U.S. DEPARTMENT OF ENERGY

Liquefied Natural Gas Safety Research

Report to Congress
May 2012

United States Department of Energy
Washington, DC 20585

Message from the Assistant Secretary for Fossil Energy

The Explanatory Statement accompanying the Consolidated Appropriations Act, 2008[1] and the House Report on the House of Representatives version of the related bill[2] requested the Department of Energy to submit a report to Congress addressing several key liquefied natural gas (LNG) research priorities. These issues are identified in the February 2007 Government Accountability Office Report (GAO Report 07-316), *Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification*.

In response to this request, the Department of Energy tasked Sandia National Laboratories (SNL) with expanding the scope of the Department's LNG safety research program to address the research priorities identified in GAO Report 07-316. To accomplish this, SNL performed LNG field research and testing and conducted advanced computational modeling, simulation, and analyses over a three year period from May 2008 through May 2011. This report contains the findings, results, and conclusions of this research.

I am pleased to submit the enclosed report entitled, *Liquefied Natural Gas Safety Research Report to Congress*. The report was prepared by the Department of Energy's Office of Fossil Energy and summarizes the progress being made in this important area of research. This report is being provided to the following Members of Congress:

- **The Honorable Joseph R. Biden, Jr.**
  President of the Senate

- **The Honorable John Boehner**
  Speaker of the House of Representatives

- **The Honorable Daniel K. Inouye**
  Chairman, Senate Committee on Appropriations

- **The Honorable Thad Cochran**
  Vice Chairman, Senate Committee on Appropriations

- **The Honorable Dianne Feinstein**
  Chairman, Senate Subcommittee on Energy and Water Development
  Committee on Appropriations

- **The Honorable Lamar Alexander**

[1] Explanatory Statement accompanying Public Law 110-161 (Dec. 26, 2007) at page 570.
[2] H.Rept. 110-185 accompanying Energy and Water Development Appropriations Bill, 2008 (H.R. 2641) at page 73.

Ranking Member, Senate Subcommittee on Energy and Water Development
Committee on Appropriations

- **The Honorable Harold Rogers**
  Chairman, House Committee on Appropriations

- **The Honorable Norm Dicks**
  Ranking Member, House Committee on Appropriations

- **The Honorable Rodney P. Frelinghuysen**
  Chairman, House Subcommittee on Energy and Water Development
  Committee on Appropriations

- **The Honorable Pete Visclosky**
  Ranking Member, House Subcommittee on Energy and Water Development
  Committee on Appropriations

If you need additional information, please contact me or Mr. Jeff Lane, Assistant Secretary, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Charles D. McConnell

Executive Summary

The February 2007 Government Accountability Office Report (GAO Report 07-316), *Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification*, identified several key Liquefied Natural Gas (LNG) research priorities highlighted by a GAO-convened panel of experts on LNG safety in order to provide the most comprehensive and accurate information for assessing the public safety risks posed by LNG tankers transiting to LNG facilities. To address these issues, Congress provided funding to the Department of Energy (DOE) to expand their LNG safety research program to focus on the major LNG research priorities contained in the GAO report. Sandia National Laboratories (SNL) supported the DOE in this effort starting May 2008 through May 2011 by conducting a series of large-scale LNG fire and cryogenic damage tests, as well as detailed, high performance computer models and simulations of LNG vessel damage resulting from large LNG spills and fires on water.

The key findings from these efforts include the following:

- For the large breach and spill events considered, as much as 40 percent of the LNG spilled from the LNG vessel's cargo tank is likely to remain within an LNG vessel's structure, leading to extensive cryogenic fracturing and damage to the LNG vessel's structural steel. In addition to the cryogenic damage, the heat fluxes expected from an LNG pool fire would severely degrade the structural strength of the inner and outer hulls of an LNG vessel. The extent of the cryogenic and fire damage on an LNG vessel resulting from large spills and associated pool fires would significantly impact the LNG vessel's structural integrity, causing the vessel to be disabled, severely damaged, and at risk of sinking.
- Current LNG vessel and cargo tank design, materials, and construction practices are such that simultaneous, multi-cargo tank cascading damage spill scenarios are extremely unlikely, though sequential multi-cargo tank cascading damage spill scenarios may be possible. Should sequential cargo tank spills occur, they are not expected to increase the hazard distances resulting from an initial spill and pool fire; however, they could increase the duration of the fire hazards.
- Based on the data collected from the large-scale LNG pool fire tests conducted, thermal (fire) hazard distances to the public from large LNG pool fires will decrease by at least two to seven percent compared to results obtained from previous studies.
- Risk management strategies to reduce potential LNG vessel vulnerability and damage from breach events that can result in large spills and fires should be considered for implementation as a means to eliminate or reduce both short-term and long-term impacts on public safety, energy security and reliability, and harbor and waterways commerce. Approaches to be considered should include implementation of enhanced operational security measures, review of port operational contingency plans, review of emergency response coordination and procedures, and review of LNG vessel design, equipment and operational protocols for improved fire protection.

LIQUEFIED NATURAL GAS SAFETY RESEARCH

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I. Legislative Language

This report responds to legislative language set forth in the Explanatory Statement accompanying the Consolidated Appropriations Act, 2008 (2008 Act)[3] and the House Report on the House of Representatives version of the related bill[4].

The Explanatory Statement, at page 570, provides as follows:

> "… *The Department is directed to submit to the House and Senate Committees on Appropriations a report on liquefied natural gas (LNG), as outlined in the House report…*"

House Report 110-185, at page 73, similarly requested the Department of Energy to address several key LNG research priorities in a liquefied natural gas report:

> "… *Liquefied Natural Gas (LNG) Report.—The February 2007 Government Accountability Office report, 'Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification,' found that the most likely public safety impact of an LNG spill is the heat hazard of a fire, but disagreed with the specific heat hazard of a fire and cascading damage failure conclusion, which is used by the Coast Guard to prepare Waterway Suitability Assessments for LNG facilities. Additionally, GAO found that the Department's 'recently funded study involving large-scale LNG fire experiments addresses some, but not all, of the research priorities identified by the expert panel.' Therefore, the Committee directs the Department to incorporate the following key issues, as identified by the expert panel, into its current LNG study: cascading failure, comprehensive modeling (interaction of physical processes), risk tolerability assessments, vulnerability of containment systems (hole size), mitigation techniques, the effect of sea water coming in as LNG flows out, and the impact of wind, weather, and waves.*"

II. LNG Cargo Tank Breach and Spill Analyses

For this study, the larger classes of Moss and Membrane LNG vessels were analyzed. The dimensions of the vessels considered are summarized in Table 1. The sizes selected span many of the LNG vessels used in the U.S., including the largest LNG vessels in operation today.

Table 1. Dimensions of Moss and Membrane LNG Vessels Evaluated

Dimension	Moss	Membrane
Length	280 m (924 ft)	330 m (1090 ft)
Breadth	45 m (150 ft)	54 m (178 ft)
Draft	10.4 m (34 ft)	11.5 m (38 ft)
LNG Cargo Capacity	140,000 m^3	260,000 m^3

[3] Explanatory Statement accompanying Public Law 110-161 (Dec. 26, 2007).
[4] H.Rept. 110-185 accompanying Energy and Water Development Appropriations Bill, 2008 (H.R. 2641) at page 73.

