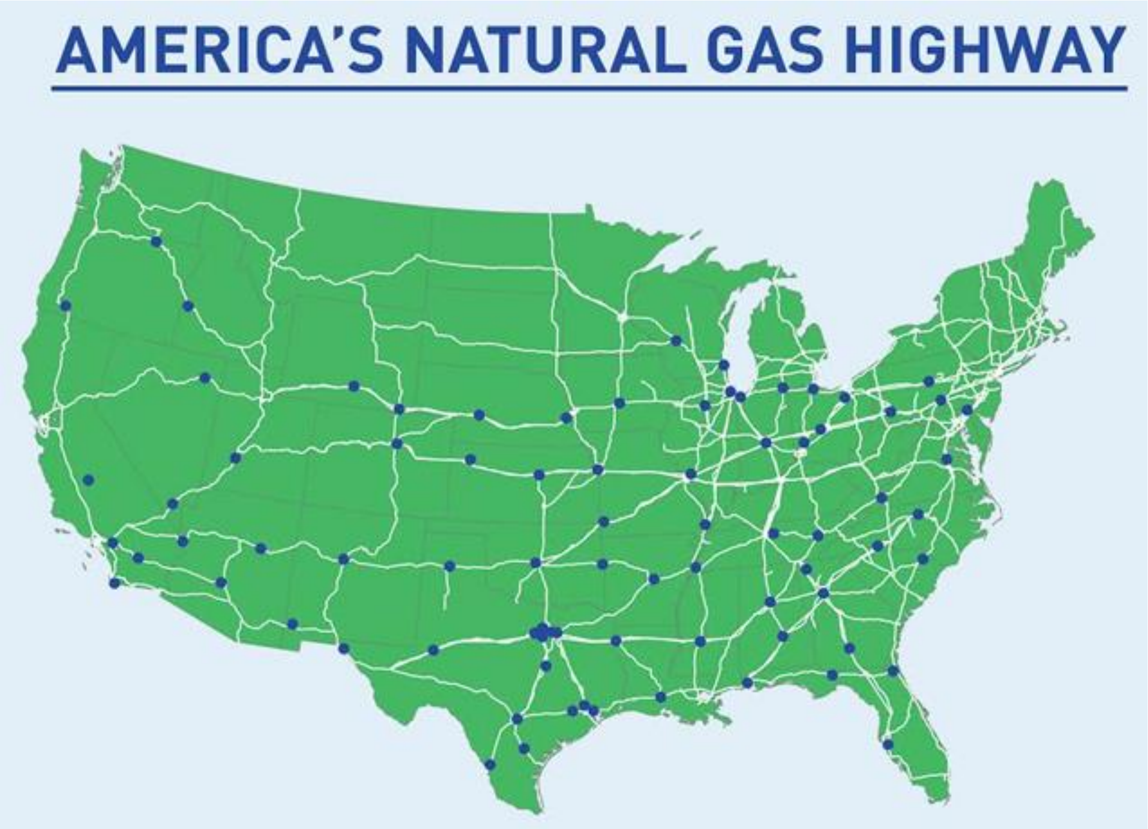
- LNG is used in heavy-duty vehicles, typically vehicles that are classified as "Class 8" (33,000 - 80,000 pounds, gross vehicle weight).
- Typical transportation applications are

  -refuse haulers

  -local delivery

  -transit buses.

LNG fueling station network



http://www.cleanenergyfuels.com/buildingamerica.html

LNG transport fuel Industry

- Transport LNG Producers/Distributors (*e.g.*, Clean energy, Southeast LNG)
- LNG Tanker Truck Operators (*e.g.*, Transgas, Southeast LNG)
- LNG Vehicle Fueling Stations (*e.g.*, Applied LNG Technologies, Clean Energy)
- LNG Vehicle Storage Tanks (*e.g.*, Chart Inc., Cryogenic Fuels Inc.)

Advantage of LNG as transportation fuel

- Strong reduction of SO_x and NO_x emissions
- Zero particulates
- Reduction of CO_2 emissions
- LNG fueled engines have a lower noise production
- Lower dependency on oil
- Gas will be dominant in the future

Hazards in using LNG as transportation fuel

- Fire on Bridge
- Pooling and Brittle Failure of Bridge
- Phase Change and Overpressure
  - -Vessel overpressure failure
  - -Rapid Phase Transition (RPT)
  - -Boiling Liquid Expanding Vapor Explosion (BLEVE)
  - -Vapor Cloud Explosion (VCE)
- Cryogenic Burns/Frostbite
- Environmental Effects

Research Problems

- Assessment of LNG safety requires identification of hazards and safeguards associated with each stage of LNG supply chain
- Relative risk comparison between other fuel supply chain and LNG supply chain is needed for assessing relative safety of LNG
- LNG safety risks in road transportation is normally associated with

  -Mechanical failure

  -High-impact crash

  -Terrorist attack
- Risk Assessment of bulk delivery and fuel storage at LNG fueling station should be performed
- LNG vehicle fuel tanks are more at risk than LNG tankers due to

  -Broader range of applications

  -Less well-trained personnel

Research problems (contd.)

