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Proposed Research

Cascading Failure of LNG Ships (Cryogenic Damage, Fire)

Mitigation (Structural Breach, Fire)

Briefing to Dr. Parfomak of the Congressional Research Service
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Sandia National Laboratories

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Cascading Failure of LNG Ships
Proposed Research

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

Methodology: Develop cryogenic failure models using sub-scale controlled experiments for validation. Incorporate cryogenic failure models in large-scale ship models examining structural failure. Validate elements of the large-scale structural failure models with full-scale sub-section experiments.

Cascading Failure of LNG Ships

Proposed Research

Objective 2: Determine if intentional attacks could result in fire-induced damage to the ship structure that would lead to cascading (multi-tank) structural failures and catastrophic release of LNG. Evaluate confined space explosion potential.

Methodology: Investigate thermal flux resulting from burning spills and its effect on tank insulation and structural response leading to cascading failure. Model potential for spilled LNG to vaporize and deflagrate, and assess cargo tank damage

Cascading Failure of LNG Ships
Proposed Research

Objective 3: Develop an expected timeline for cargo release based on the postulated failure scenarios.

Methodology: Employ large-scale structural ship models with validated failure models to evaluate cascading failure due to cryogenic or fire-induced failure. Develop various cargo release timelines based on sequence of events.

Cryogenic Failure

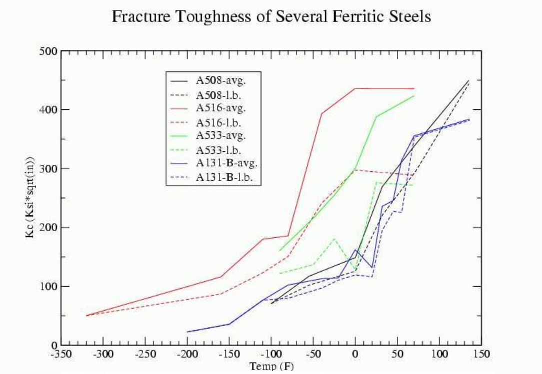
Proposed Plan

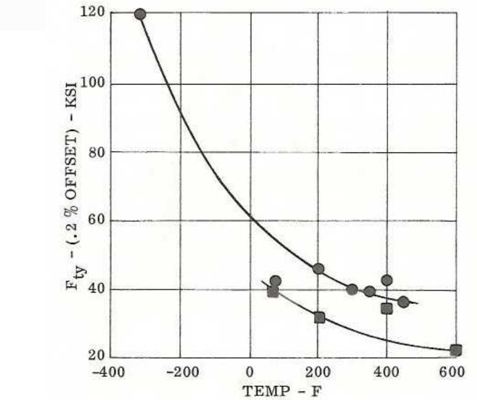
- Small-scale exploratory experiments
- Failure model validation
- Full-scale numerical simulations incorporating validated failure model
- Large-scale experimental validation addressing key architectural features and boundary conditions

Cryogenic Failure: Exploratory Investigations

- Experimental verification of cryogenically-induced failures in representative naval ship materials and components.
  - Small-scale discovery experiments
  - Numerical simulations to guide specimen design (predicted stress states, boundary condition effects)
  - Representative key architectural features (welds, stiffeners, splice joints, etc)
  - Validation of initial cryogenic failure assumptions
    - Toughness-temperature transition curves
    - Linear elastic failure models
    - Assumptions to be verified
  - Experimental measurement of the stress state in harsh environment (diagnostic selection and validation)
  - Verification of LN_2 as a surrogate cryogenic fluid

Cryogenic Failure:
Why do we expect failures from exposure to LNG?





- At LNG temperatures, ship steels are hundreds of degrees F below Nil Ductility Transition Temperature; far onto lower shelf fracture behavior; as brittle as steel alloys can get.
- At LNG temperatures, the yield strength of ship steels can be elevated by as much as a factor of 2.
- Spill scenarios generate thermal strains that can exceed the elastic limit of ship steels.
- Empirical evidence from LNG spills during normal operations show that fracture will occur.

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

Source: A. Valudolon (2000)

Cryogenic Failure: Failure Models

- Need a failure criterion that will work for cryogenic damage as well as more mundane late time structural overload failures.
- Propose a locus of temperature and strain pairs to define failure. This can represent Linear Elastic Fracture Mechanics for cryogenic damage and ductility exhaustion for structural overload.

Cryogenic Failure: LEFM Based Failure Criterion

- Failure occurs when the applied K equals K_{Ic}

$$K \approx C\sigma\sqrt{\pi a}$$

- K_{Ic} can be estimated for material of construction – function of temperature.
- The stress, σ, can be computed from boundary value problem solved by FEA – in the elastic range it is linearly related to strain.
- "a" the inherent flaw size is unknown. Can estimate "a" from relatively small scale simple experiments that are sufficiently instrumented to reveal strains and temperatures. Solving the equation above using the lower bound value for K_{IC} and the upper bound value for σ gives a critical value of a" of about 0.02 inch. Flaws of this size and larger are expected in welded steel.
- In conjunction with analysis of the experiment, the above can be synthesized into a failure locus of temperature and strain.

Cryogenic Failure:
Structural Overload Failure Criterion

- At temperatures above cryogenic, ductility data are available or attainable for ship steels.

