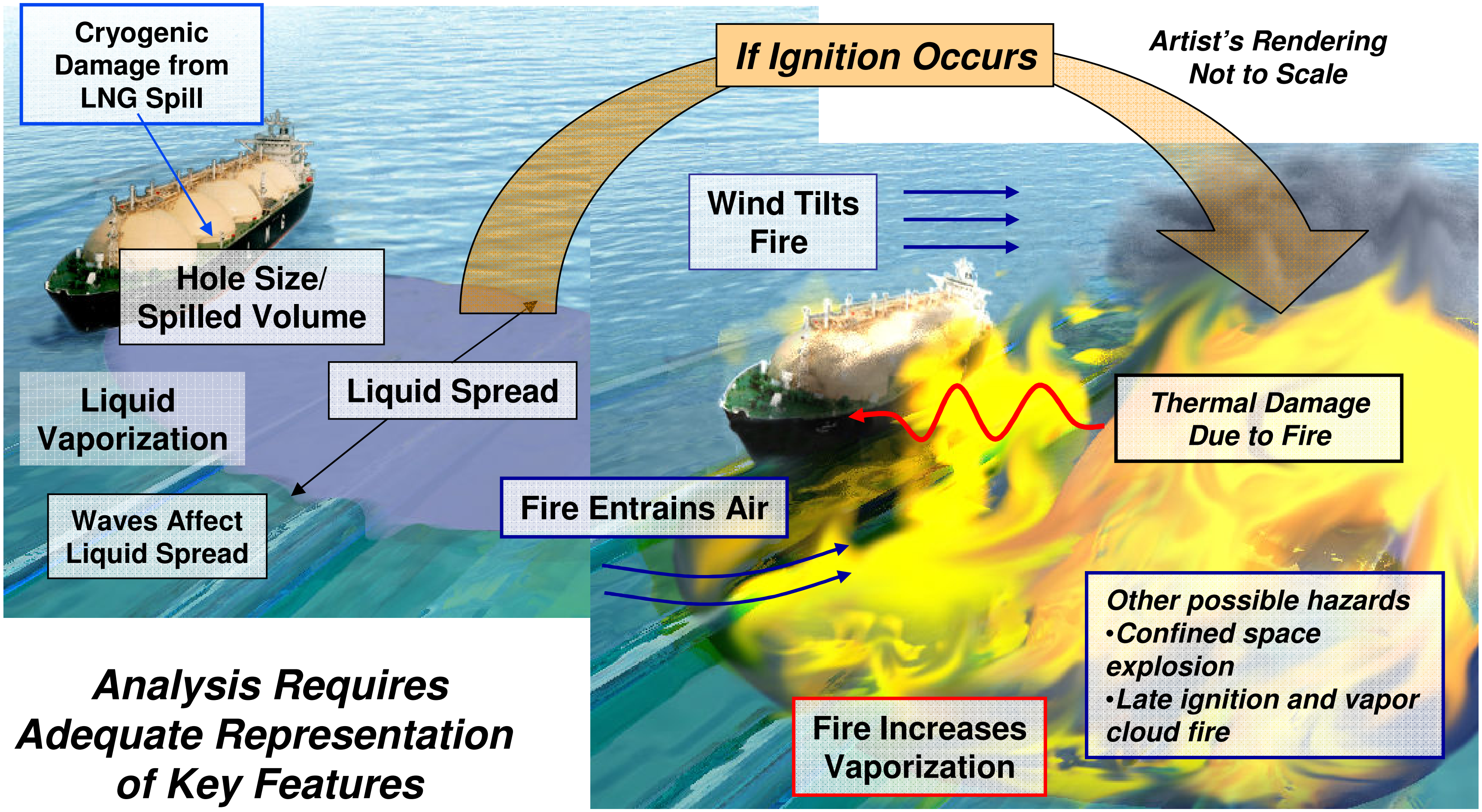
DOE/Sandia National Laboratories Coordinated Approach for LNG Safety and Security Research

Staff Subcommittee on Gas, NARUC Summer Committee Meetings, Seattle, WA
July 19, 2009

Anay Luketa
Fire and Aerosol Sciences
Sandia National Laboratories

Christopher J. Freitas, Program Manger, Natural Gas Storage, Pipeline Reliability, and LNG, Office of Oil and Natural Gas
United States Department of Energy

Key Features of LNG Spills Over Water



Analysis Requires Adequate Representation of Key Features

A Coordinated Plan for LNG Safety and Security Research

1. **LNG Fire Physics – In progress**
   - Objective: Determine thermal hazard distances for large-scale LNG pool fires
   - Obtain data on surface emissive power, flame height, and burn rate
2. **Cascading Failure - In progress**
   - Objective: Determine if cryogenic or fire-induced damage to the ship leads to cascading (multi-tank) structural failures and catastrophic release of LNG
   - Develop models and perform reduced-scale experiments
3. **Mitigation – Start after task 1 and 2**
   - Objective: Develop mitigation options to reduce the risk to ships at land-based and deep water ports.