- Hazards identification and consequence analysis of LNG spill on bridges are another concern
- Research should be performed on probable consequences of :

  -cryogenic deterioration of bridge material (*e.g.*, concrete, anchorages, tendons)-brittle efffect

  -Fire and radiation effect on bridge materials

4. LNG Hazard Assessment and Mitigation

Outline

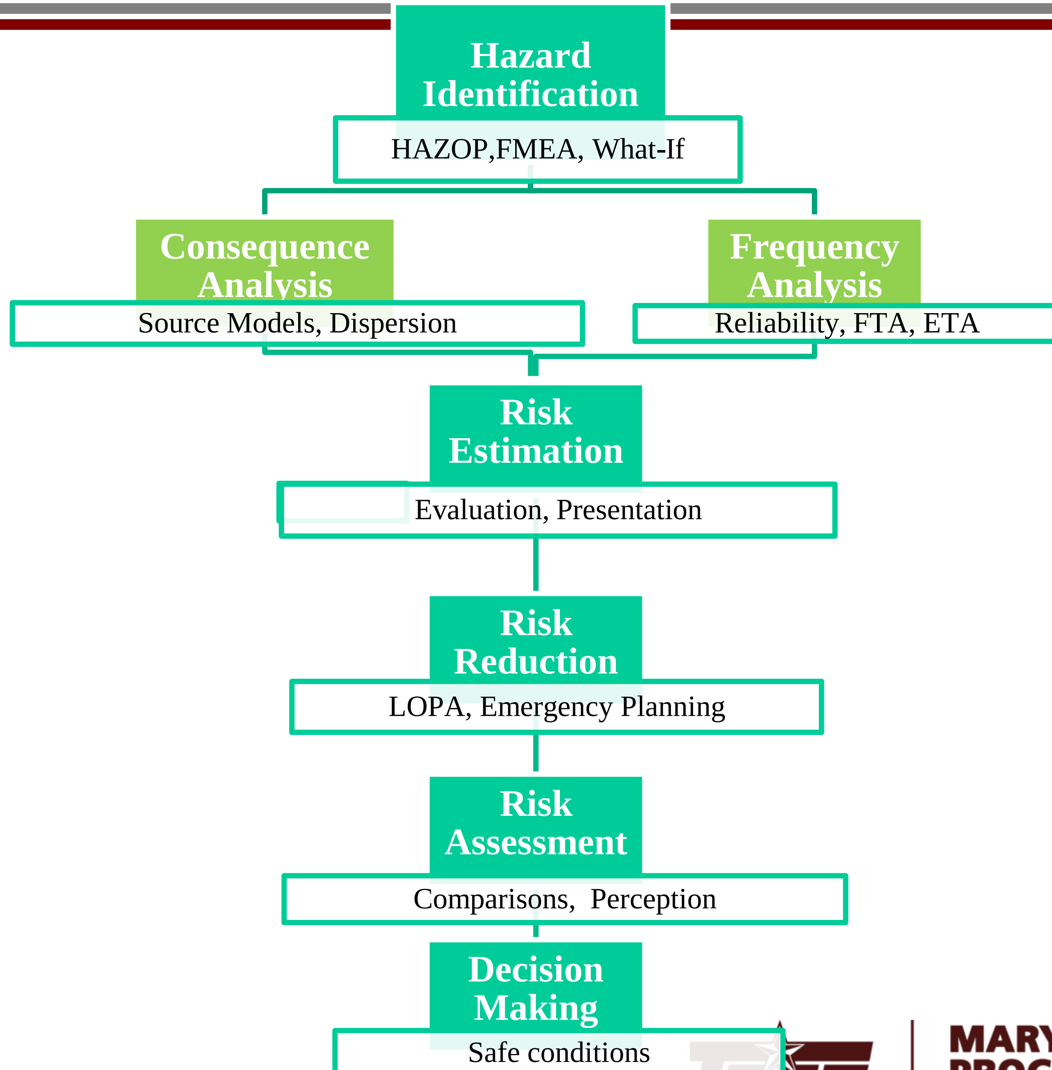
- Introduction
- LNG Risk-Based Approach for facility siting.
- LNG mitigation measures
  - Passive
  - Active
  - Procedural