The geometric models, which were created using detailed structural drawings of actual LNG vessels, are shown in cross-sections in Figures 1 and 2.

Figure 1. Moss LNG Vessel cross-section.

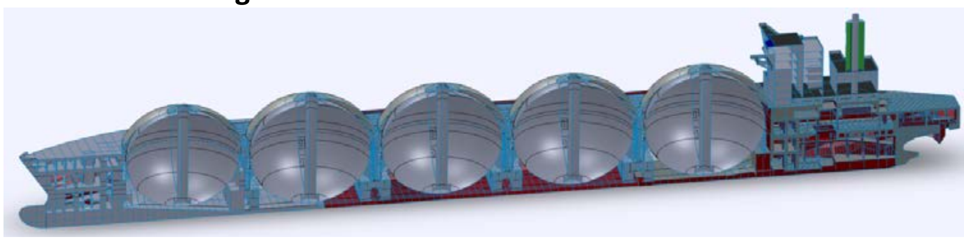
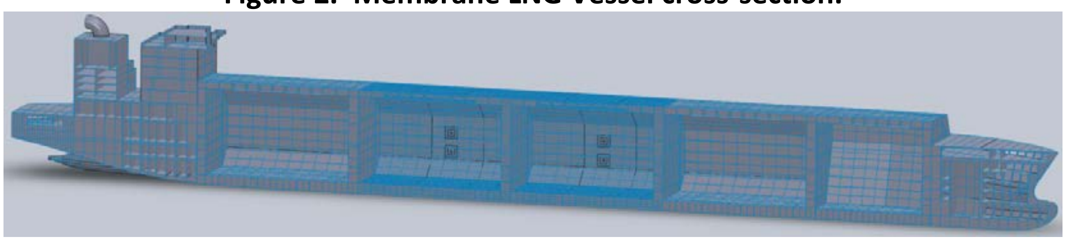


Figure 2. Membrane LNG Vessel cross-section.



LNG Cargo Tank Breach Analyses

Many potential accidental and intentional damage scenarios have been considered for LNG hazard analyses in previous DOE-directed public safety analyses for large LNG spills over water, including Hightower et al., 2004 and Luketa et al., 2008. For this study, Sandia reassessed threats and potential credible event scenarios for LNG marine transportation with marine safety, law enforcement, and intelligence agencies. The evaluations considered a wide range of possible threats. These included accidents, as well as intentional events such as attacks with shoulder-fired weapons, explosives, and attacks by small to medium size boats and aircraft. Potential threats and possible breach events are always site-specific and will vary depending on the location of the LNG vessel, such as inner harbor, outer harbor, or offshore Deep Water port.

The breach sizes calculated were based on detailed, two- and three-dimensional, shock physics/structural interaction and damage models. The breach modeling included detailed representations of the LNG vessel's structural design and materials of construction, cargo tank construction and materials, and the location and energy content of the threats identified. The range of breach sizes calculated for specific threats are presented in classified reports, but Table 2 provides a summary of the range of the cargo tank breach sizes considered for this study. To simplify integration with the structural geometry and construction of LNG vessels, square holes were assumed in all analyses.

Table 2. LNG Cargo Tank Breach Sizes Considered

Type	Breach Area	Breach Dimension
Very Small	0.005 m^2	(0.25 ft x 0.25 ft)
Small	0.5 m^2	(2.3 ft x 2.3 ft)
Medium	2-3 m^2	(5.0 ft x 5.0 ft)
Large	5 m^2	(7.3 ft x 7.3 ft)
Very Large	15 m^2	(12.7 ft x 12.7 ft)

The breach events evaluated can occur at a range of locations. While many accidental and intentional threats fall into the very small and small breach size categories, the major focus of the spill and damage analyses were for medium to very large hole sizes that are difficult to analyze without the use of high performance modeling and computing capabilities.

LNG Spill Analyses

To determine the extent of LNG flow during a breach event, three-dimensional computational fluid dynamics (CFD) analyses of the internal and external flow of LNG from a breach of Moss and Membrane LNG cargo tanks were performed for the small through very large hole sizes. The spill analyses considered the entire flow physics of the problem, including the draining of the breached cargo tank, the timing and flow of the LNG internal and external to the vessel, and LNG vaporization during a spill. The flow modeling and analysis conducted are presented in detail in Figueroa et al., 2011. Figures 3 and 4 show examples of LNG flow analyses conducted for the Moss and Membrane LNG vessels.

Figure 3. Moss LNG vessel spill and internal flow analysis example.

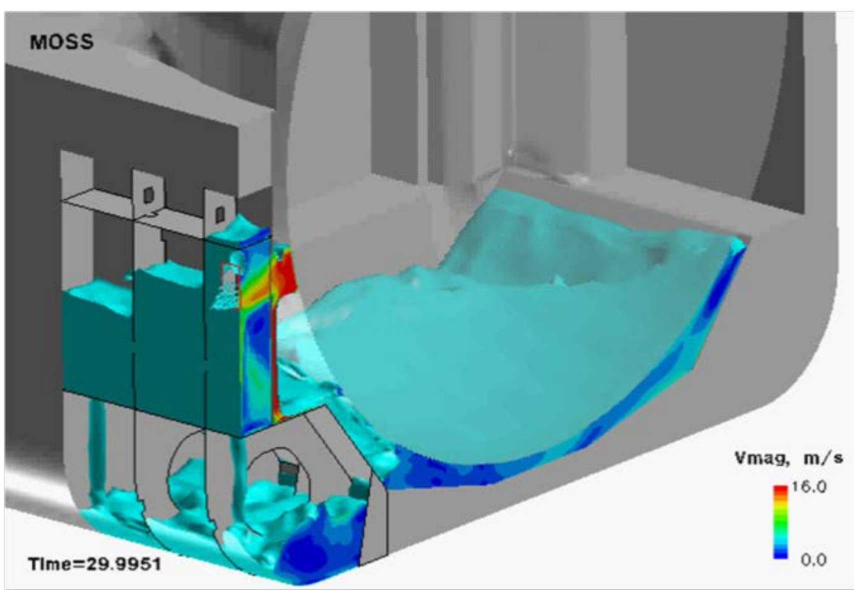
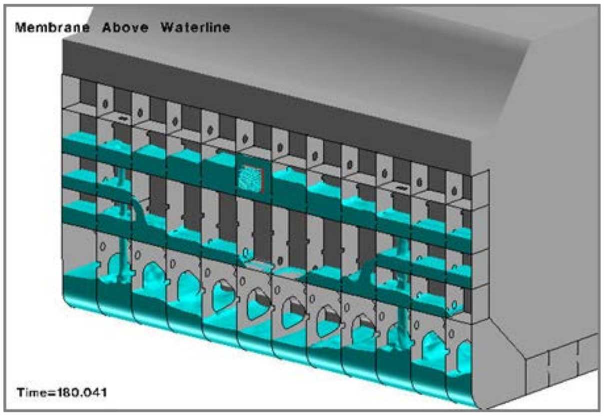
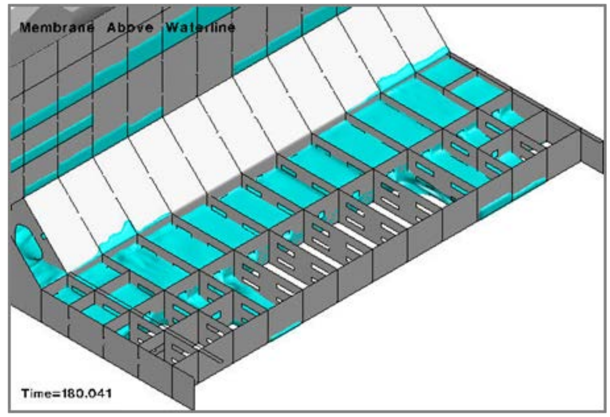


Figure 4. Membrane LNG vessel spill and internal flow analysis examples.