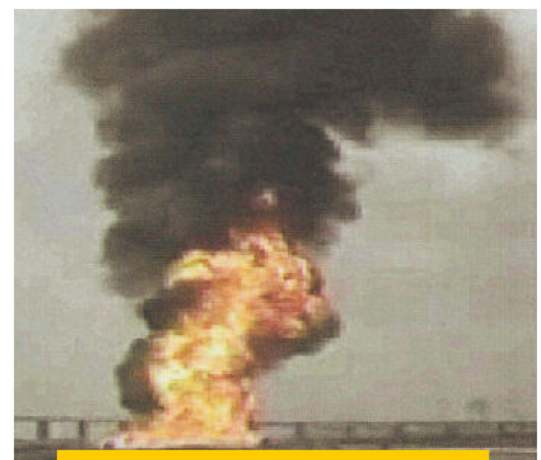
LNG Pool Fires

- Large scale experimental data is needed to develop and validate fire models to address current spill and hazard assessment deficiencies
- LNG fires do not produce smoke like typical hydrocarbons at scales tested to date (35 m diameter or less).
- Emissive power data inconclusive at large scale
- Flame height and burn rate uncertain
- We expect smoke shielding to occur in LNG spill fires of very large diameter (100’s of meters), but no data at these scales.

SNL 7.9 m
JP-8 pool fire

SNL 10 m
LNG pool fire

SNL 23 m
LNG pool fire



Montoir 35 m
LNG pool fire

Large LNG Pool Fire Tests at Sandia

Experiment Description

- Concrete-lined soil-bermed reservoir
- LNG gravity released onto a 120-m diameter water pool
- Reservoir, pool, and perimeter instrumentation to measure burn rate, flame height, and heat flux (smoke shielding)

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 Pool Fire on Water

First Test

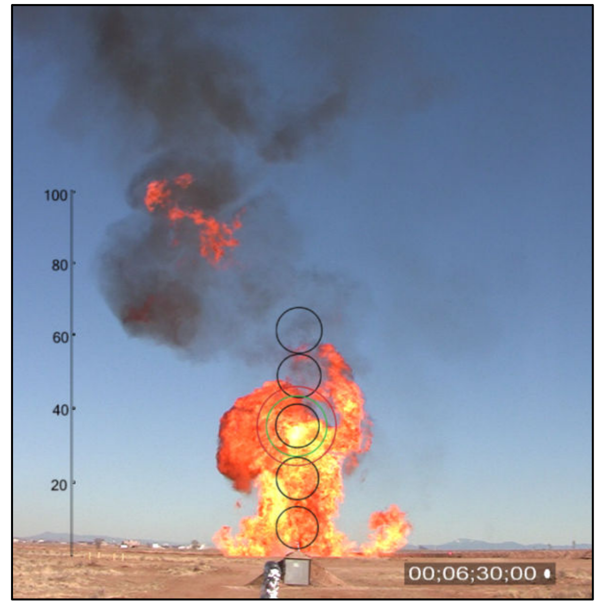
- First test conducted on February 19th, 2009 at Sandia
- Pool diameter of 23 m. Test designed to result in a 35 m to 40 m pool, but too much vapor loss. Currently addressing vapor loss issue for 2nd test.
- Conducted in a wind speed of 4.9 ± 0.8 m/s
- Flame height ~50 meters
- Flame tilt of ~50^0

Surface Emissive Power for Test 1 (23 m dia.)

- **Three different types of instruments were used to measure surface emissive power**
  - **Narrow-angle Radiometers**
  - **Wide-angle Radiometers**
  - **Infrared Spectrometers**

All measurements were in agreement

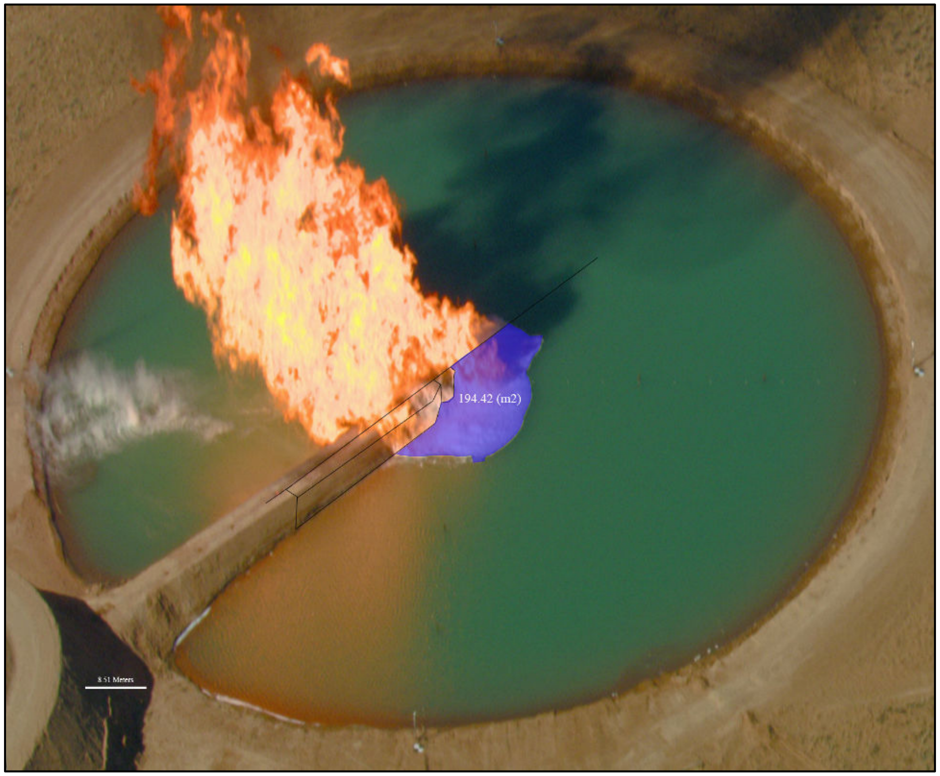
- **Results indicate a temporal and spatial average surface emissive power of approximately 150-180 kW/m²**



Gauge	Height (m)	Ave SEP (kW/m^2) 300s - 500s
1	8.5	212 ± 20
2	22.3	173 ± 48
3	36.1	95 ± 52

SEP decreased with height

Burn Rate for Test 1 (23 m dia.)