Introduction

LNG Safety Concerns

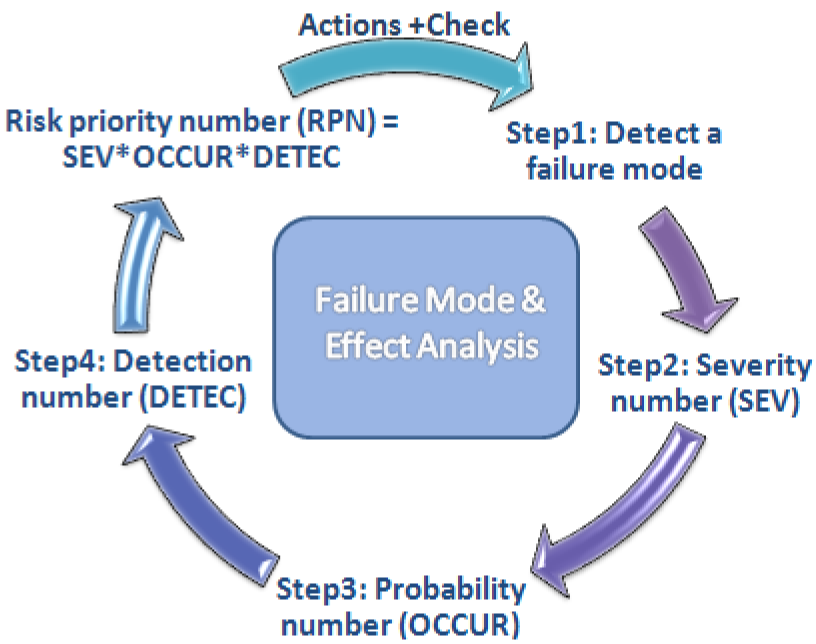
- Leaks leading to fires and explosions
- Transportation Hazards - Collisions and Grounding
- Intentional Terrorist Attacks
- Hazards during Operation - Rupture in loading/offloading operations

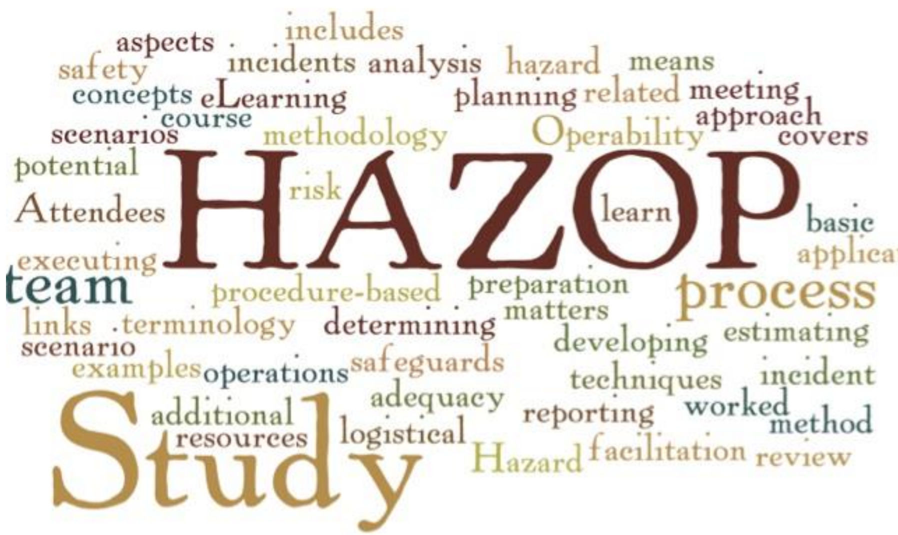
Risk Based Approach for LNG facilities



Hazard Identification

- HAZOP, FMEA





Consequence & Frequency Analysis

Consequence Analysis

- Source term modelling
- Dispersion modelling
- Fire and explosion modelling
- Effects modelling

Frequency Analysis

- Historical data
- Analytical or simulation techniques
- Expert Judgments.

Risk Estimation

- Risk – Consequence x Frequency
- **Individual risks** –probability of exposure of a person, system, or plant to a hazard or a particular level of the hazard. Example: risk of injury or fatality in performing work
- **Societal risks** – frequency or probability of outcome and the number of people (or facilities) affected, by a specified consequence level from exposure to specified hazards, represented in F-N profiles

Risk Reduction

Strategy	Description
Inherent	Reduce, eliminate hazards by using inherent safety principles
Passive	Features that do not need to be activated
Active	Devices that need to be activated in order to avoid the hazard or reduce the consequences
Procedural	An administrative action is required

- Inherent safety can be presented in all layers of protection
- However, it is especially directed toward design features

Selecting a Strategy to Reduce the Risk

- Inherent
- Passive
- Active
- Procedural

Generally decreasing reliability and robustness

- Due to the multiple hazards and technologies present in a chemical plant, a good safety program involves <u>ALL</u> strategies

- The best time to consider and implement Inherent Safety is early in process development stage

Hendershot, Dennis. *Research Needs For Inherently Safer Technology Workshop*. Houston, TX, 2008