The spill analyses indicate that for the larger breach and spill events, as much as 40 percent of the cargo tank LNG volume will likely remain within the LNG vessel. The spill and flow analyses show that for medium and larger spills, the internal flow of LNG into a Moss LNG vessel will be completed within ten to fifteen minutes, at which time the remaining LNG will all flow out onto the water. For a Membrane LNG vessel, LNG flow within the vessel for medium to larger spills will be completed in about 10 minutes, and then the remaining LNG will flow out onto the water. For smaller breach events, the spills are smaller and the spill durations longer.

The results for the external flow analyses showed that for the larger breach events, LNG pool diameters between 180 m to 350 m can be expected for the Moss LNG vessels, while LNG pool diameters between 205 m to 330 m can be expected for the Membrane LNG vessels. Smaller breach events result in spills of much smaller volumes of LNG and have much smaller pools.

The flow results obtained should be considered as providing qualitative information on the general pattern, timing, and magnitude of the internal and external LNG flows for different breach and spill events.

III. Large LNG Pool Fire Experimental Results

The focus of the efforts for this part of the study was to improve the understanding of the physics and hazards of large LNG spills and fires on water. The key LNG pool fire issues to be addressed included:

- Determining the Surface Emissive Power (SEP) of large LNG pool fires;
- Determining the fuel vaporization rate of LNG fires on water; and
- Determining the flame height to diameter ratios for large LNG pool fires.

This effort was accomplished through the collection of data obtained during a series of LNG pool fire tests on water. A summary of the test data collected is presented here, while the detailed test data and results are presented in Blanchat et al., 2010.

Shown in Figure 5 is the large scale LNG pool fire test site. The site design included: 1) using soil excavated from the creation of a two meter deep, 120 m diameter pond to create a 310,000 gallon compacted soil LNG storage reservoir; 2) covering the reservoir with a double insulated cover and insulated liner to minimize LNG vaporization; 3) use of prefabricated reinforced concrete pipes to transport the LNG from the base of the reservoir to the center of the pool; and 4) use of simple, liftable plugs to allow gravity-driven high LNG flow rates from the reservoir to the pool. This approach enabled LNG flow rates representative of large spills, while minimizing the need for cryogenic rated high flow volume pumps, associated hardware, and fire rated LNG storage tanks.

Figure 5. Large-scale LNG pool fire test site.

Numerous cameras, spectroscopic diagnostics, and heat flux sensors were used to obtain extensive heat flux, flow rate, and fire size data from the resulting fires for each test. The spreading pool fire area was photographed with the aid of gyroscopically stabilized cameras deployed in U.S. Air Force helicopters.

Figures 6 and 7 are pictures of the two large LNG pool fires, conducted in February 2009 and December 2009.

Figure 6. LNG Test 1 – 21 m diameter LNG spill and pool fire.

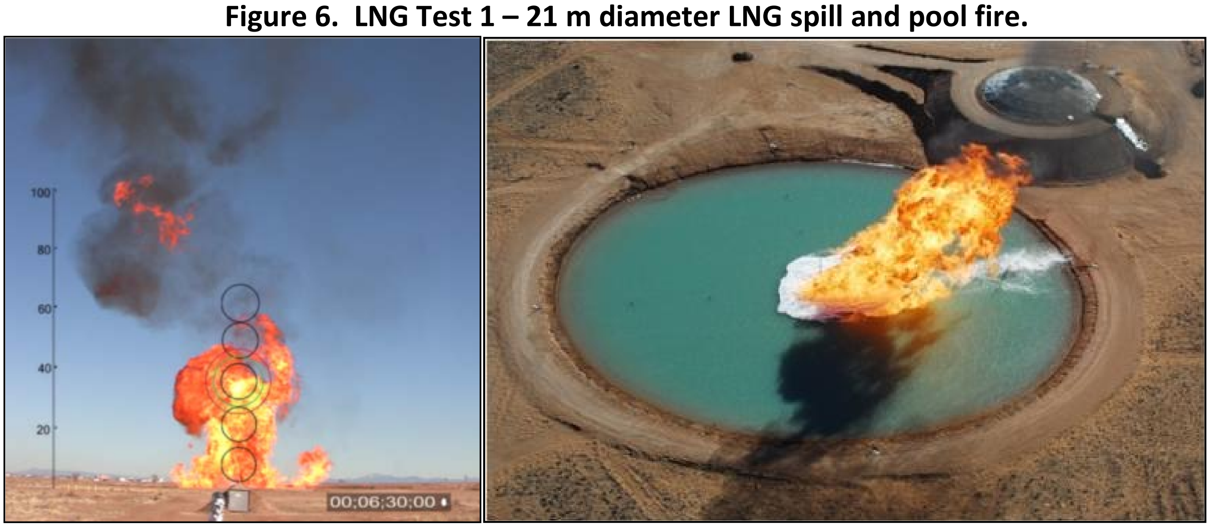


Figure 7. LNG Test 2 – 83 m diameter LNG spill and pool fire.

A summary of the major pool fire parameters measured during these tests are provided below in Table 3.

Table 3. Large LNG Pool Fire Data

Test	Volume Discharged (gallons)	Avg. Flame Height (m)	Flame Diameter (m)	Wind Speed (m/s)	Flame Tilt (degrees)	Vap. Rate (kg/m^{2}s)	Surface Emissive Power (kW/m^2) (narrow/wide)
1	15,000	70	20.7	4.8	50	0.15	238/277
2	52,000	146	56 (83 m spill)	1.6	Negligible	Not obtained	316/286

The thermal radiation spectra as a function of height and time were acquired using a scanning mid-infrared (1.3-4.8 µm) spectrometer. Analyzed spectra determined that the dominant contributor to the thermal radiation was from broadband soot emission. The overall thermal radiation reaching the spectrometer was attenuated by atmospheric water and CO_2 which resulted in a decrease in intensity at different wavelength bands. In LNG Test 2, at ~40 m to 103 m above the ground surface, the data is fairly consistent with spectra-derived flame temperatures of between 1300-1600°C and emissivity values between ~0.3 -0.4.

In both of the tests conducted for this study, there was no evidence of smoke shielding. There were a few instances when small amounts of smoke were seen in LNG Test 2 during the production of large scale vortices that rolled up from the base of the flame when the fire exhibited a puffing behavior. Very little smoke shielding was also observed in pool fire data obtained from a previous, smaller scale (~10 m diameter) test conducted by SNL.

