DOE/Sandia National Laboratories Coordinated Approach for LNG Safety and Security Research

Briefing to NARUC Staff Subcommittee on Gas
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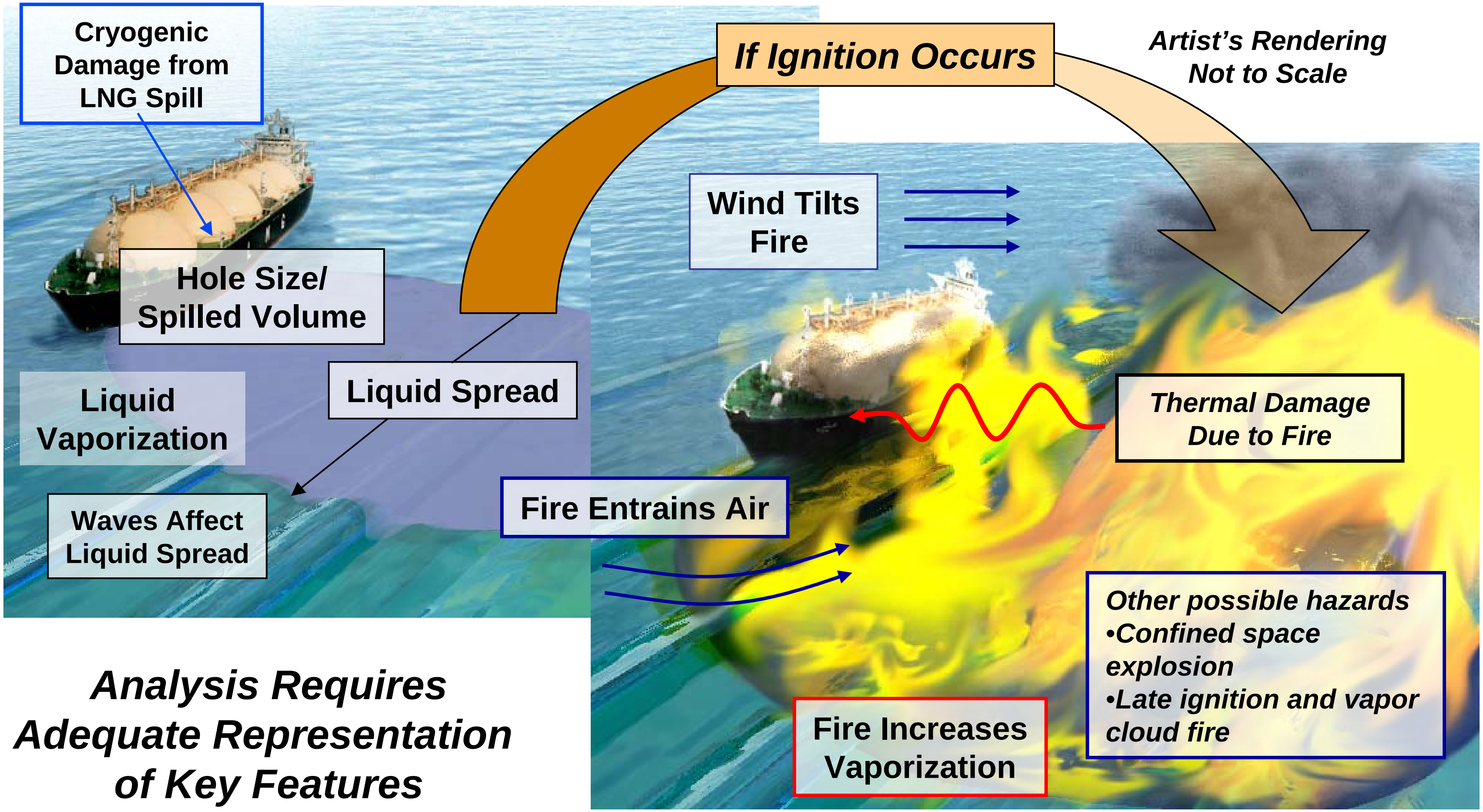
Key Features of LNG Spills Over Water



Analysis Requires Adequate Representation of Key Features

GAO-07-316 Maritime Security - Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification

February 2007

Conclusions

"…Understanding and resolving the uncertainties surrounding LNG spills is critical, especially in deciding on where to locate LNG facilities….