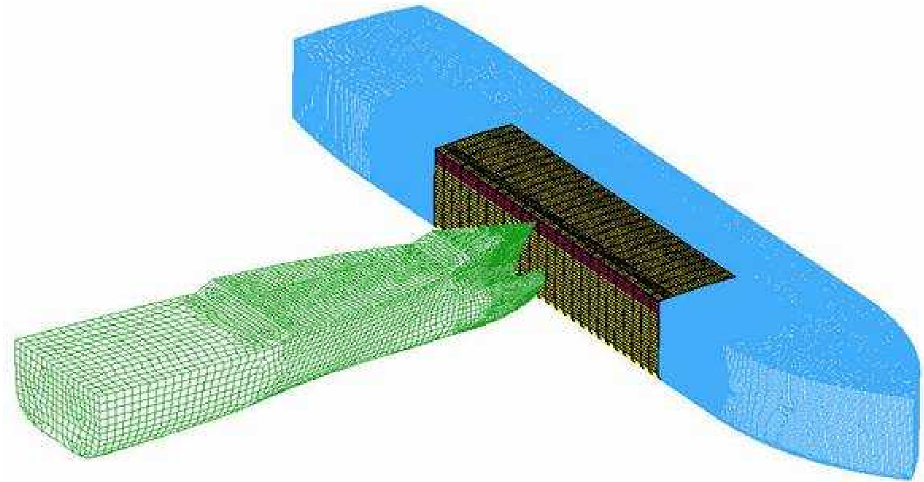
- Such ductility data are readily cast into a failure locus of temperature and strain.

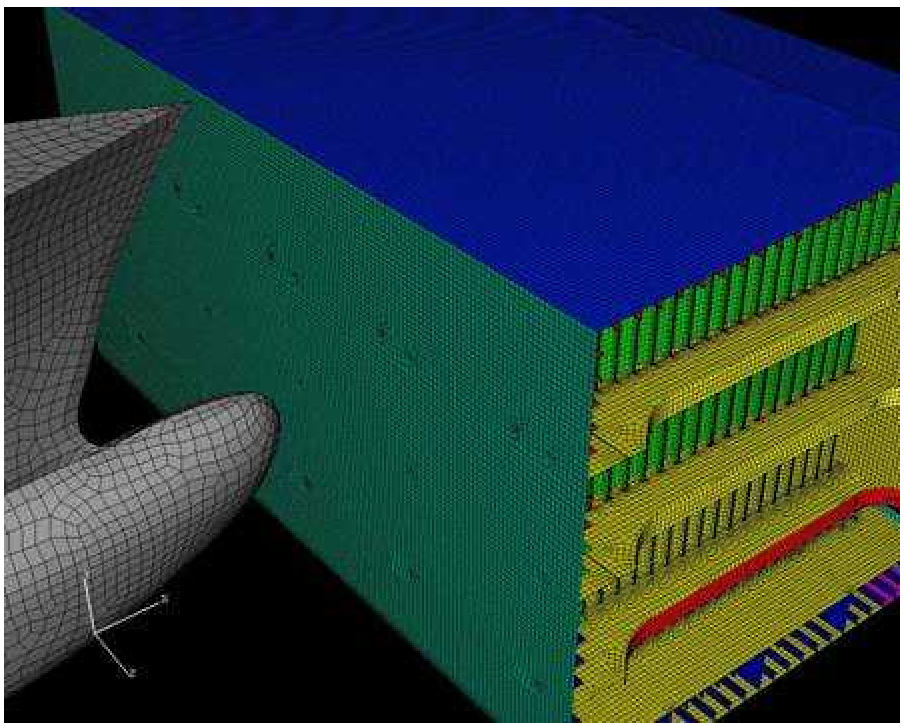
Cryogenic Failure:
Caveats

- LEFM, as applied here, will be statistical in nature – failure is dominated by size, location, and orientation of inherent flaws in the material (base plate and weldments).
- Modeling of a complete ship will require use of structural finite elements (beams, plates, etc.).
- The simple strain, temperature failure criterion proposed for ship failure estimates will require calibration based on the uncertainties identified above. This will require more complex experiments (and associated analyses) on large scale structural sections.

Double Hull Tanker Collision (2001)
Demonstration of Capability

Impact analysis with penetration simulated using an explicit dynamics finite element code.