The trend in the data from these tests indicate that the SEP for LNG fires on water level off at about ~280-290 kW/m^2 and might be expected for spreading pools with diameters in the range of 100 m. This is a reasonable value for use in hazard calculations for structures, such as the LNG vessel or shoreline areas, adjacent to or near the fire. Larger LNG fires would likely have some smoke shielding in the upper portions of the flame plume that will lower the overall flame-average SEP for far afield objects.

The collected data showed some unique and unexpected results. Specifically, the fire diameter was not the same size as the spreading pool diameter, as had been assumed by most analyses to date. Previous studies with stagnant pools in pans resulted in fire diameters the same size as the pool diameter. However, in all such studies, the pans had edges that can result in flame stabilization that would not be available in open water scenarios. The data collected further showed that in both very light and significant cross-winds, the flame will stabilize on objects projecting out of the fire, suggesting the vessel itself will act as a flame anchor.

Flame Height-to-Diameter Testing

To develop a flame height-to-diameter correlation, a large (3 m diameter) gas burner was used to create fully turbulent methane fires at the Sandia Thermal Test Complex, which more closely simulates large fire behavior. The data collected was compared with other common height-to-diameter correlations conducted for smaller and less turbulent fires. The Sandia data collected suggests that the fire height for large LNG spills would be much lower than often used in many fire hazard analyses. The Sandia data suggest the fire height-to-diameter ratios for LNG pool fires greater than 300 m in diameter would be less than 1.5 and would approach 0.7 for LNG pool fires about 1,000 m in diameter. Previously, many studies used a constant height-to-diameter ratio of 1.5. The data from the two large LNG pool fire tests conducted as part of this study closely match the gas burner flame height-to-diameter correlation identified.

IV. LNG Vessel Thermal/Structural Analyses

This section provides a summary of the development of LNG vessel structural steel thermal material property data, LNG vessel cryogenic fracture and fire damage testing and analysis, and development of cryogenic and fire thermal loading models needed to identify the time varying thermal stress states on a vessel structure during a large LNG spill and fire. The detailed material testing, and thermal damage testing and analysis efforts conducted are presented in two technical reports Kalan and Petti, 2011 and (Figueroa et al., 2011).

LNG Vessel Structural Steel Material Property Testing

It is well known that many structural steels are susceptible to low temperature brittle fracturing and high temperature softening. In order to perform the thermal (both cryogenic and high temperature) structural damage analyses required for LNG vessels during a spill and fire, information on vessel structural steel material properties and material response at extreme temperatures (from -161°C for cryogenic LNG temperatures and up to 1000°C for LNG fire temperatures), as well as suitable damage models were required. In both cases, neither existing data nor appropriate damage models existed for LNG vessel steels for this range of temperatures. Therefore, a series of material property and material failure tests were performed on two American Bureau of Shipping (ABS) steels representative of the structural steels used in standard LNG vessel construction. The data collected was used to develop cryogenic fracture and fire-induced structural damage models based on vessel structural features, stress states, and temperatures. The material and cryogenic fracture and damage response testing is summarized here, but is discussed in detail in Kalan and Petti, 2011.

ABS Grades A and EH round bar tensile test data were collected at temperatures ranging from -161°C to 800°C. In addition, notched tension specimens and Charpy V-notch testing was performed from -191^{o}C (far below the brittle transition region) to -24^{o}C (above the brittle transition region) for both ABS steels. The tensile test data showed low residual strength (20 percent of yield strength) of LNG vessel steels at LNG fire temperatures for extended periods. The Charpy V-notch energy absorption test results showed low fracture toughness for both materials at cryogenic LNG temperatures, highlighting the susceptibility to fracture of LNG vessel structural steels if contacted by LNG for any extended period.

LNG Vessel Cryogenic Fracture Testing

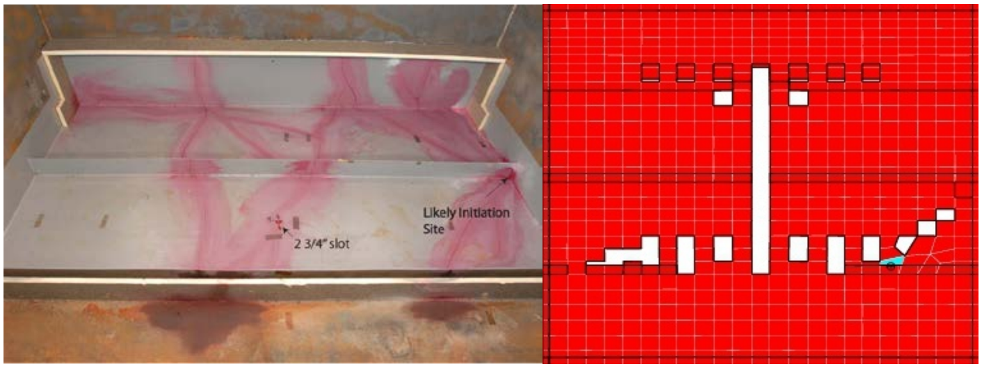
In order to predict how structural sections of an LNG vessel would respond to contact with cryogenic LNG, we conducted a series of large scale LNG spill and fracture tests on ABS Grades A and EH steels. Three series of fracture tests were conducted that included testing of large steel plates that were constrained on their edges, and the testing of large, welded, three dimensional, steel structures representative of LNG vessel structural elements and vessel construction approaches. For these tests, a region in the center of the plate or structure was cooled with liquid nitrogen, which was used for safety considerations. However, testing conducted with LNG showed similar cool down rates of the steel as using liquid nitrogen. The cooling rate and cooling distribution from each test was monitored at several locations on the plates and structures using thermocouples, and fractures were identified after each test. The tests were conducted with prescribed flaw sizes, boundary conditions, and flow rates to provide extensive, high quality data to develop and validate a cryogenic fracture and damage model.

From the fracture data collected, a vessel fracture damage model was developed and was used to predict structural fracture for several simulated LNG vessel structural elements. The development and validation of the cryogenic damage model is discussed in detail in Petti et al., 2011. For verification of the fracture and damage model, a finite element model of a large test structure was developed, and a cryogenic flux was applied to the model that represented the cooling rate data measured in the large structure tests. The cracking observed was compared to the fracturing predicted from the structural model. What was important was to predict the general direction, amount, and propagation of fractures and cracks through structural elements based on the identified temperature and stress states.

Figure 8 shows a comparison of model predictions and test data, and shows that the general extent and direction of cracking is similar relative to crack directions and elements damaged.

These efforts verified that damage could be estimated based on the LNG flow, temperature, and the stress state of the vessel structure.

Figure 8. Comparison of damage analysis to experimental test results.



LNG Vessel Structural Cooling Evaluation

The internal and external regions of the LNG vessel's structure that come into contact with spilled LNG become cooled. To determine cooling rates, experimental data was obtained from a series of structural steel cooling experiments. LNG was pooled on ¾ inch thick carbon steel plates with various surface coatings that included bare steel, primed only, and primed and painted surfaces. The tested surface coatings used consisted of primers and paints used on LNG vessels. The temperature response of the test plates was used to estimate convective heat transfer coefficients. The data and supporting analyses lead to an estimation of lower and upper bound heat transfer coefficients of 400 and 1080 W/m^2-K. The test data also showed that cooling occurs essentially only in the area in contact with the LNG. Based on this data, the regions identified from the flow analysis that come into contact with LNG were reduced linearly in temperature from 20^oC to -148^oC over 10 minutes.