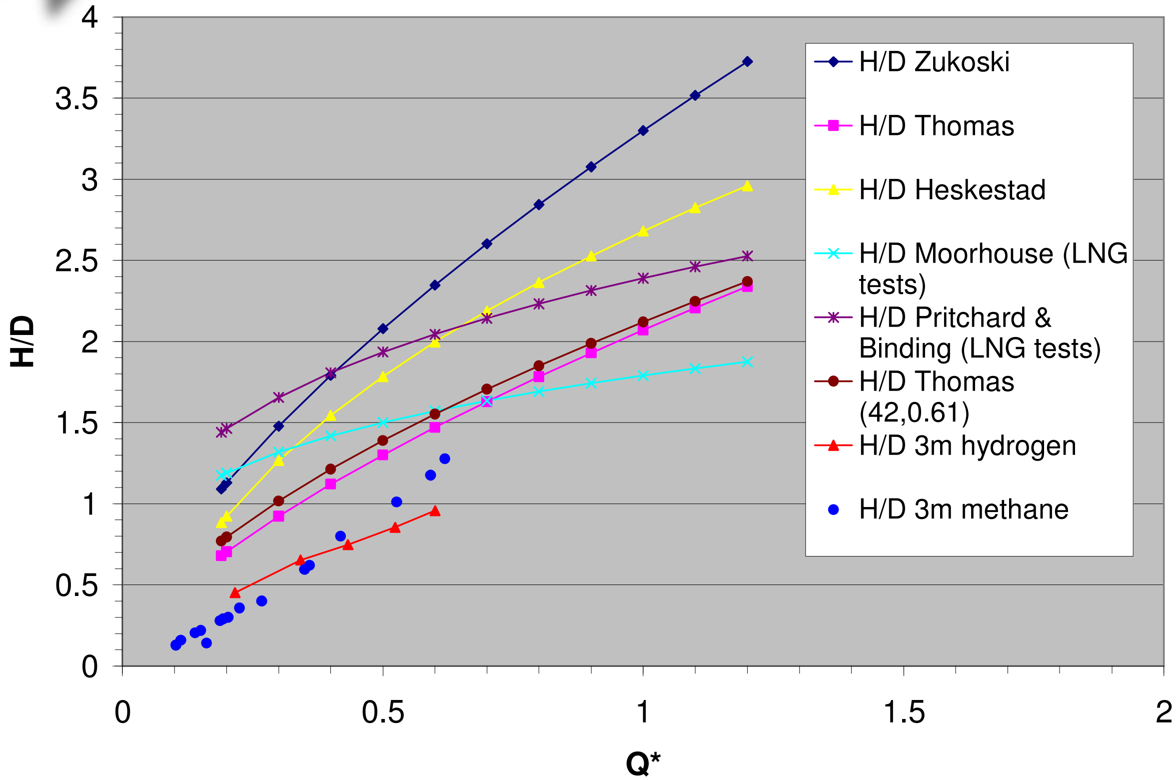


Burn rate determined by dividing the spill rate by the pool area

$$Burn\ \ rate = {}^{Spill\ Rate}\!\big/_{Pool\ Area}$$

Pool Area (m^2)	Pool Diameter (m)	Spill Rate (kg/s)	Regression Rate (kg/m^2s)
413.5 ± 51.6	22.9 ± 1.4	53.3 ± 0.9	0.13 ± 0.02

Flame height/diameter ratio from Reduced Scale Tests - 3 m burner



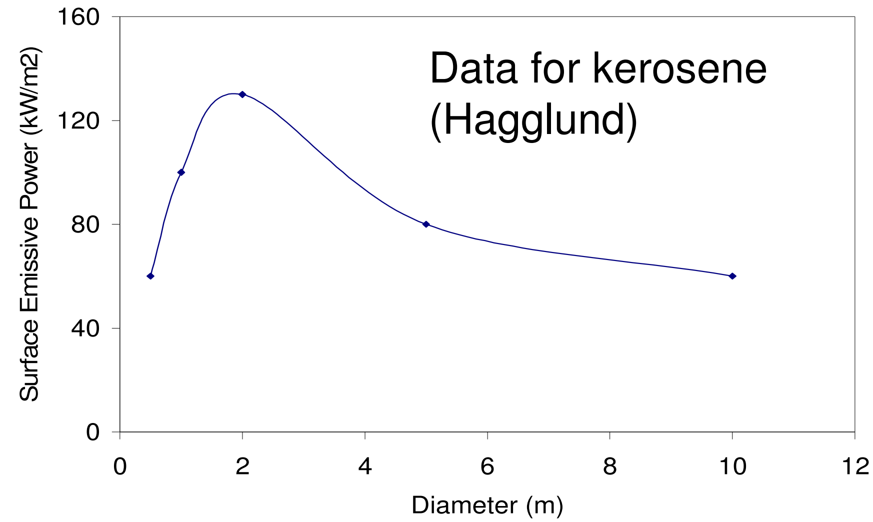
Test conducted in Flame Test Cell at Sandia using 3 m burner

100 m, Q* = 0.47
70 m, Q* = 0.57
35 m, Q* = 0.82
23 m, Q* = 1.0

- Note that smaller Q* values mean larger diameter
- H/D data falls below all of the correlations, suggesting a lower height to diameter ratio for large scale LNG pool fires
- H/D values are between 0.25 and 0.5 for anticipated pool diameters of 200 to 500 m.