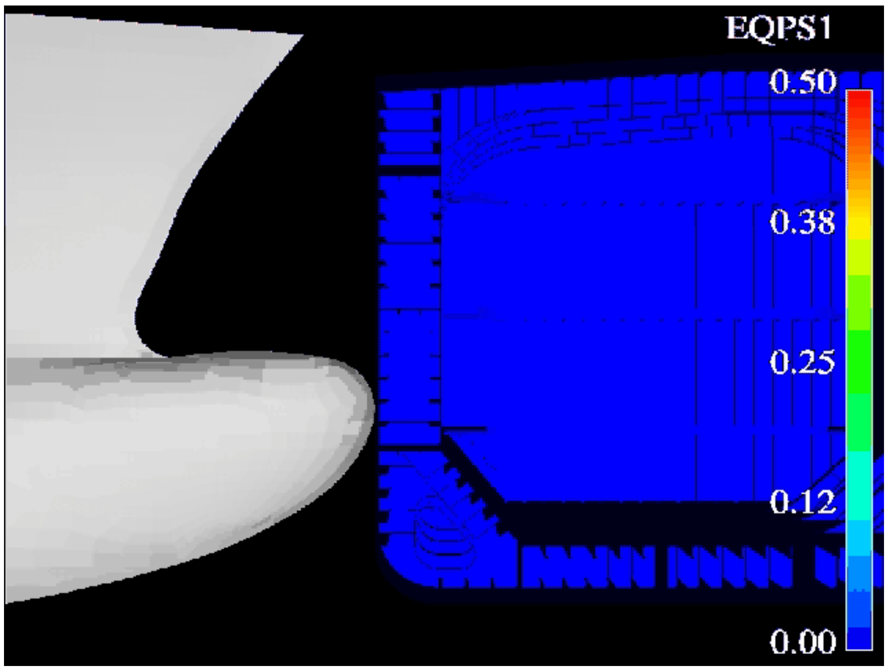




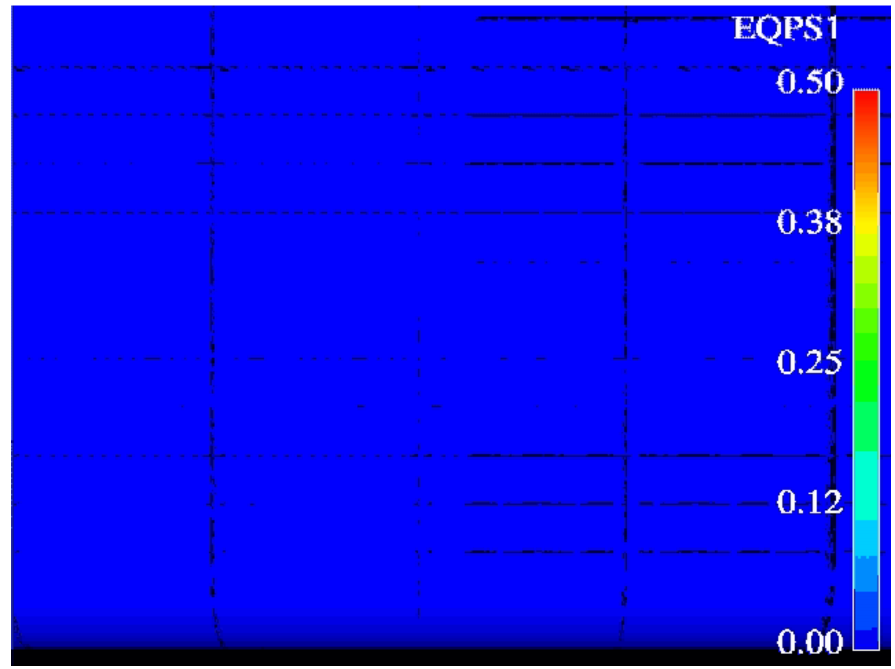
Mesh size in this analysis was about 10cm x 10 cm.

Double Hull Tanker Collision (2001)
Demonstration of Capability

Simulation Results – penetration and hole size.