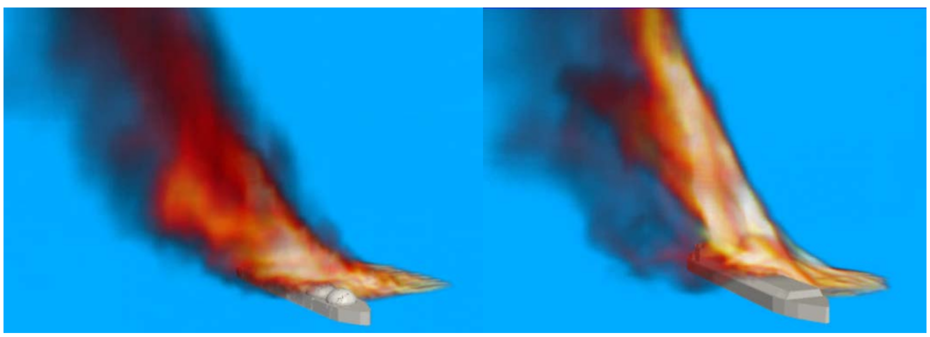
The cooling of LNG vessel steel in contact with seawater was also evaluated. The cooling rates were determined using a finite difference heat transfer analysis. The analysis calculated ice growth depending on the water/ice or water/vessel interface temperature. At interface temperatures below the freezing point of seawater (-1.9°C), the analysis allowed ice to accumulate. For a case with a reasonable external current velocity (1 knot) and for a wide range of bulk seawater temperatures, it was determined sufficient ice forms to insulate the outer hull and allow it to cool to temperatures approaching the temperature of the LNG. The cooling rate calculated was close enough to the cooling rate value determined for air to support using the same cooling rates for vessel steels above and below the waterline contacted by LNG.

LNG Vessel Structural Heating Evaluation

LNG vapors burn at temperatures of about 1500°C, which will negatively impact an LNG vessel's structural integrity if a fire lasts for a significant period of time. For medium to larger spills, the flow analysis indicated the maximum pool diameters would be approximately 180 m to 350 m. Using these pool diameters, pool fire analyses were conducted to estimate the thermal heating rate of the LNG vessel's structural steel. Fuego, a CFD fire code developed and used by Sandia, was used to estimate the envelope of an LNG fire on LNG vessels under various environmental, wind, and humidity conditions. Historical wind speed information was obtained from the National Data Buoy Center (www.ndbc.noaa.gov) for various harbors in the U.S. and was evaluated to obtain a typical wind speed for these harbors. Based on this data, an average wind speed of 9 m/s (20 mph) was considered directed toward the LNG vessels.

As shown in Figure 9, the analyses suggest that in average winds, fire can overlay onto the vessels and impact the tops and sides of the vessels, which should be included in evaluating vessel and cargo tank damage and integrity during a fire.

Figure 9. Large pool fire impacts on Moss and Membrane vessels.



The surface emissive power obtained from the large LNG pool fire experiments was used to define the LNG pool fire heating rates to the LNG vessel structures. Based on these analyses, the temperatures of the outer hulls were calculated to reach approximately 1000^{o}C, while the inner hulls can reach about 775^{o}C. These results compare favorably with vessel hull heating data collected from cargo tank insulation damage testing discussed later in this report. The results suggest that the outer and inner hull structural elements exposed to LNG pool fires for more than 10-20 minutes can experience about a 75 to 80 percent reduction in strength.

V. LNG Vessel Cascading Damage Analyses

The key LNG vessel damage issues Congress wanted addressed as part of this study included:

- Improved understanding of cryogenic fracture and damage to LNG vessels;
- Improved understanding of fire damage to LNG vessels; and
- Improved understanding of the potential for cascading damage from a large spill.

A summary of the cryogenic and fire related vessel damage analyses and the potential for cascading damage to the vessel from an initial spill is presented in this section, while the detailed modeling and analysis results are presented in Petti et al., 2011. The focus of the LNG vessel cascading damage analysis efforts was to use detailed vessel structural and thermal damage models, along with high performance computing resources, to improve the ability to assess and predict cascading damage potential to an LNG vessel from an initial spill.

LNG Vessel Structural Analysis Model Development

For the final vessel cascading damage analyses, detailed finite element structural analysis models were created for both the Moss and Membrane LNG vessels. For the structural analyses, elements with 0.1 m (4 inch) edge lengths were used in the regions where damage and fracturing could potentially occur to allow all of the major structural elements, including the longitudinal stiffeners attached to the inner and outer hulls, to be modeled explicitly in detail. In regions outside of the areas of potential fracturing, the elements were gradually increased to a maximum of approximately 1 m, with most elements in the 0.3 m to 0.5 m range. This helped to reduce the structural analysis complexity and computing resources needed. This approach produced two structural models, each with between four and five million elements.

To ensure the proper mass distributions, both the steel density and the thickness of the shell elements need to be defined as input parameters in the structural models. In the detailed mid-ship sections of the vessel, the thickness of the steel plating was set to the as-built thicknesses since all of the major structural elements were modeled explicitly. For the less detailed fore and aft sections, where the longitudinal stiffeners were not modeled explicitly, the thickness of the inner and outer hulls was increased to account for both the global and local stiffness lost by not including these members. In addition to the thickness of the steel plating, the densities of the blocks in various sections of the vessels were adjusted to account for various non-structural items including LNG cargo, cargo tank insulation, piping, machinery, anchors, fuel, water, etc.

LNG Vessel Damage Analysis Approach

From the spill and flow analyses conducted, the medium to very large breach events give very similar overall LNG flow results within the vessel structures, with the major difference being some variation in the timing of cooling of different regions. For this reason, a single detailed structural damage analysis was performed for each type of LNG vessel. For these analyses, gravitational loads, exterior seawater hydrostatic loads, and internal LNG cargo tank hydrostatic loads were applied to the vessel structural models to first obtain the initial stress states of the vessels. ABS Grade A and EH steels were used to model the structural steel in each vessel. For regions with lower fracture toughness materials (ABS Grades A, B, D, and E) ABS Grade A properties were used, and in regions with higher fracture toughness materials (ABS Grades AH32, AH36, DH32, DH36, EH32, and EH36) ABS Grade EH properties were used. This was done to simplify the structural model input and quality assurance checks needed. The initial load condition chosen was the Summer Arrival Condition where the LNG cargo tanks are 97 percent filled for the Moss LNG vessel and 98.5 percent filled for the Membrane LNG vessel.