…Additional research to resolve some key areas of uncertainty could benefit federal agencies responsible for making informed decisions when approving LNG terminals and protecting existing terminals and tankers, as well as providing reliable information to citizens concerned about public safety."

GAO-07-316 Maritime Security - Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification

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Recommendation for Executive Action

“To provide the most comprehensive and accurate information for assessing the public safety risks posed by tankers transiting to proposed LNG facilities, we recommend that the Secretary of Energy ensure that DOE incorporates the key issues identified by the expert panel into its current LNG study.

We particularly recommend that DOE examine the potential for cascading failure of LNG tanks in order to understand the damage to the hull that could be caused by exposure to extreme cold or heat.”

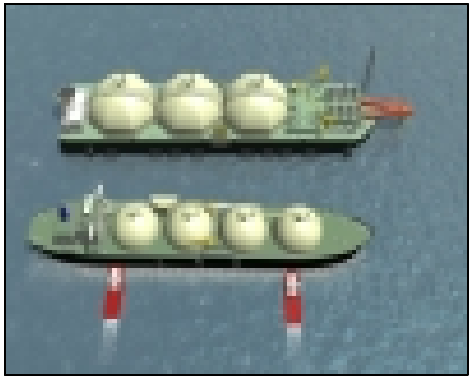
Expert Panel's Ranking of Need for Research on LNG Experts Suggest Future Research Priorities to Determine the Public Safety Impact of an LNG Spill

Rank	Research area	In Progress	Proposed
1.	Large fire phenomena	√	
2.	Cascading failure		√
3.	Large-scale spill testing on water	√	
4.	Large-scale fire testing	√	
5.	Comprehensive modeling: interaction of physical processes		√
6.	Risk tolerability assessments	√	
7.	Vulnerability of containment systems (hole size)	√	
8.	Mitigation techniques		√
9.	Effect of sea water coming in as LNG flows out		
10.	Impact of wind, weather, and waves		

Source: GAO

Sandia LNG Activities

- December 2004, DOE "Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill over Water", SAND2004-6258
- Classified Vulnerability Analysis & Breach Research
- USCG
  - Cabrillo Deepwater Port (California), January 2006, US Coast Guard "Review of the Independent Risk Assessment of the Proposed Cabrillo Liquefied Natural Gas Deepwater Port Project", SAND2005-7739
  - New England Deepwater Ports (Massachusetts) April 2006, US Coast Guard "Independent Risk Assessment for Neptune and Northeast Gateway Deepwater Ports", report by Acutech Consulting Group for USCG
  - Calypso Deepwater Ports (Florida)
  - Others in progress
- Large Scale Spill and Fire Research
- Proposed Cascading Failure Research



LNG Spill Safety Analysis and Risk Management Guidance

SAND2004-6258

- Provide direction on hazards analysis
- Identify "scale" of hazards from intentional events
- Provide direction on use of risk management to improve public safety
- Provide process for site-specific evaluations

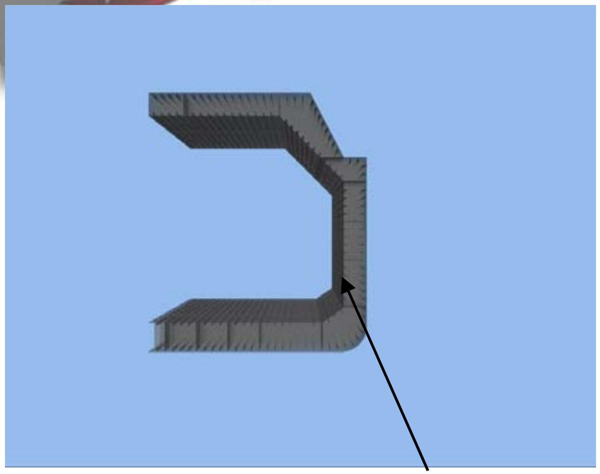
Study used many resources: experts from academia, government and industry on LNG vessel design and operations, explosion and fire modeling, terrorism, and risk management