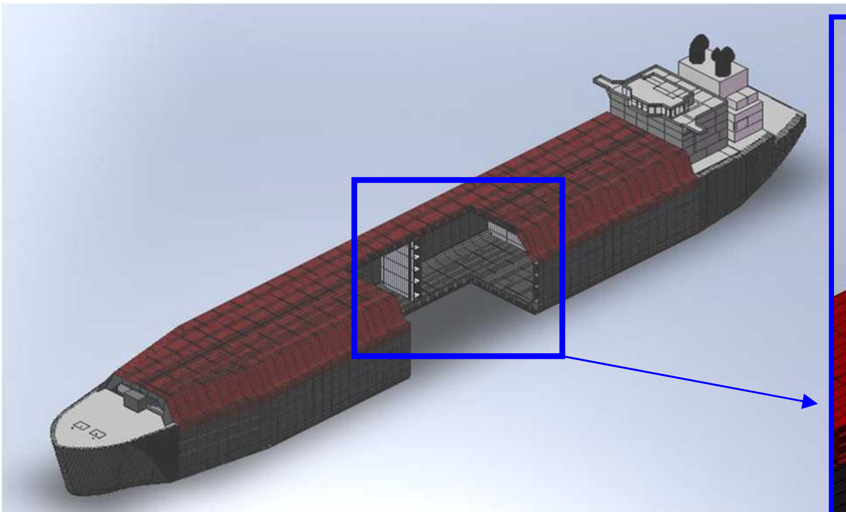


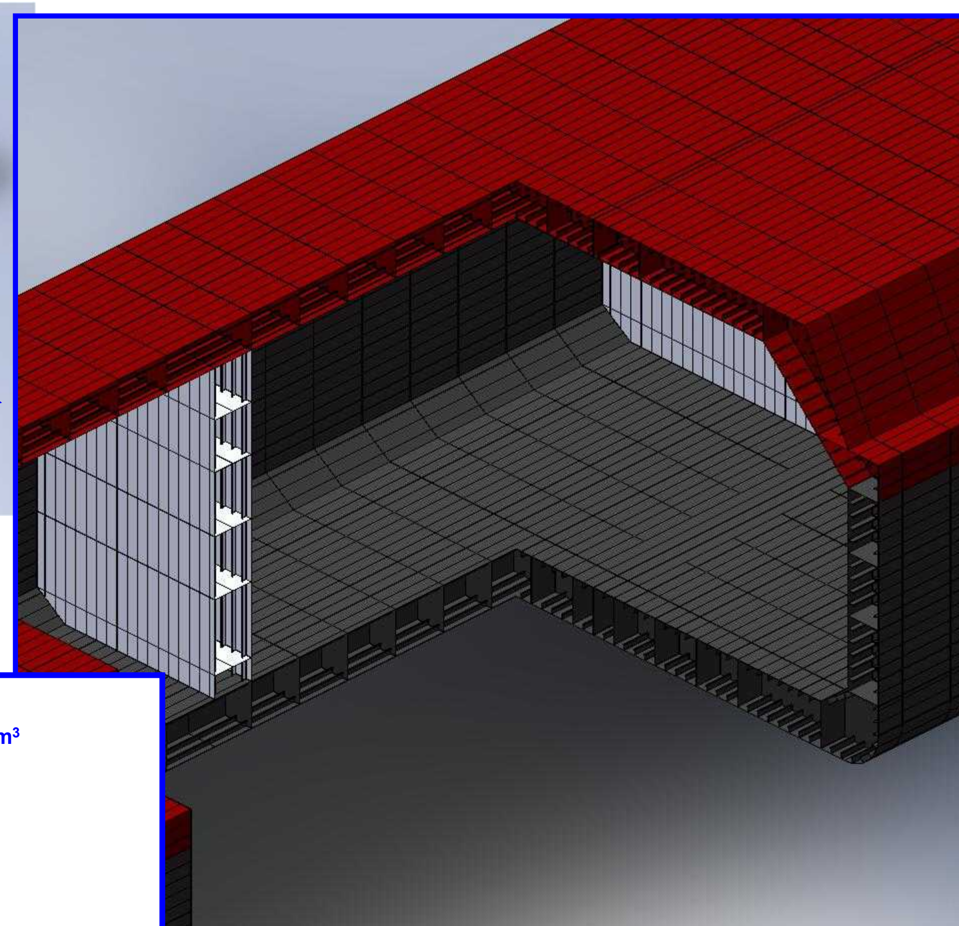
Section view



View from outside

Full-Scale Ship Cascading Failure Analysis

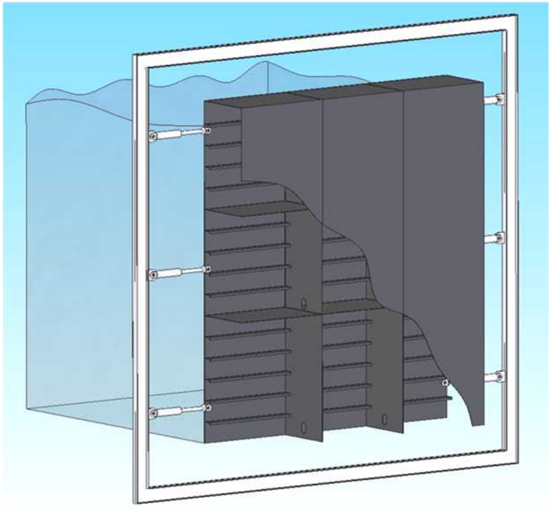


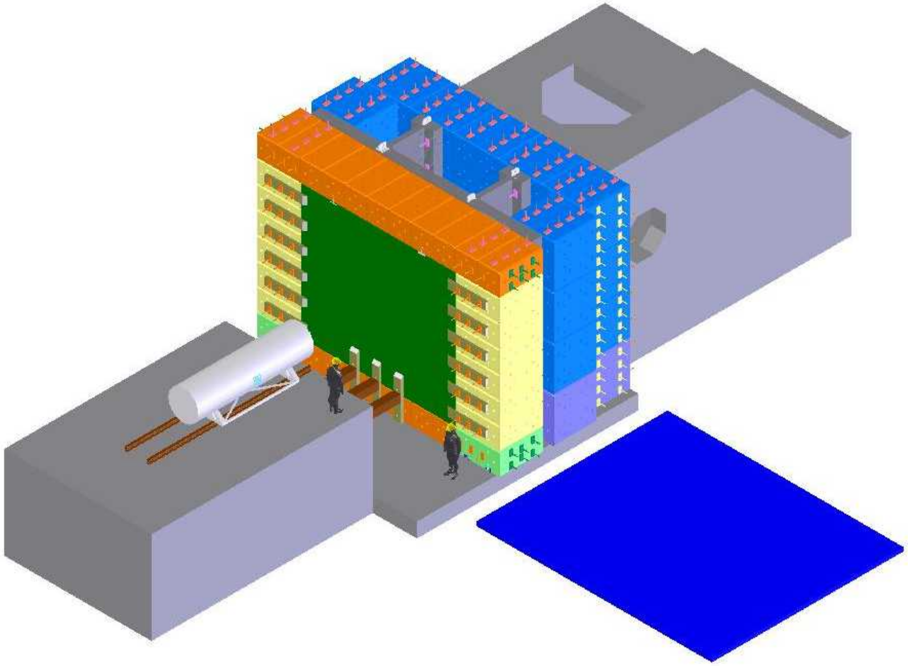


Class	Membrane Designs			
	145,000 m³	**155,000 m³**	**215,000 m³**	**265,000 m³**
Tanks	4	4	5	5
Length (m)	283	288	315	345
Width (m)	44	44	50	55
Draft (m)	11.4	11.5	12	12
Class	**Moss Designs**			
	138,000 m³	**145,000 m³**	**200,000 m³**	**255,000 m³**
Tanks	5	4	5	5
Length (m)	287	290	315	345
Width (m)	46	49	50	55
Draft (m)	11	11.4	12	12.5