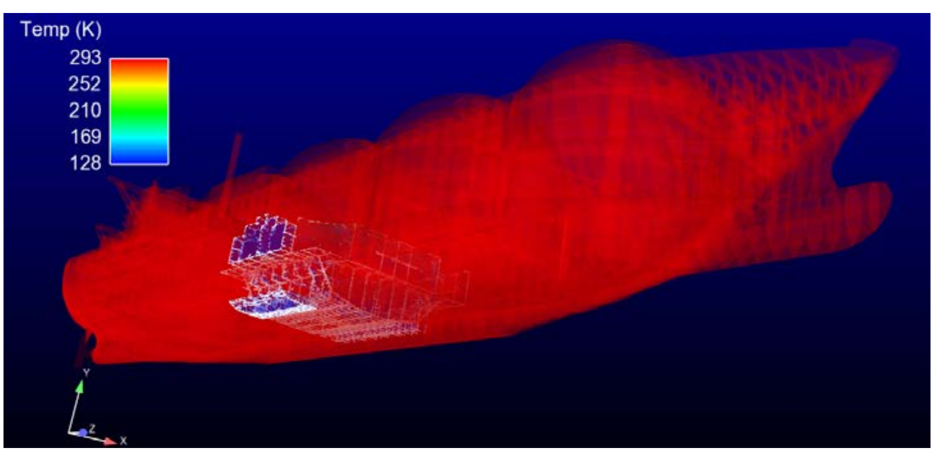
After establishing the initial load and stress states and vessel stability and draft of the structural analysis models for these conditions, temperature changes were applied to the structural models in accordance with the LNG flow, cooling rate, and fire heating rate values discussed in previous sections of this report. These thermal changes, along with the initial stress states and structural steel material properties, were used to track the progression of calculated damage (summarized below) for the LNG vessel. All vessel damage analyses were conducted using high performance computing resources, and the structural damage models were run using approximately 500 parallel computer nodes, each with multiple processors.

Moss LNG Vessel Medium to Large Spill Damage Analysis

The flow analysis showed widespread LNG contact with steel plate surfaces within 30 seconds of a large breach event. As the flow progressed, different regions started to cool at different times. These delays were used to simulate the timing of the flow of LNG within the space surrounding the cargo tank for up to approximately 14 minutes. Beyond that time, the LNG has filled the internal spaces and spills out onto the water. The initial analysis assumed that spilled LNG would not come into contact with the LNG vessel's structure just above the bilge area. However, in some cases the LNG could come into contact with this area. Because of this, the final structural damage results presented include damage in the bilge area in estimating the worst case damage scenarios.

An example of the resulting structural cryogenic damage from a large cargo tank breach and spill is shown in Figure 10.

Figure 10. Example of Moss vessel damage due to cryogenic LNG flow.

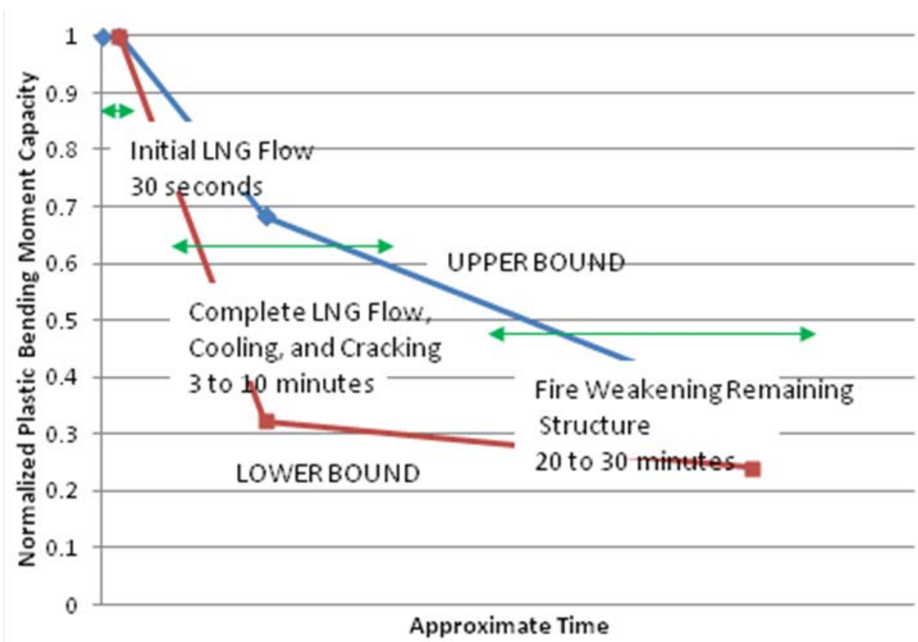


The white colored elements indicate the structural elements that reached the critical fracture damage criterion. The transparent view of the vessel shows both the cryogenic cracking and damage in the outer and inner hull surrounding the cargo tank. The significant damage to the inner hull causes the outer hull to deform upward into the vessel as the hydrostatic pressure from the seawater is no longer resisted by the damaged vessel's inner and outer hulls. The estimated displacement of the outer hull could be as much as one meter. The analysis predicts cryogenic cracking will occur throughout the portions of the vessel that were exposed to LNG flow. No damage was predicted to occur in regions beyond where the LNG flowed.

Based on the cryogenic structural damage analysis, much of the inner hull near a large breach event was damaged. As a result of the pool fire, much of the vessel's structure near the fire on both the side and top of the vessel will reach temperatures of between 775^{o}C and 1000^{o}C for the inner and outer hulls. At these temperatures, the vessel's structural steels are severely weakened, having less than 25 percent of their original strength, and will deform significantly.

Based on the combined cryogenic and fire damage estimated, the plastic bending moment capacity for the Moss LNG vessel as a function of time is presented in Figure 11.

Figure 11. Moss LNG vessel reduction in plastic bending moment capacity for large spills.



The plastic bending moment capacity is defined as the bending moment that would lead to the entire cross-section of the vessel yielding and creating essentially a plastic *hinge*. The plastic bending moment capacity is often used in extreme event risk analyses to evaluate the level of residual structural capacity following an extreme event.

The moment capacity is normalized by the full undamaged plastic moment capacity of the section. The cryogenic damage causes an approximate 30 to 70 percent reduction within

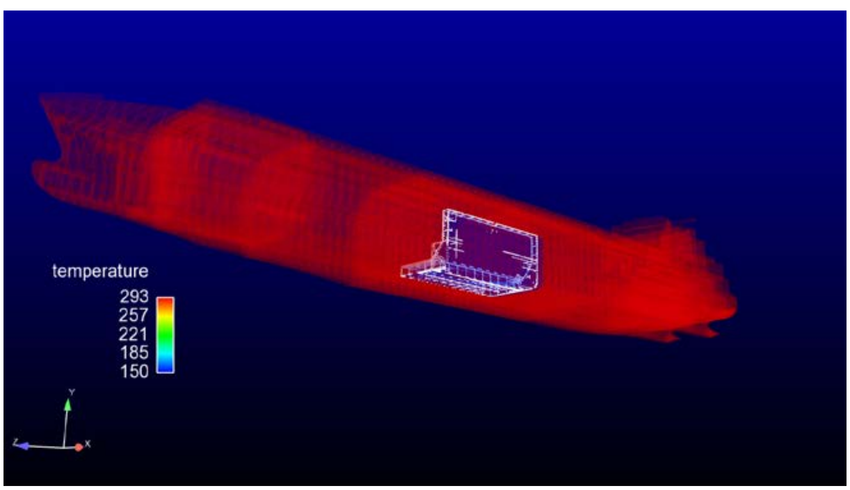
3 to 10 minutes, with the fire causing an additional 10 to 20 percent reduction between 20 and 30 minutes. However, the upper bound capacity estimates assume that the cross-section is in a condition to obtain the full strength of the materials without section buckling. However, the cryogenic damage modeling shows local buckling and material displacement that suggests that the lower bound moment capacity could occur since the sections of the inner and outer hull at the top of the vessel are affected by the fire and have little resistance to tension.