Structural Analysis Approach for Attack and Breach of LNG Ship

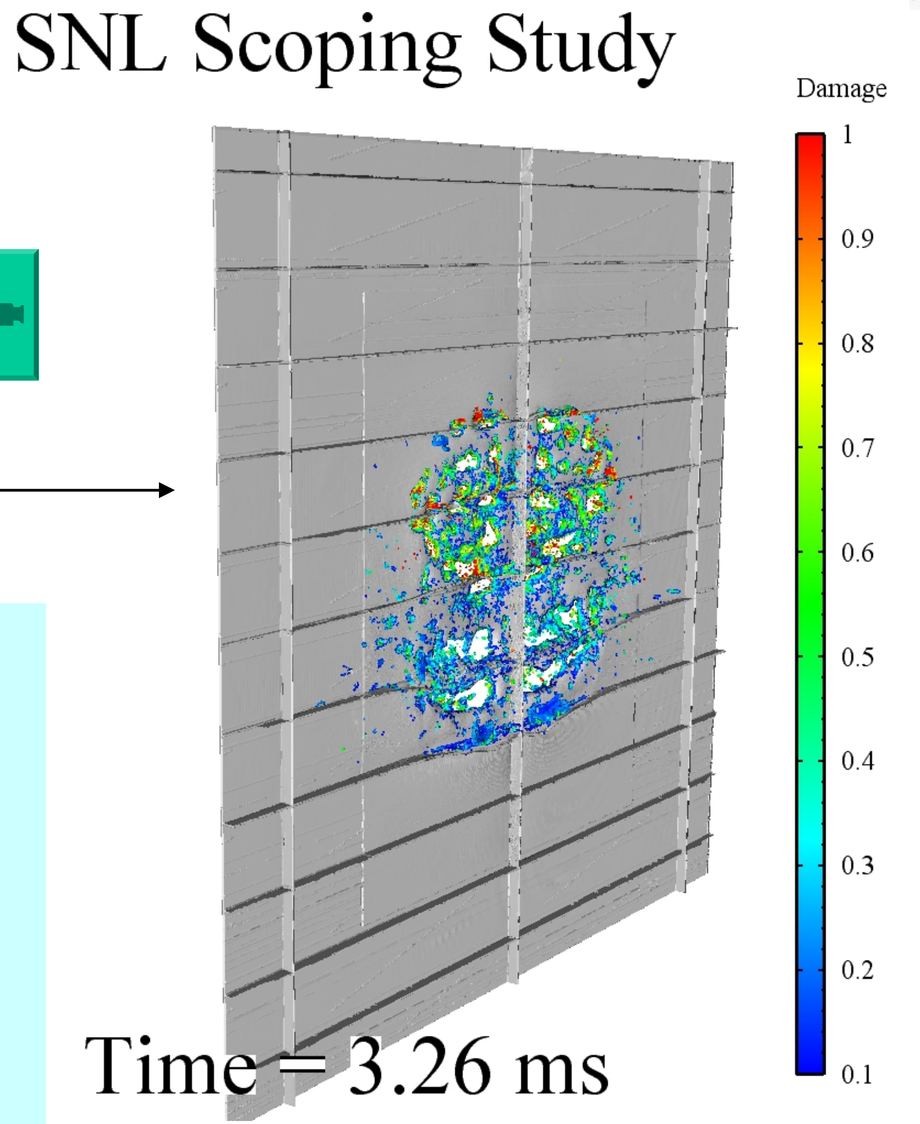
Detailed 3-D ship calculations using the shock physics code, CTH, developed at Sandia

- Multi-dimensional, multi-material shock wave propagation and material motion.
- Structure modeled using finite elements - billions of nodes required to resolve thin-walled structures
- Using massively parallel computers, 1000 - 3000 processors
- Full scale, detailed model geometry
- Water, LNG, and thermal insulation on tank included
- Assessing different explosive charge shapes, sizes, and standoff distance from hull