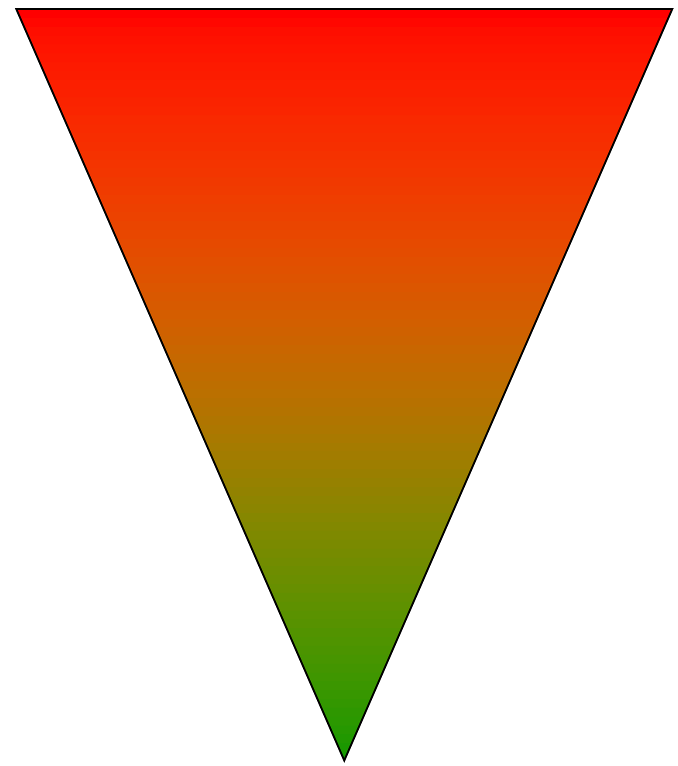
Controlling of Hazards to Reduce Risks

- Hazards that cannot be eliminated should be controlled
- An acceptable level of risk is achieved by a design that reduces the likelihood of a hazardous event occurring or that mitigates the consequences of such an event.
- When hazard elimination is not possible, the next best options are engineered solutions. These solutions can be either passive or active.

Layers of Protection Analysis (LOPA)

- A process of evaluating the effectiveness of Independent Protection Layers in reducing the likelihood or severity of an undesirable event.
- Drive the consequence and/or frequency of potential incidents to an acceptable risk level using independent protection layers (IPLs)