Cryogenic Failure: Large-scale Validation Testing

- Determination of service loads in representative hull sections (hull design effects)
  - Input from USCG naval architects and designers
  - Independent analysis
- Boundary condition effects
- Load frame design
- Spill rate effects





- Demonstrated expertise in large scale test and validation

Cascading Failure Due to Fire

Proposed Research

- A large spill is likely to result in a large fire that would partially engulf the ship.
- Thermally induced structural failure is likely if the temperature of the structural steel of the vessel reaches a critical value.
- A flux and temperature profile will be calculated based on the cargo discharge timeline.
- These initial conditions will be coupled to a thermal and structural response models capable of predicting ship response with blast and thermal damage.
- Failure criteria for relevant materials (especially foam insulation) will be identified.

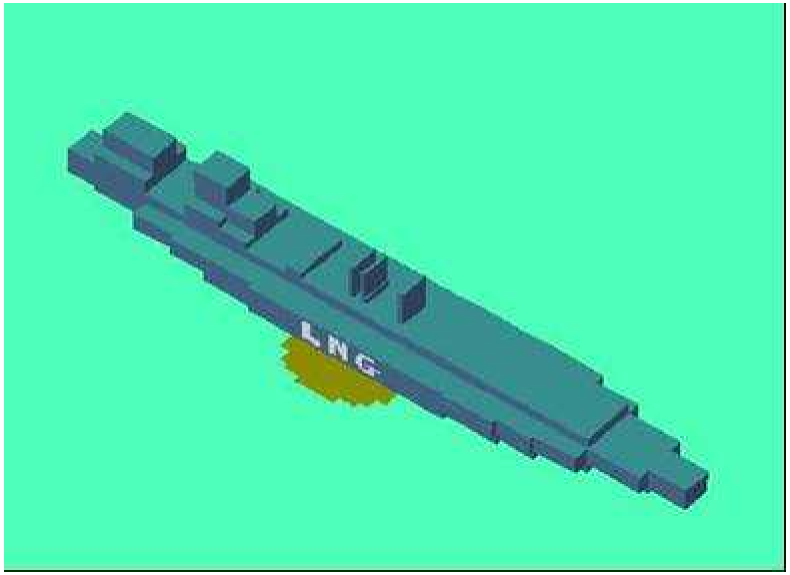
Cascading Failure Due to Fire
Previous Research

- Simulations were performed and the results compared to experimental data in order to assess the validity of current fire code models for this application.
- The available data sets for such an assessment, along with identification of which simulations were performed for assessment, are shown below.
- *The size (diameter) of the pools/spills anticipated for the scenarios of interest greatly exceeds anything that has been experimentally investigated to date with LNG.*

Data Set #	Analyzed to date	Fuel	Description
A1	Yes	LNG	Montoir 35 m pool on land
A2	Yes	LNG	Croce 15 m x 1.8 m pool in trench
A3	Yes	LPG	Mizner 20 m pool on land
A4	No	LNG	Mizner 20 m pool on land
A5	No	LPG	Mizner 20 m pool on water
A6	No	LNG	Mizner 20 m pool on water
A7	Yes	LNG	Burro dispersion over water
A8	No	LNG	SNL unconfined spread over water
A9	Yes	LNG	Mass fire behavior (Heskestad comparison)

Cascading Failure Due to Fire
Previous Research

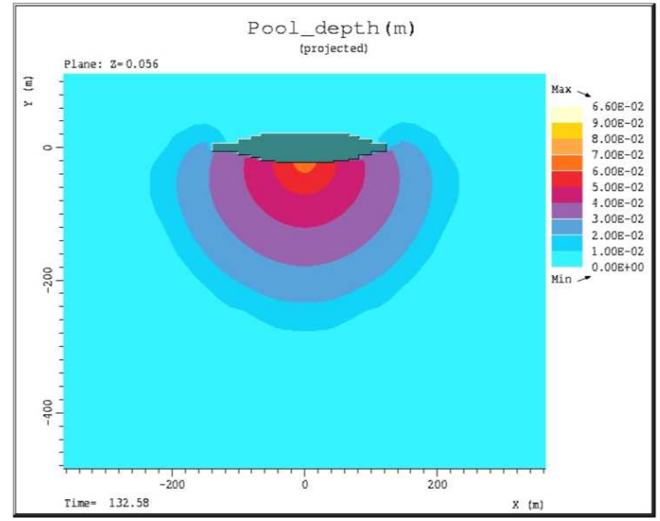
- Analysis of a scenario involving a prismatic membrane LNG tanker with a 10 m^2 hole penetrating both hulls at the waterline (one tank).
- 12,500 m^3 of LNG was assumed spilled - constant spill rate of 77 m^3/s (hydrostatic head of 15 m and a discharge coefficient of 0.9).
- LNG empties from the tank and disperses on the sea surface in 162 seconds (assuming calm winds and no waves).
- The initial area of the LNG pool was assumed to be 680 m^2. Evaporation from the pool was calculated by Vulcan.