Sample 3-D Calculation Result



View of inner hull damage →



(1 ms = 1/1000 second)

- Thin structures are resolved using adaptive mesh refinement
- Lower portion damaged from impact of water thrown inward from blast
- Upper portion damaged from thrown fragments from outer hull

A Coordinated Plan for LNG Safety and Security Research

1. LNG Fire Physics – In progress
   – Objective: To determine if calculated thermal hazard distances can be reduced from conservative estimates by an order of magnitude for large-scale LNG pool fires.

2. Cascading Failure - Proposed
   – Objective: Determine if intentional attacks could result in cryogenic or fire-induced damage to the ship structure that would lead to cascading (multi-tank) structural failures and catastrophic release of LNG. Develop an expected timeline for cargo release based on the postulated scenarios

3. Mitigation - Proposed
   – Objective: Develop mitigation options to reduce the risk to ships at land-based and deep water ports. Where appropriate, provide benchmark test data and analyses required to plan mitigation strategies.

LNG Fire Physics Research

- Reduced-scale Tests in SNL's Thermal Test Complex (TTC) – In Progress
  - Objective: Determine the flame height as a function of pool diameter and the critical diameter for mass fire behavior to obtain best estimates of fire surface area

- Large-scale LNG pool fire tests - In Progress
  - Objective: To determine trends in flame height, smoke production, and burn rate

- CFD model development for LNG pool fires - Proposed
  - Objective: To use CFD and analysis to predict fire behavior at the scales of interest and to provide guidance to industry.

Small Scale LNG Pool Fire Tests

Q* correlation for flame height & mass fire

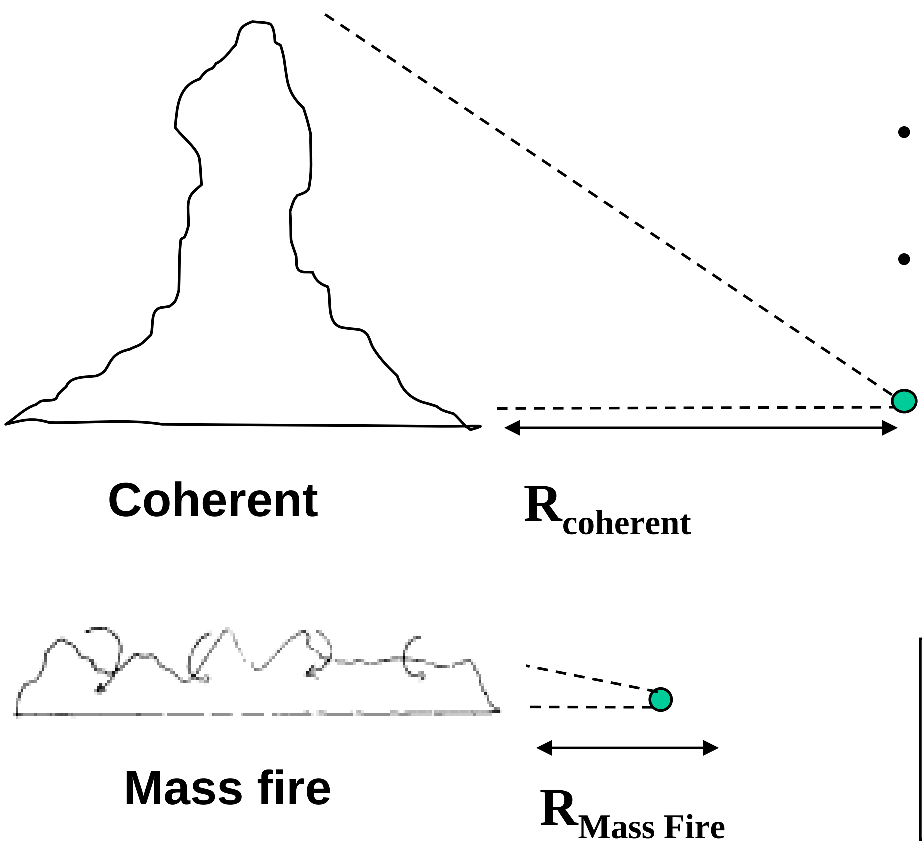
Thermal Test Complex at Sandia, 3 m diameter gas burner capability