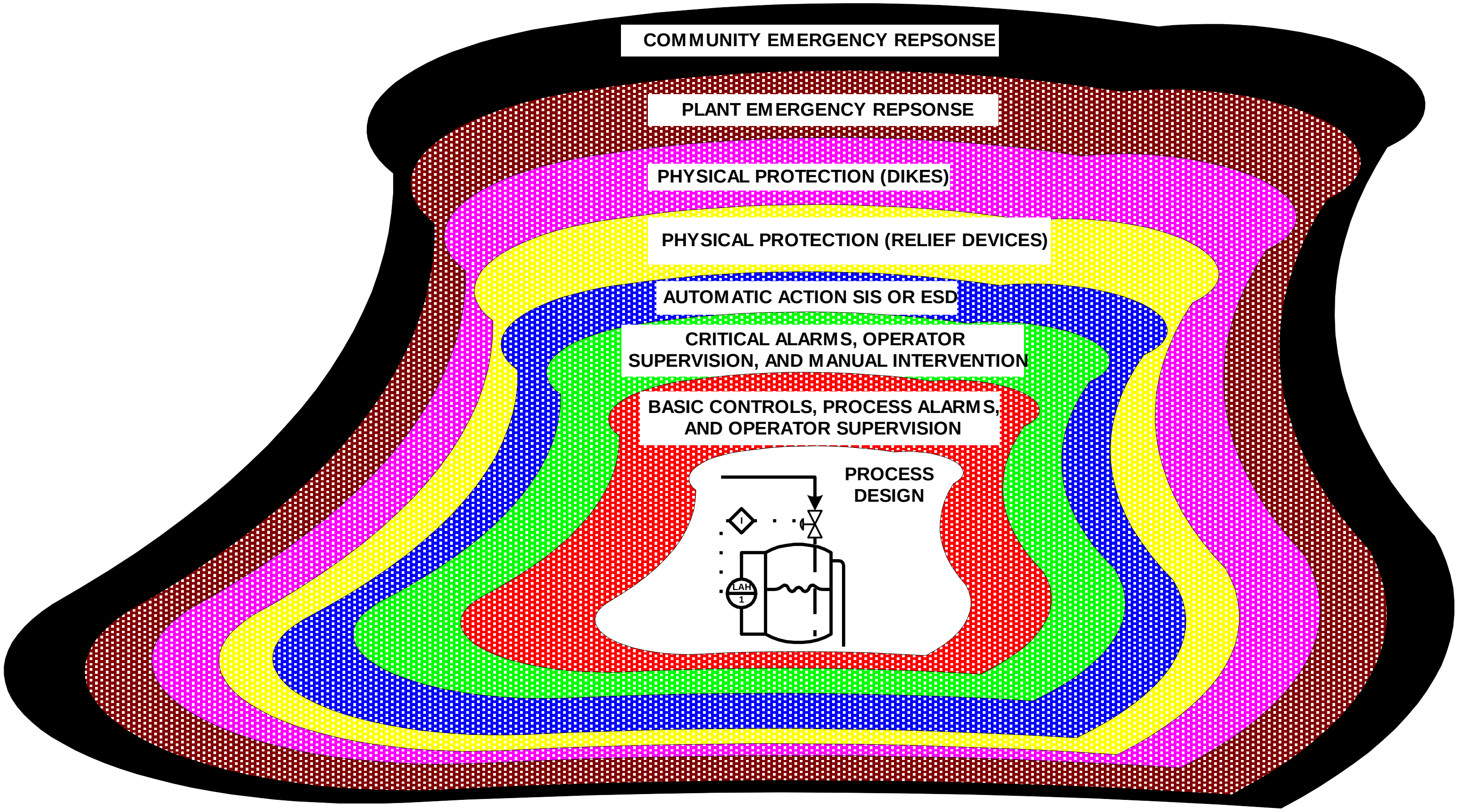
Unacceptable Risk



Acceptable Risk

Risk = frequency * consequence

The LOPA "Onion"



Hierarchy of Mitigation Measures

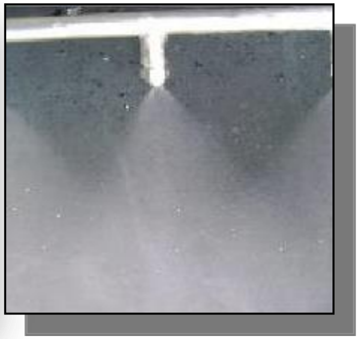
	Measure	Example
Passive	Eliminate hazard	• Substitute with nonhazardous material/process conditions
	Prevent release (reduce frequency)	• Upgrade metallurgy or design of equipment • Reduce leak sources (eliminate flanges, drains, small bore piping, etc.) • Rate equipment for maximum upset pressure
	Control size of scenario	• Minimize confinement • Minimize congestion • Utilize spill control dikes, curbs, etc., to limit extent of pool fires and limit vapor • Dispersion from pools of flashing liquids • Minimize release rate—provide process flow restrictions (either Limiting pipe • Size or adding restricting orifices) to reduce the potential severity of a release • From downstream equipment • Reduce inventory of hazardous (can reduce duration of fire and gas • release scenarios)
	Mitigate effect to building occupants	• Relocate personnel (especially personnel that are not essential) • Design or upgrade existing building to protect occupants from explosion, fire, or toxics • Tightly seal windows and tight double doors (airlocks) to minimize toxic/flammable gas and smoke ingress

Active Mitigation Measures

Measure		Example
Active	Prevent release (reduce frequency)	• Safety instrumented systems
	Control size of scenario	• Fire and gas/emergency shutdown systems (reducing quantity released) • Fixed/automatic active fire fighting systems
	Mitigate effect to building occupants	• Issue occupants with personal protective equipment (PPE) for hazards

Fan type

Conical type



Fog type

Water Curtains as Active Mitigation Measures

Expansion foams

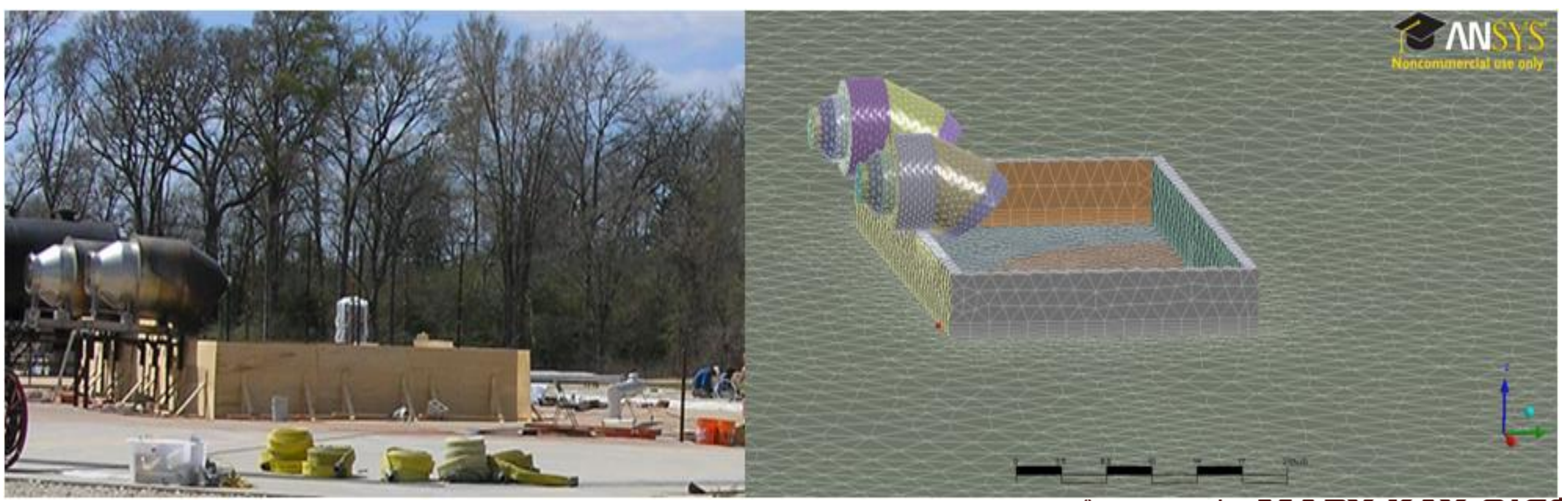
- Expansion foam is considered as an important safety measures
  - To control LNG fire
  - To reduce downwind vapor concentration