23 m LNG pool fire on water
Summary

- **Surface Emissive Power ~150-180 kW/m²**
- **Burn Rate ~0.13 kg/m²s**
- **L/D ~2**
- **Tilt ~50°**
- **T_{flame} ~1250°C**
- **ε_{flame} ~0.3-0.8**

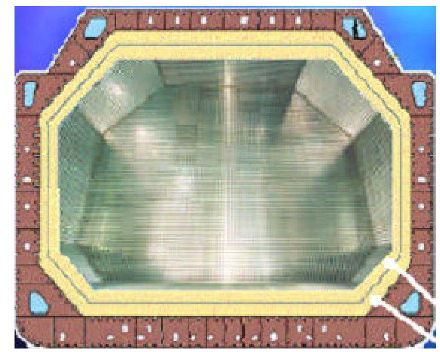


For 100 m test:

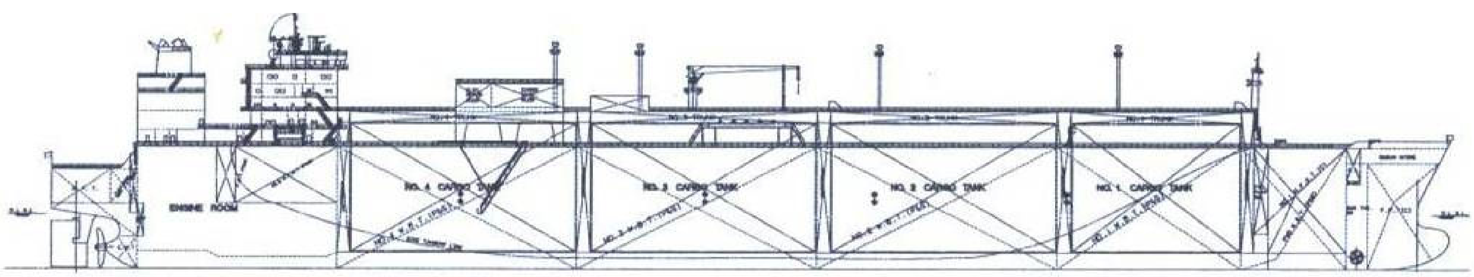
- **Expect to measure a lower surface emissive power. Other hydrocarbons indicate a peak value then decreases with increasing diameter.**
- **Expect a flame height of approximately 75 m based on reduced scale experiments**
- **No indications that the burn rate will change appreciably**

Cascading Damage Research

- **Purpose is to determine the extent of damage to an LNG ship in the event of a breach**
- **Damage to hulls can occur from a pool fire or from direct contact with LNG**



MOSS **MEMBRANE**

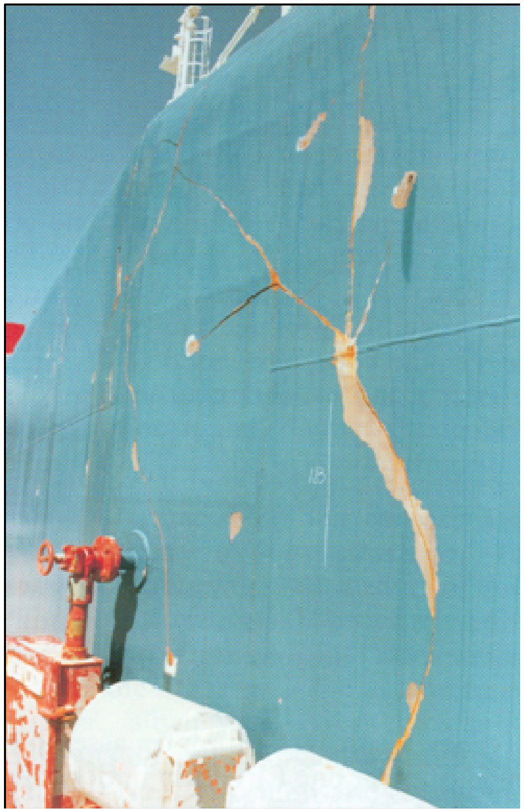


LNG distributed among 4 to 6 individual tanks separated by cofferdams

Cascading Failure Due to Cryogenic Damage

Questions to be answered:

- **Ships materials have demonstrated brittle fracture from LNG exposure. Under what conditions will a crack occur?**
- **Will an adjacent tank fail in the event of a breach of one tank?**
- **If so, what are the time and length scales of the event?**



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

Source: A. Valudolon (2000)