- Flame height for LNG pool fires (~100 m) is uncertain. Mass fire behavior is also unknown.
- Previous studies have not used burners which result in fully turbulent fires (i.e. different physics).
- Controlled fuel flow rate experiments.
  - **develop flame height correlation**
  - **investigate mass fire behavior**
- Will compare correlation to measured flame heights from large scale tests.

3-m diameter hydrogen test observed by the DOE/NARUC LNG Partnership on 3/21/2007

Flame Coherence vs. Mass Fire

Very different thermal radiation view factors



- Height/diameter (L/D) ratio is between 1.0 and 2.0 based on current flame height correlations for pool diameters 200 – 500 m
- Large fires (D>100 m) generally break up into 'mass fires', characterized by a low L/D ratio (< 0.5) e.g. forest fires
- Presently unknown at what diameter very large LNG fires will exhibit mass fire
- Use Q* correlation to predict mass fire

Thermal hazard distance will be reduced with lower flame height

Thermal hazard distance: 5 kW/m² heat flux is the commonly used value for establishing fire protection distances for people (30 second exposure causes 2nd degree skin burns (blisters) at this distance)

DOE/SNL Large Scale LNG Spill Fire Experiments
Purpose, Approach, and Anticipated Benefit

- Anticipate a significant increase in Liquefied Natural Gas (LNG) tanker deliveries to U.S. ports
- Public safety concerns from an accidental or intentional spills have increased
- While improvements have been made over the past decade in assessing hazards from LNG spills, the existing experimental data is much smaller in size and scale than many postulated large accidental and intentional spills
- Large scale experimental data is needed to develop and validate fire models to address current spill and hazard assessment deficiencies
- DOE and SNL will perform LNG spill fire experiments (on water) at intermediate to large scale (~40 m up to 100 m diameters)
- Experiments will generate knowledge on fire parameters such as smoke generation and shielding, flame height, thermal flux, and burn rate as a function of pool size

- **Potential to significantly reduce hazard distances from an LNG spill over water**

Smoke Shielding

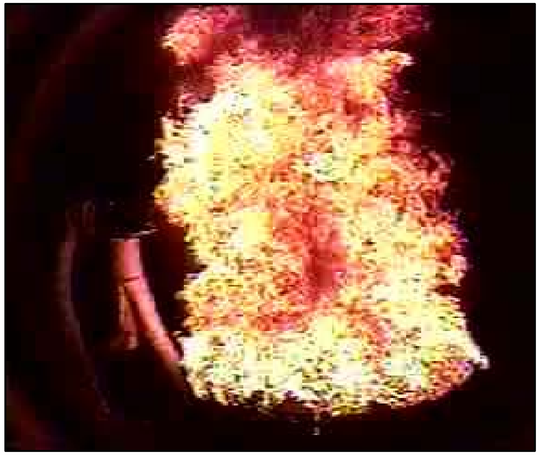
Fact: Emissive power decreases with increasing fire size due to smoke shielding

- LNG (100% methane) spill and pool fire on water
- 300 gpm spill rate
- 10 m diameter fire
- SNL Water Impact Facility

No smoke shielding at 10 m scale

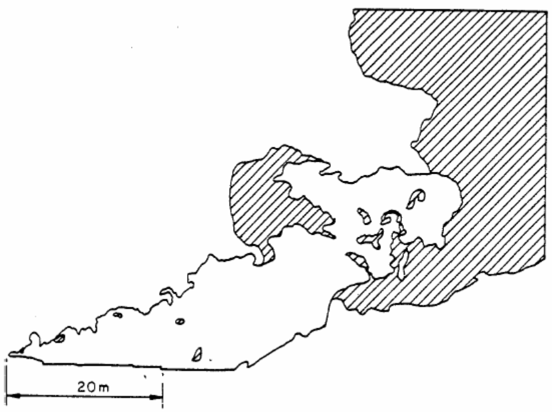
Smoke Shielding

JP8 – 2 m (SNL)



JP8 – 3 m (SNL)

JP8 – 20 m (China Lake)



LNG – 20 m

Maplin Sands Tests – 1982

LNG – 35 m

Montoir Tests – 1989

?????