Procedural Mitigation Measures

Measure		Example
Procedural	Prevent release (reduce frequency)	• Mechanical Integrity Inspection • Permits for hot work, lockout/tagout, line breaking, lifting, etc.
	Control size of scenario	• Manual active fire fighting systems
	Mitigate effect to building occupants	• Emergency response plan including, as appropriate: evacuation, escape routes, shelter-in-place, etc. • Evacuate building occupants during start-up and planned shutdowns

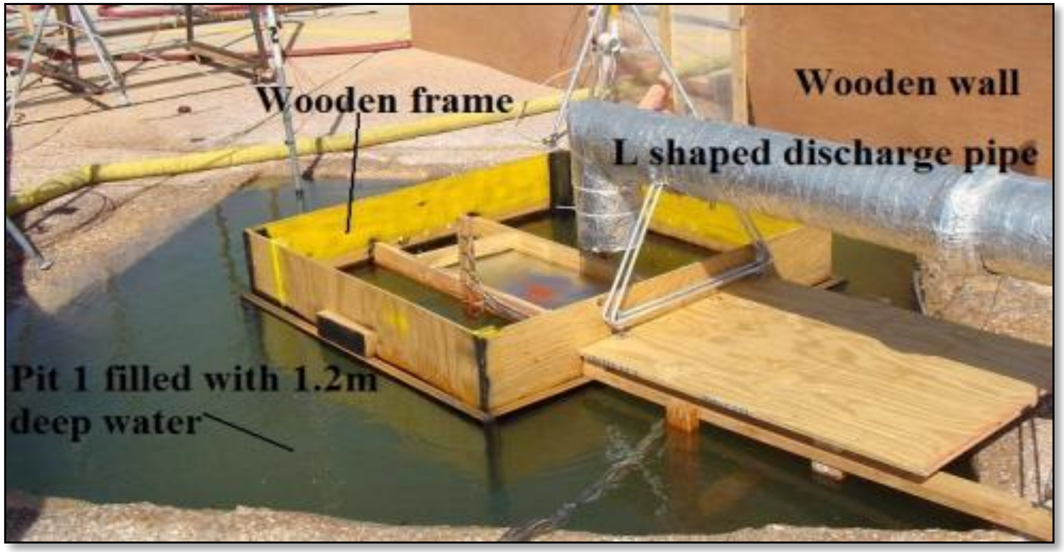
LNG Vapor Dispersion modeling with CFD

Field test setup



Controlling LNG Vapor Cloud using Water Curtain

Experiment design



- ❑ **Facility: Brayton Fire Training Field**

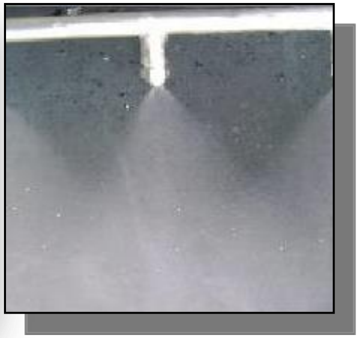
Pit 1 (3m x 3m x 1.22m) filled with water up to 1.2m

Wooden confinement (1.52m x 1.52m x 0.31m)

3 types spray: Fan, Conical and Fog


Fan type


Conical type


Fog type

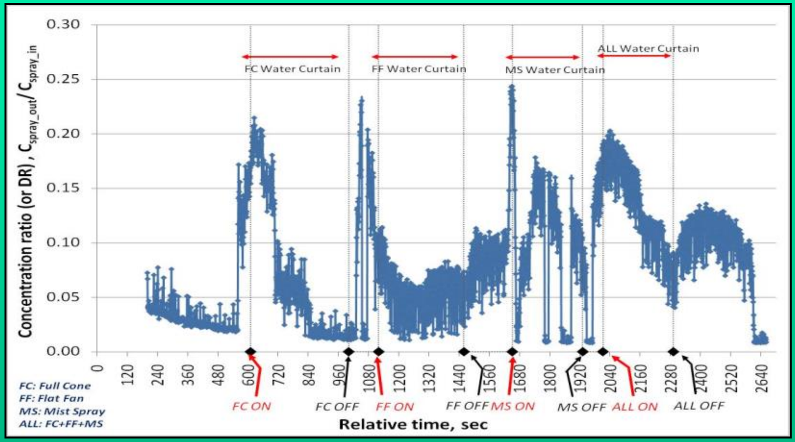
Controlling LNG Vapor Cloud using Water Curtain