LNG Cascading Damage Approach

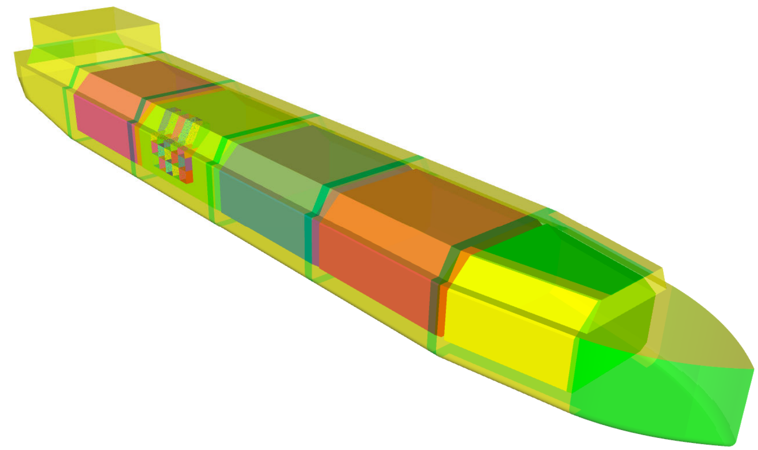
- Experimental testing of cryogenically-induced failures for development & validation of cryogenic failure models
  - Toughness-temperature transition curves
  - Linear elastic failure models
- Two vessels examined: Membrane and Moss
- One to three breach scenarios are planned to be evaluated for each class of ship
- Conditions analyzed are near shore, calm water

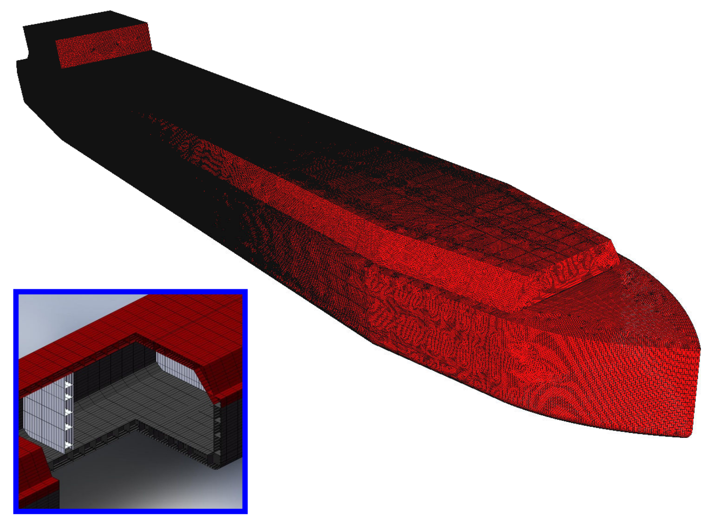
Each scenario must examine:

- Extent of LNG flow
- Cooling of the steel structure
- Determine extent of damage due to cryogenic temperatures
- Model external fire and heat-up of steel structure
- Assess continuing load redistribution as damage progresses

Full Vessel Model Development

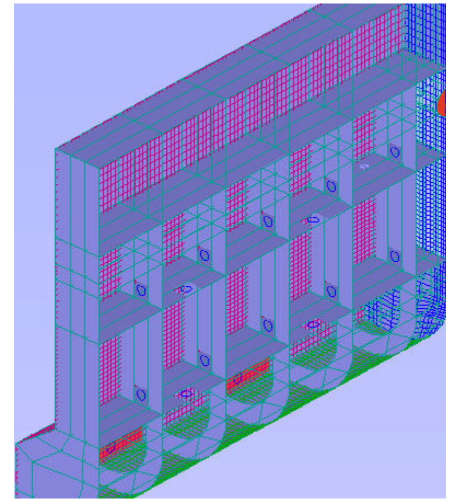
- Using detailed drawings and information on Membrane and Moss vessel
- Consulted with naval architect to review data for full vessel Finite Element Model development
- Structural components will be explicitly represented
- Weight distribution for non-structural items and LNG cargo will be represented