Based on the reduction in plastic moment capacity, the vessel is judged to have essentially no remaining structural strength in the affected region, and will most likely be disabled, severely damaged, and at risk of sinking. Based on the flow and damage analysis, the LNG vessel's structural design limits the LNG flow to the initially damaged region, and the four remaining cargo tanks not breached during the initial event should be unaffected by the cryogenic damage. Also, because the Moss cargo tanks are independent and do not rely on the vessel's hull structure for support, a simultaneous release of LNG from the undamaged cargo tanks due to cascading failure is considered highly unlikely.

Membrane LNG Vessel Medium to Large Spill Damage Analysis

The flow results were used to develop a series of cooled regions for the cryogenic damage analysis. Widespread LNG flow between the inner and outer hulls occurs within 2 and 3 minutes, with subsequent filling of the compartments. At approximately 6 to 10 minutes into the spill, a significant portion of the ballast tank and areas between the inner and outer hulls are filled. While complete filling of the ballast compartments and areas between the double hulls does not occur, the open spaces are small and would contain cold LNG vapor and therefore, the entire ballast tank was included as one large, cooled region. Finally, the same assumptions were made for the Membrane vessel as the Moss vessel regarding cooling rates below the waterline and the eventual entrainment of seawater into the vessel for some breach events and their inclusion in the damage conclusions. Figure 12 shows an example of the Membrane vessel with temperatures and damage plotted.

Figure 12. Example Membrane vessel damage due to cryogenic LNG flow.

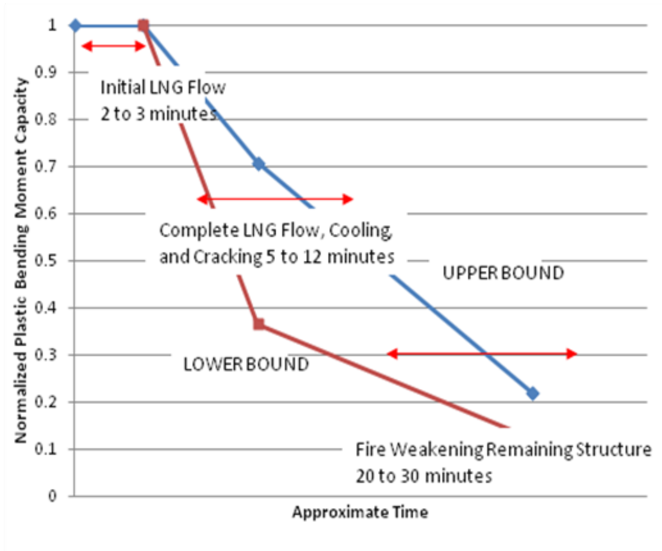


The white colored elements indicate the cryogenic fractures calculated after reaching the critical strain criterion during cooling. The transparent view shows both the cracking in the outer hull and inner hull surrounding the cargo tank. Here, the extent of the damage to vessel structure surrounding the breached cargo tank can be seen. The analysis predicts cracking will occur throughout the entire cooled region, which reflects those portions of the vessel that were exposed to LNG flow.

The damage was predicted to occur primarily near the cooled region boundaries. This is likely an artifact of the sharp gradient from cool to warm material along this boundary. Once the cracks occurred in the structural model, these elements were removed, and much of the stress was reduced in the interior of the cooled region, preventing further apparent damage. The cryogenic fracture and cracking in an actual event is expected to extend throughout much of the cooled region, especially in areas of flaws or stress concentration such as welds, corrosion, and so on. As with the Moss vessel analysis, no damage was predicted to occur in regions outside of the cooled areas. The effective damage to the Membrane LNG vessel is initially localized on one side of the vessel. The majority of the inner and outer hull was damaged, severely reducing the ability of the vessel to resist hydrostatic loads from the surrounding seawater. Unlike the Moss LNG vessel, in which the LNG cargo tank is structurally independent from the inner hull, the Membrane LNG vessel's inner hull provides the structural support for the cargo tank. With the damage to the inner hull, the cargo tank in the affected region will likely not be capable of fully containing the LNG cargo that remains below the breach. This would lead to additional inner hull damage and expanding damage of the inner hull to both sides of the vessel.

From the fire analysis, much of the vessel structure near the fire on both the side and top of the Membrane LNG vessel could reach temperatures of between 775°C and 1000°C for the inner and outer hulls. Since the LNG vessel's inner hull and internal structural members provide the structural support for the Membrane cargo tanks, thermal degradation of both the outer and inner hulls from an LNG pool fire would likely cause damage to the cargo tanks. Based on the cryogenic and fire damage estimated, the reduced cross-sections and weakened materials analysis results were used to estimate the plastic bending moment capacity for the Membrane vessel as a general function of time and are shown in Figure 13.

Figure 13. Membrane LNG vessel reduction in plastic bending moment capacity for large spills.



The cryogenic damage causes an approximate 40 to 70 percent reduction within 5 to 12 minutes (including several minutes to account for the slower flow calculated for the Membrane vessel design) with the fire causing a 80 to 90 percent total reduction in the plastic bending moment capacity between 20 and 30 minutes. The fire has a more significant effect on the Membrane vessel section modulus due to the greater amount of structural cross-section that is exposed to the fire.

The damage to the vessel also introduces concerns related to a reduced buckling capacity for structural regions in compression. The sections of the inner and outer hull at the top of the vessel are affected by the fire and have little resistance to tension. Based on the reduction in plastic bending moment capacity, the vessel is judged to have essentially no remaining structural strength in the affected region, and will most likely be disabled, severely damaged, and at risk of sinking.

Based on the flow and damage analysis, the LNG vessel's structural design limits the LNG flow to the initially damaged region. Although the four remaining cargo tanks were not calculated to have been breached during the initial event, the Membrane cargo tanks are integrated tanks and rely on the vessel's hull structure for support, and the release of their cargo is slightly more uncertain. One of the tanks adjacent to the initially breached tank was calculated to experience cracking in the corner of the inner hull exposed to LNG. The breach of this adjacent tank is possible, but not certain. Even so, if this adjacent tank were to experience a leak, it would most likely progress slowly and/or occur during the fire portion of the event when the fire would weaken the vessel structure in the adjacent tank. This would have the effect of extending the duration of an initial fire, but not increasing the size of the pool fire to any significant degree.

LNG Vessel Damage from Smaller Spills

For very small breach events (0.005m^2 Breach Area; 0.25 ft x 0.25 ft Breach Dimensions; from Table 2), which could occur from a number of credible intentional or accidental events, the spill rates will be more than a factor of 1,000 times less than that of the larger breach events considered. This puts small spills into categories that would typically fall within current spill detection and safety systems and allow a significantly extended response time for both Moss and Membrane LNG vessels. The large reduction in spill rates, cryogenic damage and fire damage potential suggests that should a smaller breach event occur, both Moss and Membrane LNG vessels would have sufficient time to transit to an appropriate anchorage location and work with the Coast Guard and other public safety agencies to perform a damage assessment and initiate appropriate action.