Concentration Ratio

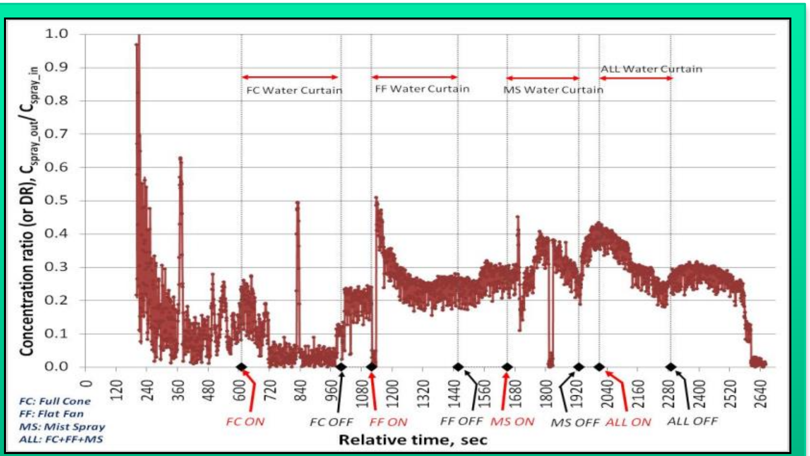
- **Dilution ratio (DR)– effectiveness of WC**

$$\text{Conc. Ratio (DR)} = \frac{\text{Average Conc.at 10m}}{\text{Average Conc.at 0m}}$$

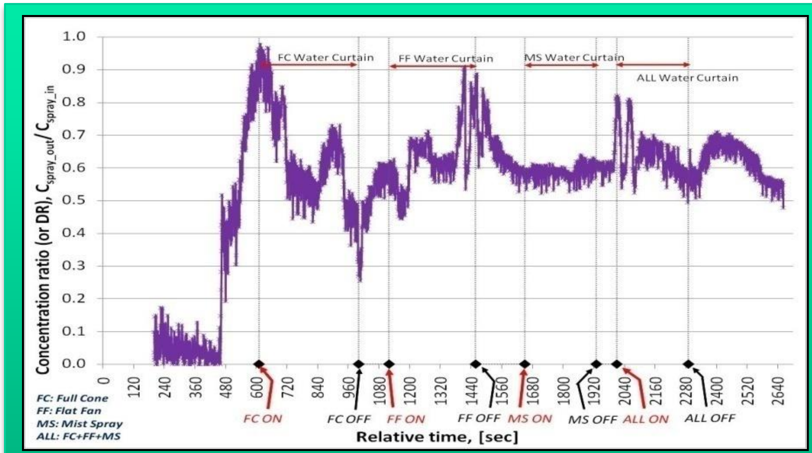
- **Assuming const. wind speed of 5.1 m/s**
- **Each water curtain showed different efficiencies in different mechanisms**



Concentration ratio at 0.5 m



Concentration ratio at 1.2 m



Concentration ratio at 2.1 m

LNG Fire Mitigation using Expansion Foam

Made in foam generators by mixing the foam solution with air to an expansion ratio, *i.e.,* 500:1