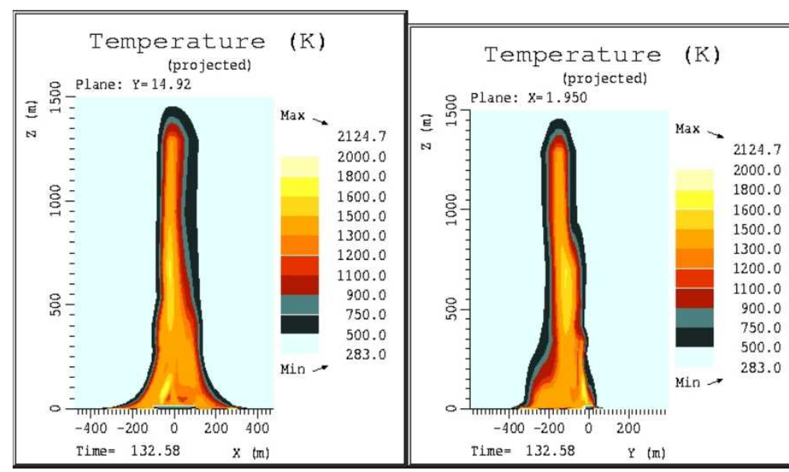
The geometric model of the ship used in the simulation

Cascading Failure Due to Fire
Previous Research

- Large pool develops (~130,000 m^2)
- Pool area stabilizes at a value where the spill rate is balanced by the evaporation rate from the pool.
- The simulation results indicate that the fire does not break up into a mass fire, but rather maintains a coherent plume and flame volume despite the very large area of the pool.
- Flame height from this fire is very high (~ 1400 m) for the ~300 s fire duration. (likely due to insufficient grid resolution).
- Higher resolution simulation is required



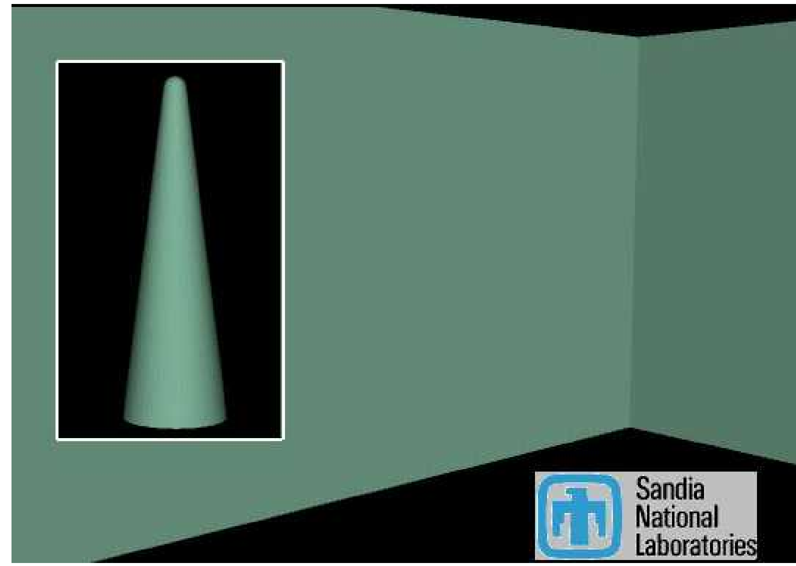
Pool area and depth



Plume height and temperature

Cascading Failure Due to Fire

- For high fidelity simulations, the SNL fire code Sierra Fuego/Syrinx will be used – can run on massively parallel platforms for unstructured grids
- Can be coupled with the thermal conduction mechanics code, Calore, for thermal response of objects
- Fuego/Syrinx has an extensive verification and validation suite with uncertainty quantification
- A pool fire of around 100 m in diameter would require a minimum of 10 million nodes.
- CTH, shock-physics code, can be used to investigate the affect of a fast deflagration between hulls on the ship