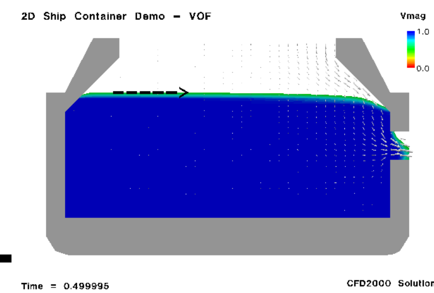




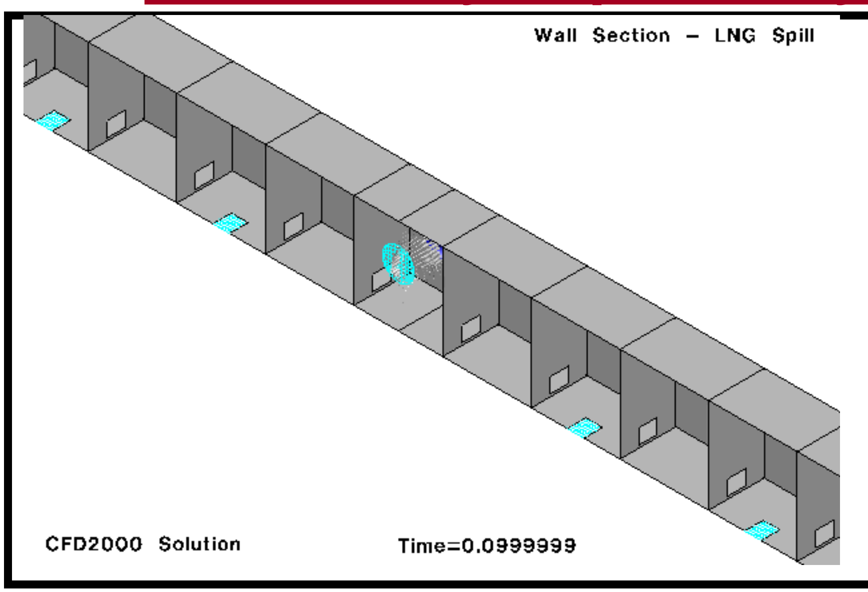
LNG Flow Analysis

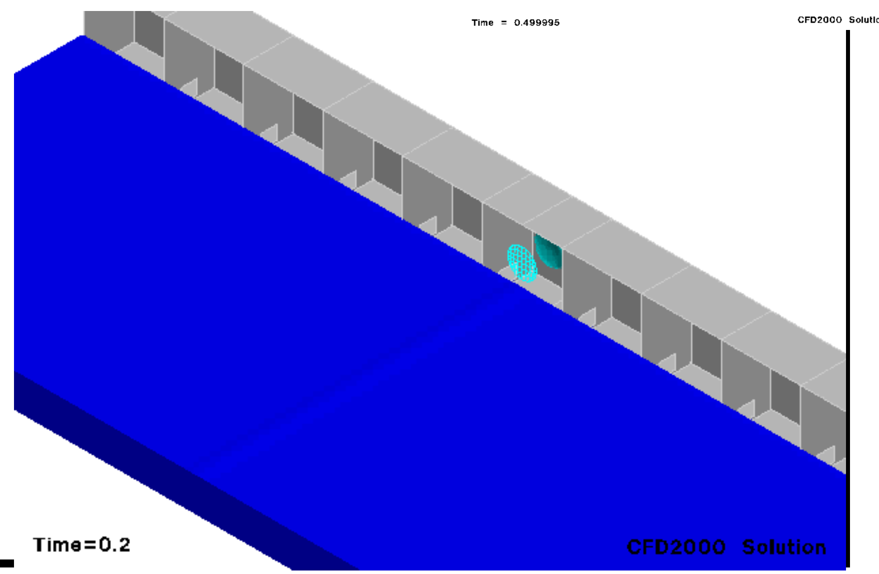
- Representations of the vessel hulls and initial breaches will be included in the flow analysis
- The flow analysis will be used to estimate the:
  - Drain time of affected tank(s)
  - Time-varying flow of LNG within the hulls
  - Size of the LNG pool formed outside the ship
- Preliminary simulations underway





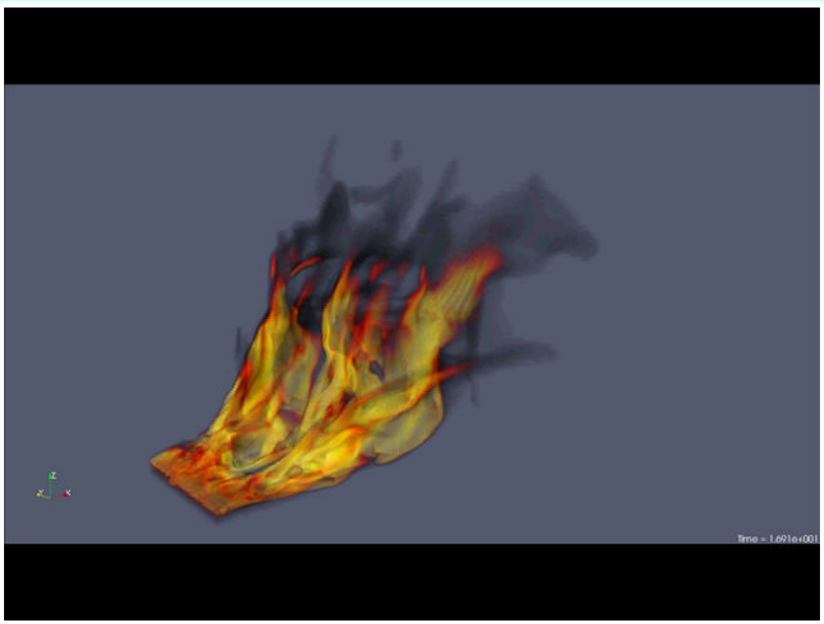
Preliminary Exploratory Simulations



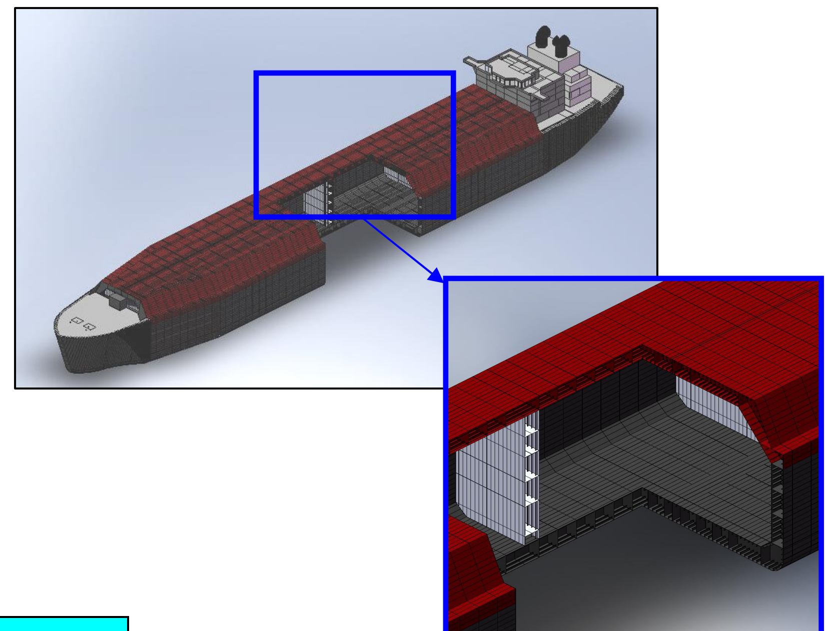


Cascading Failure Due to Fire

- **Large spill → large fire → thermally-induced structural failure?**
- **Validated large-scale pool fire simulations to determine heat flux profiles**
- **Failure criteria for relevant materials (steels, foam insulation, etc.)**
- **Coupled thermal and structural response models to predict ship response.**