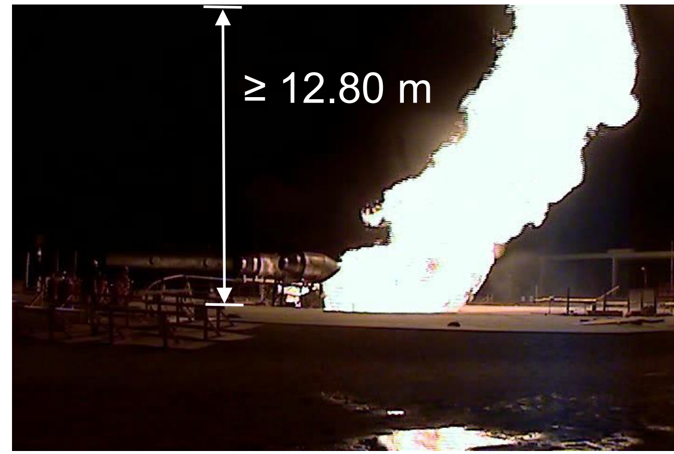
Foam generator

Expansion foam

LNG Fire Mitigation using Expansion Foam

Fire height reduction

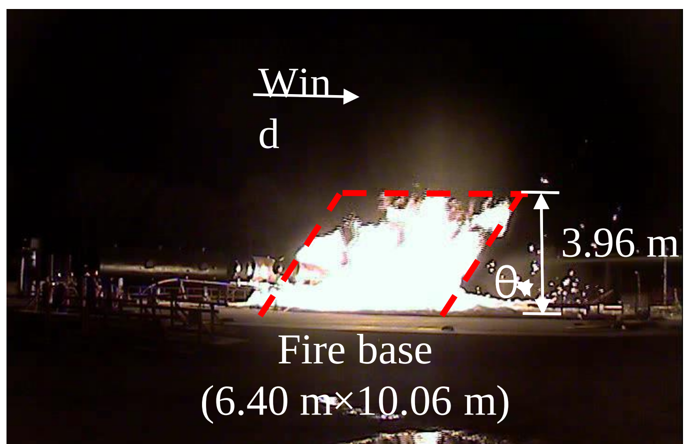
32 %
increase



1. Fire before foam application

2. Fire right after foam application

58 %
decrease



68 %
decrease

3. Fire during foam control at steady state

<March, 2009>

5. Changes in LNG Terminals

Regulations for LNG Terminals

LNG facilities are constructed according to Liquefied Natural Gas Facilities: Federal Safety Standards and regulated by Federal Energy Regulatory Commission (FERC). Federal regulations incorporate NFPA 59A (Prescriptive Standard)

Objective: Keep fire and explosion hazards onsite (*i.e.*, within the facility boundaries) in the event of a loss of a containment event.

Regulations for LNG Terminals

NFPA prescribes a series of 10 min duration design spills (also called accidental leakage), in order to analyze safety contours known as exclusion zones based on the following parameters:

Parameter	Criterion
Flammability Limit	½ LFL methane (i.e., 2.5% concentration
Radiant Heat Flux	Not exceeding 5 kW/m^2
Overpressure	Although NG vapor clouds are unlikely to produce damaging overpressures

Regulations for LNG Terminals

The exclusion zones are the regions where the potential hazard exists, and the public cannot be exposed to this hazard.

FERC *does not allow active systems* as mitigation strategies for the exclusion zone requirements. ONLY passive systems can be implemented for the accomplish of this criteria.

During the last years, FERC has clarified its interpretation of the federal requirements. These interpretations continue its evolution due to new analytical tools and new hazard criteria.

Regulations for LNG Terminals

Risk Based Analysis

The NFPA 59A and FERC have introduced risk-based analysis approaches that represent a change from the previous prescriptive approach.

There is a new chapter named: Performance (Risk Assessment) Based LNG Plant Siting.

Therefore, Likelihood or probability scenarios are integrated within the consequences analysis in order to identify injury or fatality of population nearby.

Additionally, FERC has included vapor cloud explosions hazards of flammable refrigerant releases from liquefaction processes (regarding to export terminals), which were not present in import terminals (based on vaporization processes).

Regulations for LNG Terminals

Import Terminals

FERC implemented the 2001 edition NFPA 59A to identify single accidental release scenarios.

Two types of hazardous outcomes were considered:

- Radiant heat flux (from pool fires)
- Flammable vapor dispersion

FERC required assessment of vapor dispersion from:

- Full cross-section pipe breaks
- High pressure flashing jets

DEGADIS was the software approved to calculate the boundaries derived from the ½ LFL cloud.

Regulations for LNG Terminals

Export Terminals

Refrigeration processes and the associated plants that are used to liquefy natural gas are considerably more complicated than import regasification terminals.

Due to the limited experienced with liquefaction processes, FERC and DOT had to reevaluate their requirements.

As result of this reassessment, these were the most significant changes proposed:

- New approval methodology for vapor dispersion software tools (PHAST and FLACS were accepted).
- New method of identifying single accidental leakage sources. (based on likelihood instead of prescriptive).
- Introduction of vapor cloud explosion calculations for <u>flammable refrigerants</u>

Regulations for LNG Terminals

From Import to Export Terminals

Flammable refrigerants such as chlorofluorocarbons, ammonium, carbon dioxide, and non-halogenated hydrocarbons might be more reactive than NG. (*i.e.*, ethylene can undergo vapor cloud detonation).

This new risk was not taken into account by the analysis of import terminals.

Additionally, FERC requires now to determine the zones where a 1psi overpressure can be presented in order to establish the overpressure boundary.

Conclusions

- Risk Assessment
  - Thermal Danger Zones; Tanker Danger Zones; Flammable vapor Danger Zones
- LNG has been used as transportation fuel in limited volume since 1970's
- There is an increase in interest for using LNG more in different sectors due to developments of many safety standards and rising global gas demand

Conclusions

- Though there has been fewer road incidents associated with LNG, the risks and hazards will be more with increasing use
- Safety of LNG trailer trucks and vehicle fuel tanks should be assessed and updated
- LNG industry has had a good safety record for the past 40 years
- Research needs to respond to dynamic situation