LNG ~ 200 m

The smoke shielding is expected to increase for large LNG fires, however, the amount of smoke shielding is unknown.

DOE/SNL Large LNG Fire Experiment Test Methodology

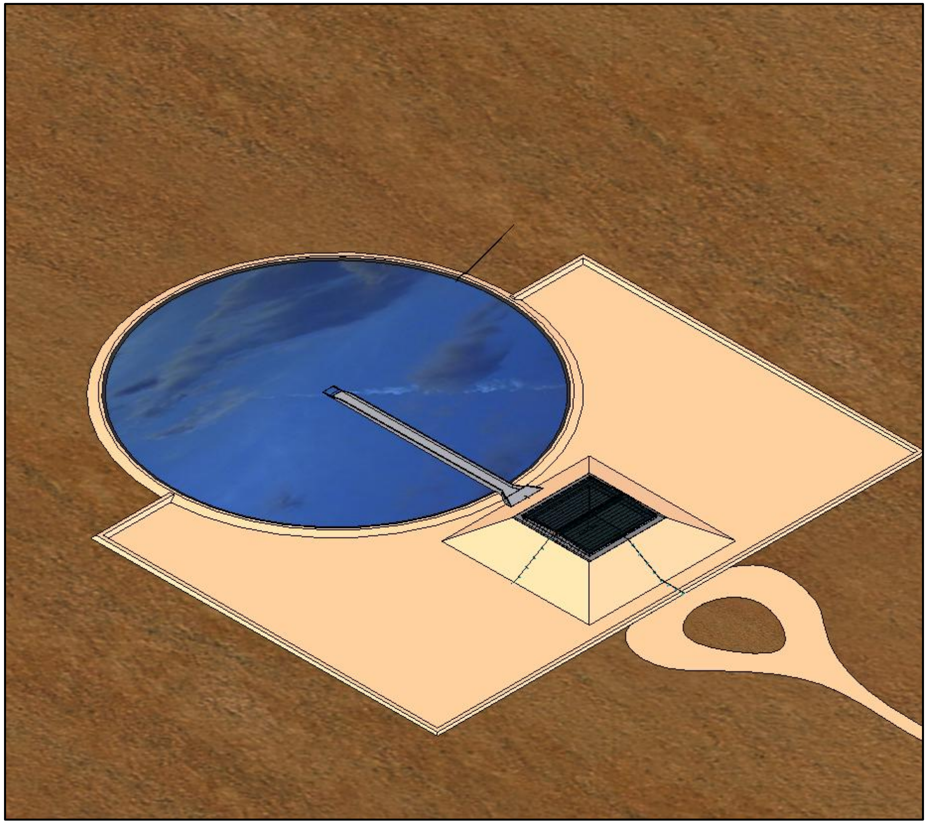
- Identify reservoir design criteria and appropriate test site
  - SNL/NM D Explosive Test Site
  - 900 m diameter hazard zone fully within Sandia property
- Construct a 120 m diameter water pool (1 m deep)
- Construct a reservoir to contain up to 310,000 gallons LNG
- Construct reservoir systems and channel to discharge LNG at pool center
- Construct LNG process fill piping
- Install reservoir, pool, and perimeter instrumentation
  - (flow rate, meteorology, video, IR, heat flux, etc.)
- Conduct minimum 3 baseline tests