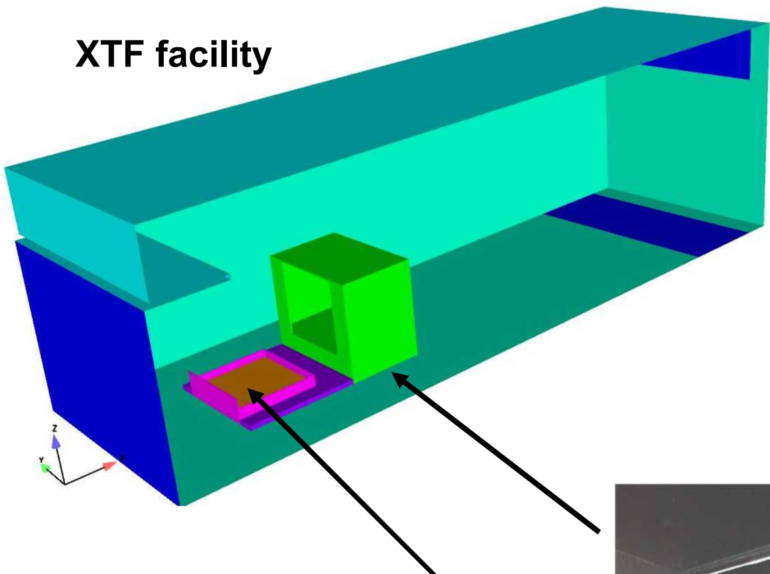


Thermal response of calorimeter from fire in crosswind

Cascading Failure Due to Fire

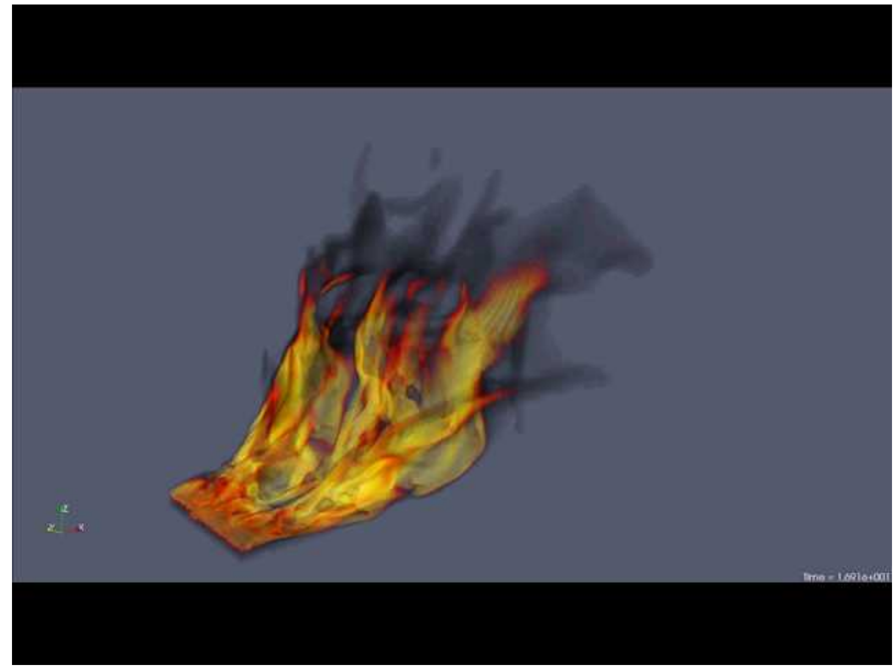
2.7 m square JP-8 pool fire in a 4 mph crosswind
Validation of thermal response of a calorimeter

XTF facility



Pool of fuel

Calorimeter within enclosure



Fuego simulation

Validation includes uncertainty quantification and grid sensitivity study

Preliminary comparison (work in progress) of temperature response of the calorimeter

Preliminary Simulations Results for Temperature within Calorimeter at various locations

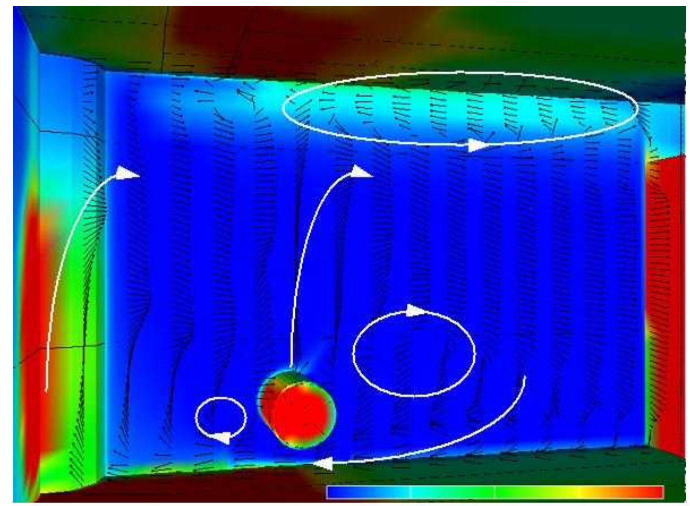
	T1	T2	T3	T4	T5	T6	T7	T8
UQ case	**Temperature (deg C)**							
set 1	1050	900	760	975	1015	1064	1043	990
set 2	1346	1329	1300	1322	1246	1291	1334	1289
set 3	865	600	505	813	872	892	806	870
set 4	1348	1424	1537	1426	1258	1432	1497	1425
set 5	1007	1081	1147	1088	1078	1137	1179	1144
set 6	1377	1397	1367	1357	1267	1327	1397	1337
Sim Ave.	**1165**	**1122**	**1103**	**1164**	**1123**	**1272**	**1209**	**1176**
Exp Ave.	**1130**	**1095**	**1065**	**1165**	**1135**	**1140**	**1180**	**1135**
%Difference	**3.140%**	**2.450%**	**3.539%**	**-0.127%**	**-1.088%**	**4.430%**	**2.480%**	**3.601%**

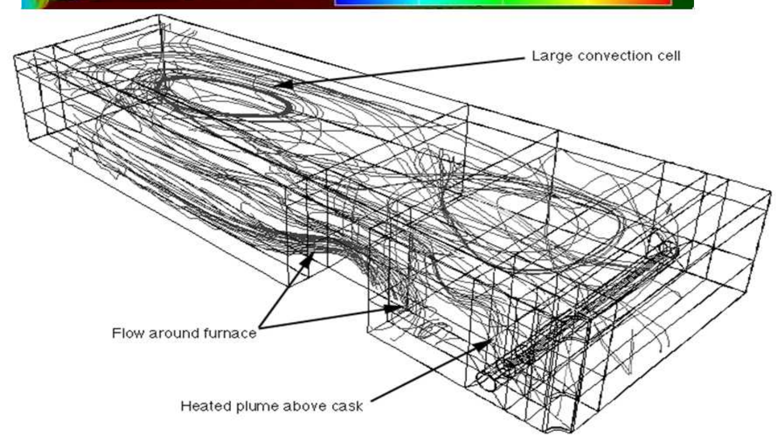
Cascading Failure Due to Fire

Application of Heat Flux BC for Thermal Response Analyses

USCG Heptane Spray Fire Experiment

Sandia conducted a series of fire tests aboard a Coast Guard test ship in Mobile, AL to investigate the thermal environment that a radioactive material package could experience during transportation.