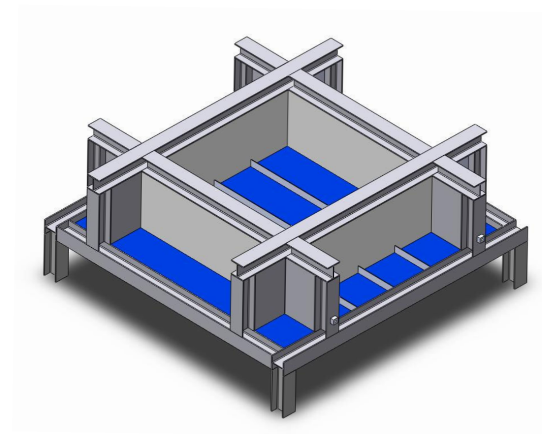
Fuego simulation for design of a weapons test

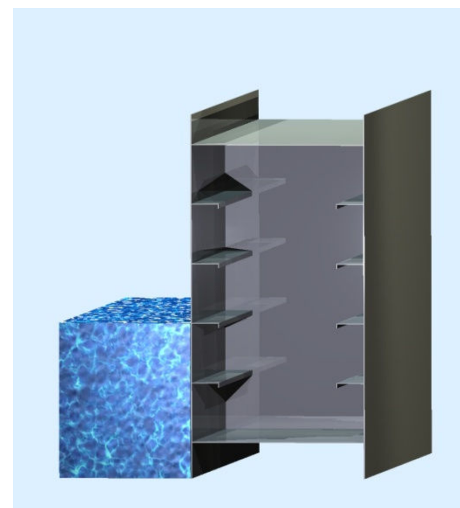


Cryogenic Damage Testing

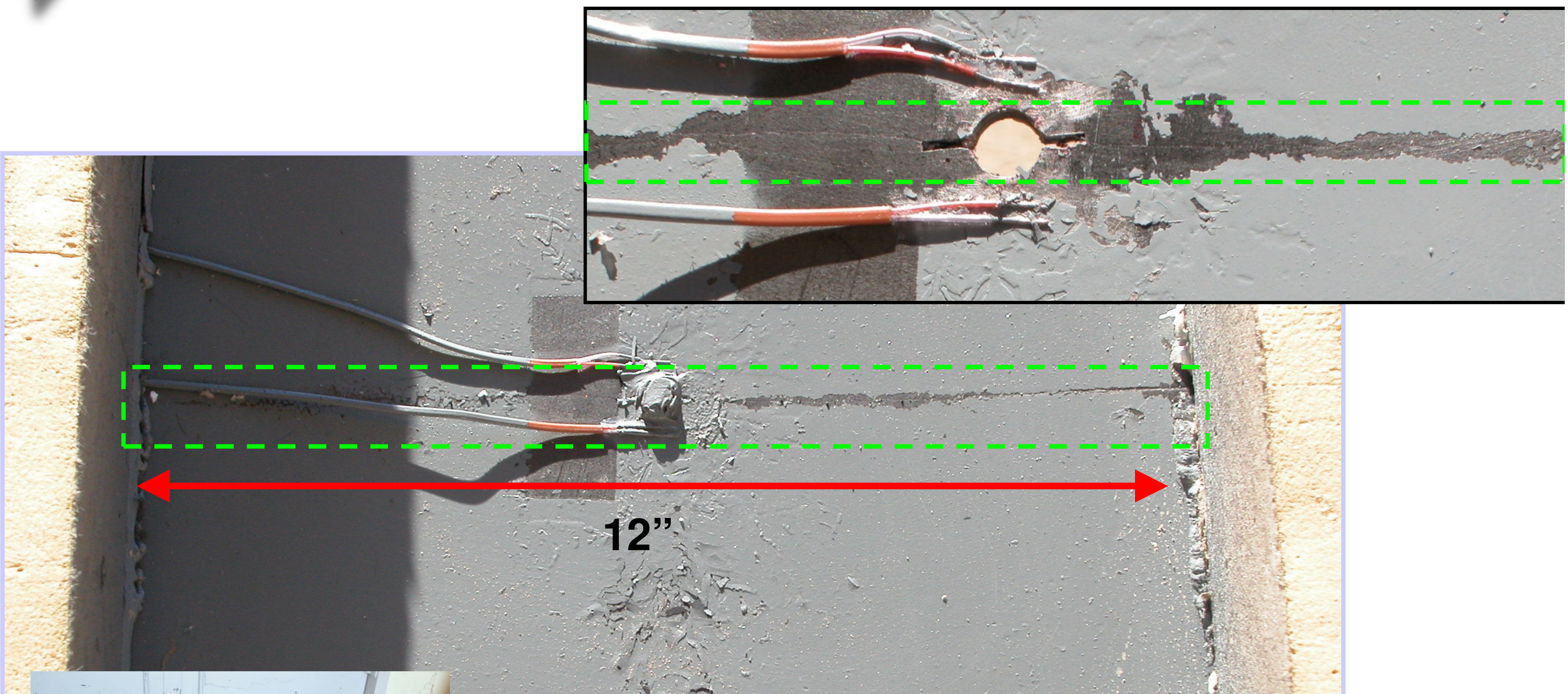
Testing Goal: Perform tests to explore thermally induced crack propagation from damaged regions. Results provide input for Damage Model