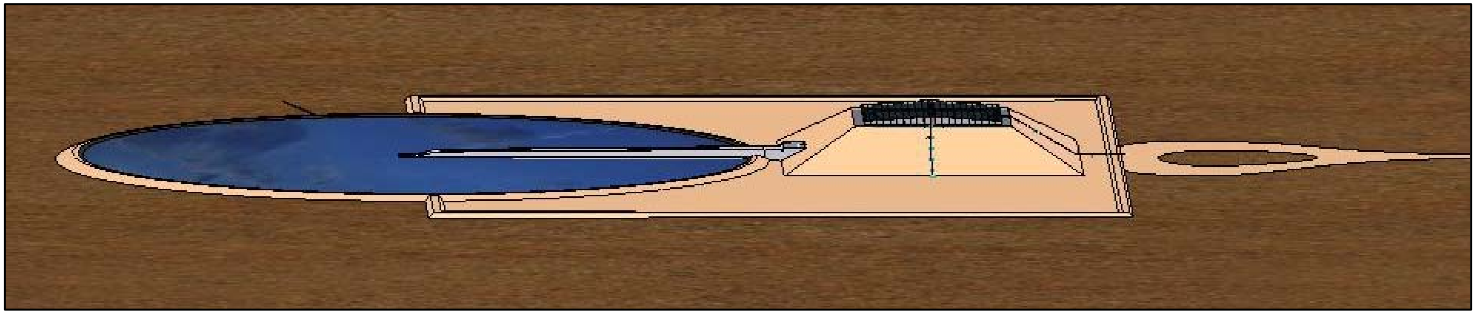
Design criteria: 1) Mass flux = 0.2 kg/m^{2}s (yielding a burn rate of 5 x 10^{-4} m/s), 2) Spread time = 3 minutes (for the 100 m diameter pool), and 3) Steady-state pool fire duration = 2 minutes. Determines a reservoir liquid capacity of 310,000 gallon (1175 m^3)

Fire Diameter (m)	LNG volume (gallons)	LNG flow rate (gpm)
40	51,000	10,000
70	154,000	31,000
100	310,000	62,000

Large LNG Experiment Description

- LNG gravity released onto a 120-m diameter water pool (1-m deep).
- Concrete-lined soil-bermed reservoir supplies pipes that extend from the reservoir bottom to a covered collector box.
- LNG flows on an open concrete channel to the center of the pool.
- Capped reservoir vents LNG vapors during the filling process.
- Large diked impoundment area in event of reservoir leakage





Cascading Failure of LNG Ships

Proposed Research

Objectives:

1. Determine if intentional attacks could result in cryogenic or fire-induced damage to the ship structure that would lead to cascading (multi-tank) structural failures and catastrophic release of LNG.

2. Develop an expected timeline for cargo release based on the postulated scenarios

Cascading Failure Due to Cryogenic Damage

Proposed Research

- Approach: Perform scaled tests on a prototypical model that has some of the typical structural features found in an LNG ship, by exposing portions of the prototype model to Liquid Nitrogen (LN).
- Test data used to confirm that computer simulations are realistic and adequately represent the physical event.
- Full-scale LNG vessels would be analyzed with specified structural degradation in locations where cryogenic damage may occur.

30-40 m^3 LNG spill on deck results in brittle fracture

Source: A. Valudolon (2000)

Cascading Failure Due to Fire

Proposed Research

1. A large spill is likely to result in a large fire that would partially engulf the ship.
2. Thermally induced structural failure is likely if the temperature of the structural steel of the vessel reaches a critical value.
3. A flux and temperature profile will be calculated based on the cargo discharge timeline.
4. These initial conditions will be passed to a simulation capable of predicting ship response with blast and thermal damage.

Mitigation

Proposed Research

Objective: Develop mitigation options to reduce the risk to ships at land-based and deep water ports. Where appropriate, provide benchmark test data and analyses required to plan mitigation strategies.

Mitigation strategies:

1. Prevent an LNG tank breach (security measures to thwart an attack are included in this category).
2. Reduce the severity of the spill.
3. Reduce fire hazards.

Structural Breach and Fire Mitigation
Proposed Research

The protection of LNG Carriers and Deepwater ports, as well as land-based facilities, should be based on a defense-in-depth strategy. In the event that active protection and structural mitigation strategies fail, it is important to develop improved methods to reduce the hazards from a pool fire.