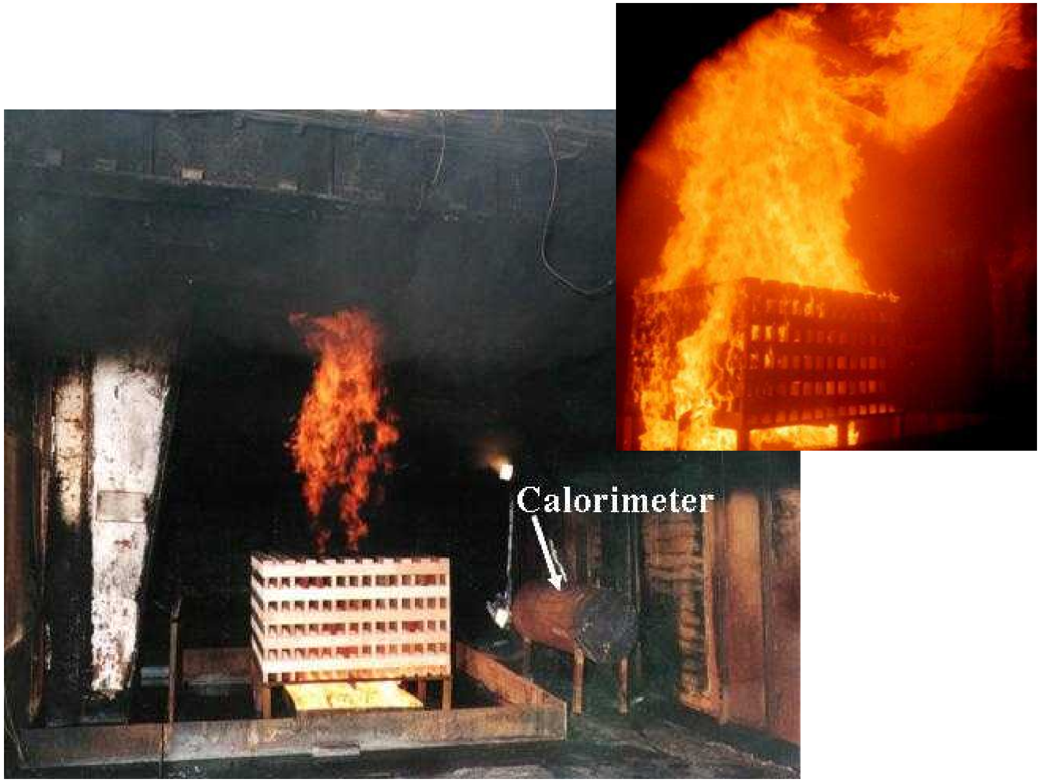


Heat transfer and air flow calculations were performed and benchmarked to experimental results.

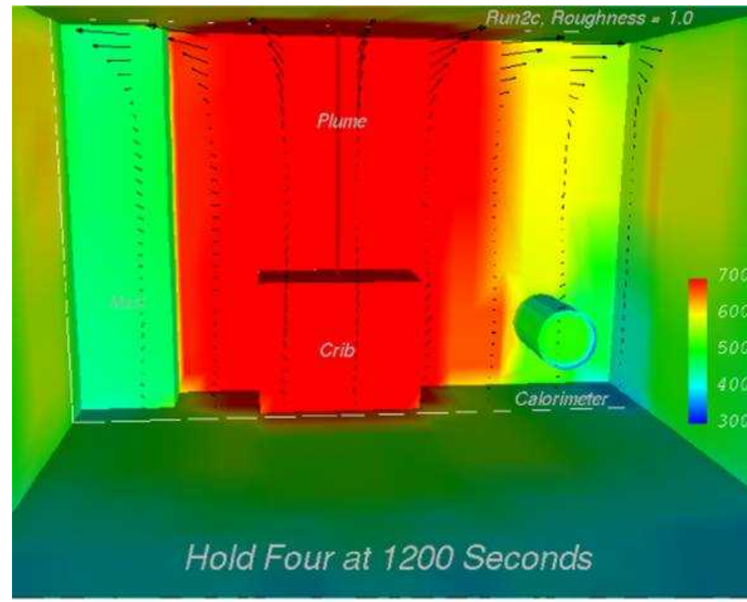
Cascading Failure Due to Fire

Application of Heat Flux BC for Thermal Response Analyses

USCG Wood Crib Fire Experiment



Sandia conducted a series of fire tests aboard a Coast Guard test ship in Mobile, AL to investigate the thermal environment that a radioactive material package could experience during transportation.



Modeling of the wood crib fire event to calculate the heat transfer to the simulated radioactive material transport package.

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.