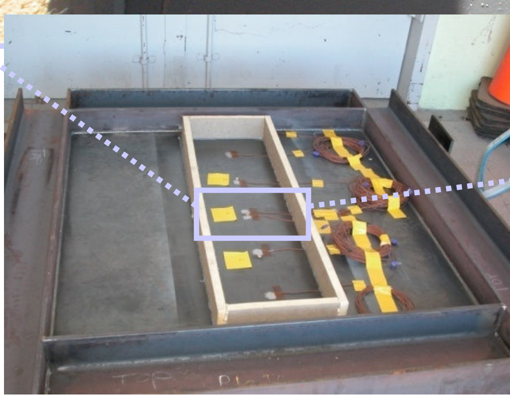
- **Phase I** – Exploratory small plate tests, subjected to LN_2 and designed to explore testing procedures
- **Phase II** (10 tests)
  - Similar to exploratory tests in size
  - Examine differences in cooling region dimensions
  - Assess crack arresters (stiffeners, welds)
  - Water backside
- **Phase III** (3 to 5 tests)
  - Larger more complex geometry, similar to outer hull section
  - Explore changes in cooling region and arresters





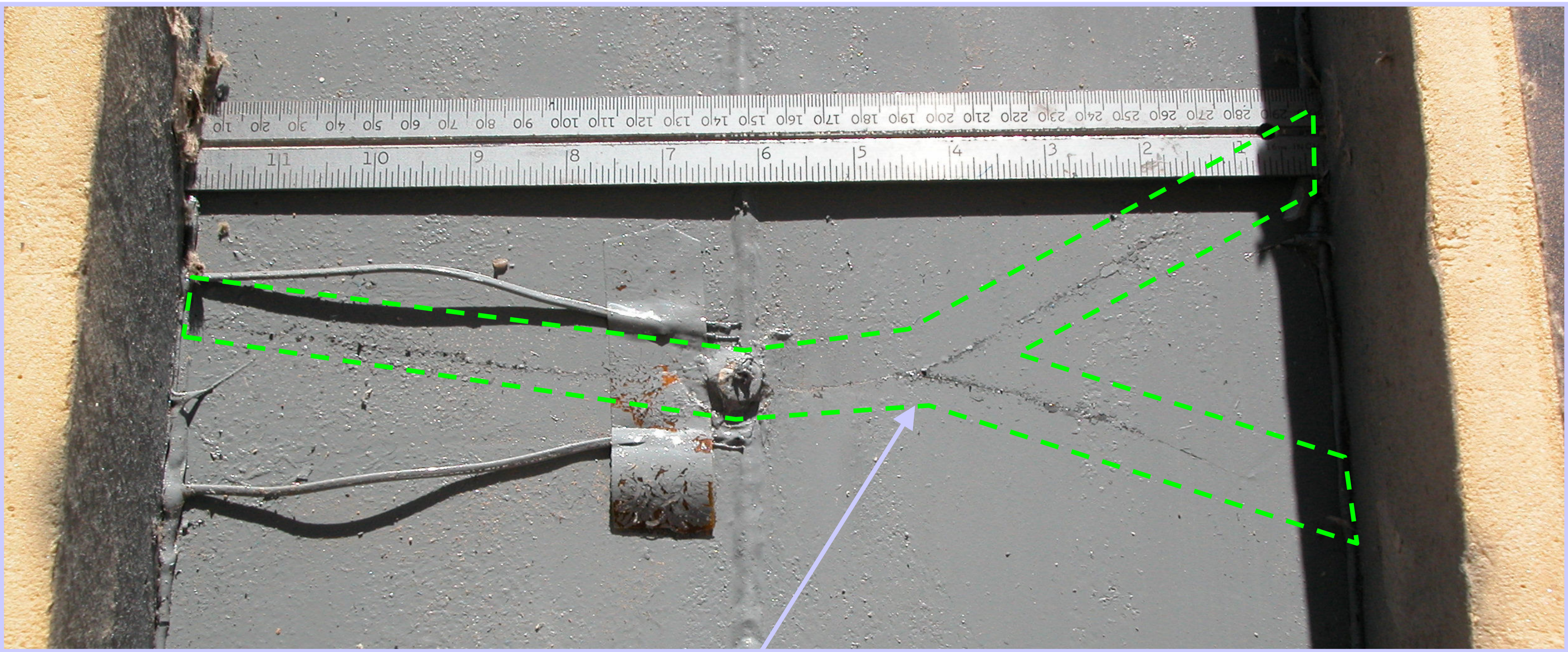
Cryogenic Damage Testing





Notched hole resulted in crack propagation

Cryogenic Damage Testing
Example II - Cracked Plate



Crack Branching

Cryogenic Damage Testing
Phase I Testing Results
Summary

- **Thermally induced fracture at cryogenic temperatures is not likely in steel plates without sufficient stress concentration and no initial stress**
  - All large steel structure have an inherent flaw distribution (e.g., cracks at weld roots, fatigue cracks, etc) and typically have high stress concentration geometries
- **Mechanical pre-load (initial stress) not required to propagate fracture – localized cryogenic temperatures are enough to generate fractures given initial flaws**
- **Notched holes provide less of a stress riser than typical inherent flaws or cracks arising from our breach scenarios**