Structural:

1. Matrix of benchmark tests and analyses to identify vulnerabilities.
2. Utilize benchmark tests to validate modeling and simulation used for damage predictions.
   - Structural damage from a boat attack
   - Structural (cryogenic) damage from small standoff devices leading to cascading failure event
   - Insider/on-board attack
3. Develop mitigation strategies and recommendations to harden the ship to attack.

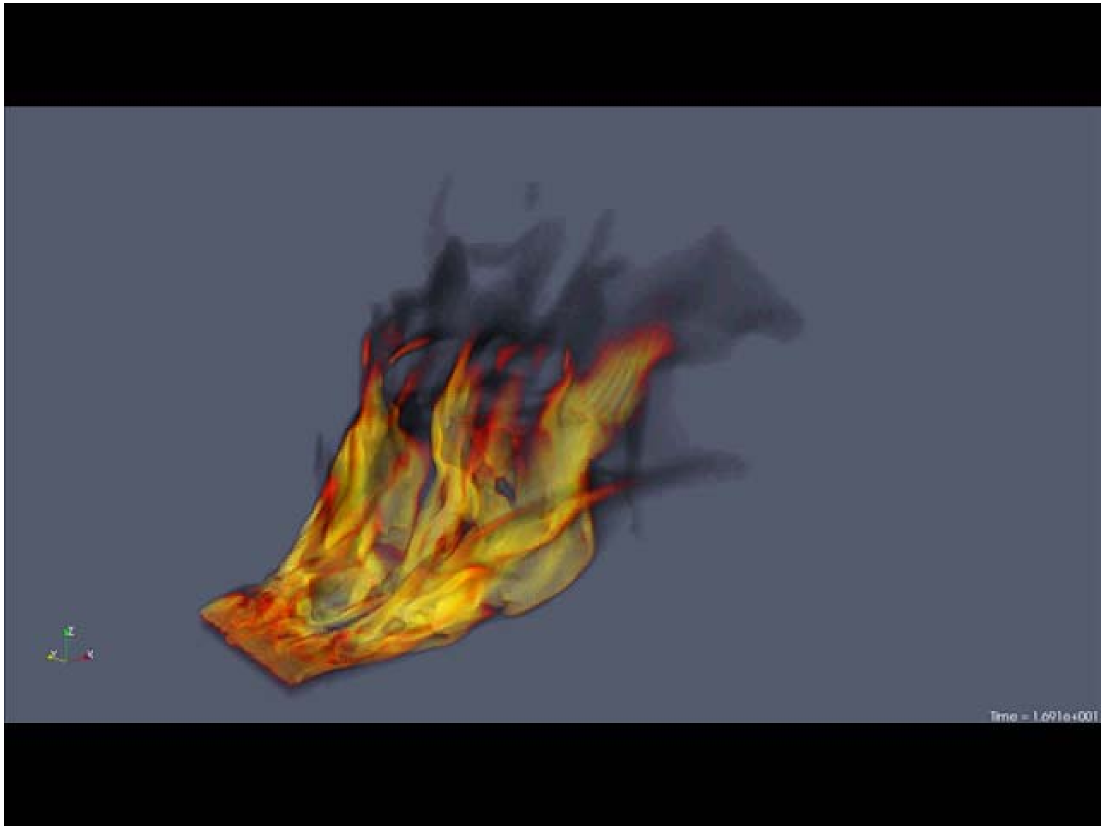
Fire: Possible methods that could be investigated include:

1. Adding heavier hydrocarbons which would increase smoke shielding.
2. Strategically adding foam to help quench the fire.
3. Heat flux smoke curtains.

Looking to the Future

- CFD model development for large-scale LNG pool fires
  - Pool regression rate model for Heat Release Rate
  - Validated soot model for Heat Flux

The design of the qualification experiment in the new cross-wind test facility with Fuego represents the accreditation test of our modeling and simulation capability by the weapons community.



Simulation for design of a weapons test using FUEGO