For small breach events (0.5 m^2 Breach Area; 2.3 ft x 2.3 ft Breach Dimensions; from Table 2), the physics of the flow conditions will reduce the LNG flow rate into an LNG vessel by a factor of approximately six, relative to the larger LNG spills, and the full cryogenic cooling and damage of all the compartments between the LNG hulls for each vessel type could take as much as six times as long. However, based on the flow analysis conducted for these holes, the LNG flow internal to the vessel reaches the keels of the LNG vessels only a few minutes later than for the larger spills. This suggests that for spills from small breach events, the full cryogenic damage could take from 10 minutes to 60 minutes longer than for the larger spills. Unfortunately, the fire damage will still occur over the original time period calculated, and therefore the overall reduction in structural capability will most likely occur within one hour of the event.

VI. Additional Cascading Damage Analyses

A number of additional cascading damage issues were addressed in this study, including:

- Cargo tank insulation damage during a fire;
- Overpressure of an LNG cargo tank during a fire;
- Impact of Rapid Phase Transitions (RPTs) during a spill; and
- LNG vaporization, deflagration, and associated damage during a spill.

A summary of the testing and analysis efforts conducted to assess the potential impacts of these kind of cascading damage scenarios is presented in this section, while the detailed test data and analyses are presented in Blanchat et al., 2011, Morrow, 2011, and Figueroa et al., 2011.

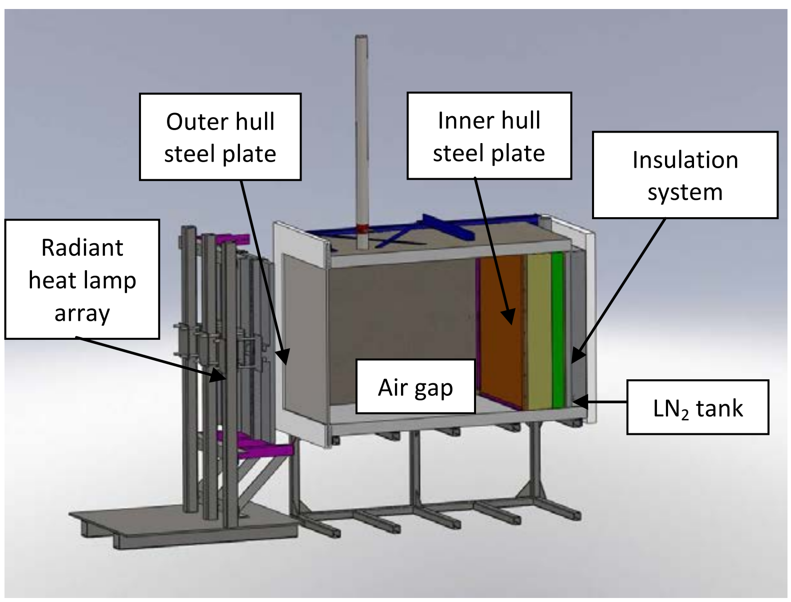
LNG Cargo Tank Insulation Fire Damage Testing

To assess the thermal resistance of LNG cargo tank insulation materials and systems in a fire, large-scale thermal damage experiments and testing were conducted on four major LNG cargo tank insulation systems (two Moss and two Membrane systems), which represent most of the current LNG insulation systems being used in U.S. ports. The testing of each insulation system was coordinated through LNG vessel designers and cargo tank insulation system manufacturers, and each insulation system tested was either provided by the insulation manufacturers or was fabricated at Sandia to the insulation system design and construction specifications provided by the manufacturers. LNG vessel representatives witnessed their insulation system test setup, experiments, data collection and evaluation, and participated in post-test insulation system inspection.

The experiments were designed to test the insulation systems for the fire durations expected from a large LNG spill. Based on the latest information on large-scale LNG spills and associated fires (Luketa et al., 2008), fires from 20 to 40 minutes long might be possible. Therefore, all the insulation systems were tested for at least 40 minutes. All tests were performed using a radiant heat assembly that allowed identical and reproducible heat flux boundary conditions for each test. All tests were performed to yield a continuous incident heat flux to the outer hull (for the membrane) or weather cover (for the Moss) insulation systems of ~270 kW/m^2. This value was based on preliminary, flame-averaged steady-state surface emissive powers measured in the large-scale LNG pool fire tests previously discussed and presented in (Blanchat et al., 2010).

The insulation tests were conducted in the test apparatus shown in Figure 14.

Figure 14: LNG cargo tank insulation testing layout.



It was approximately one meter by one meter square, and approximately two meters long and designed to allow testing of large representative LNG insulation panel systems with minimal edge effects such that a thermal environment representative of a large fire could be created. The testing apparatus included a radiant heat lamp assembly, mild steel plates representing Membrane LNG vessel outer and inner hulls or the Moss LNG vessel weather cover, an air gap inerted with nitrogen during testing, the insulation system being tested, and an aluminum tank filled with liquid nitrogen (LN_2) to represent a cold LNG cargo tank boundary condition. Liquid nitrogen was used for safety reasons, since it is not flammable, and has a similar temperature as LNG.

A summary of all the insulation test results are shown in Table 4. Heat flux was measured by heat flux gauges attached to the tank and by evaluating the change in the liquid nitrogen boil-off rate in the LN_2 tank.

Table 4. LNG Cargo Tank Insulation System Fire Damage Test Results

LNG Vessel	Insulation Type	Thickness	Fire Survivability	LN_2 Tank Heat Flux
Moss	Extruded polystyrene panel	~300 mm	> 40 min	< 7 kW/m^2
Moss	Polyurethane foam/ phenolic resin foam composite panel	~300 mm	> 40 min	< 5 kW/m^2
Membrane	Polyurethane foam and plywood panel	~300 mm	> 40 min	< 5 kW/m^2
Membrane	Perlite-filled plywood boxes	~500 mm	> 40 min	< 5 kW/m^2

LNG Cargo Tank Pressure Safety Relief Valve Evaluation

There has been much discussion on the impacts of a large LNG pool fire on increasing vaporization of LNG in undamaged tanks and the capacity of the current pressure safety relief valves to handle this increased vaporization. The concern is that if pressure builds up during a fire and cannot be adequately handled by the pressure safety relief valve systems, then a cargo tank could become over-pressurized, fail, lead to additional LNG spills, and increase hazards. A particular concern was Moss LNG cargo tanks, since some Moss insulation systems were considered to be quite vulnerable to high temperature degradation.

The significant reduction in heat transfer levels measured in the insulation damage testing discussed previously indicates that during the tests, charred insulation and soot formation is interfering with flux between the weather cover and the liquid nitrogen tank. Several possibilities exist; the atmosphere between the two surfaces could be acting as a participating media blocking heat flow. Alternatively, a very thin layer of insulation is left on the surface of the tank interfering with heat flux, or the charred insulation continues to act as a heat flux barrier along with the undamaged insulation. These possibilities suggest that different heat flux models should be considered and assessed.

Therefore, three models were considered as a way to bracket the potential range of heat flux values that an LNG cargo tank could experience during a fire. The estimates of heat flux to the cargo tank based on the experimental data and analysis from the cargo tank insulation damage testing suggests a potential range of values from 3-7 kW/m^2, with a most likely minimum value of ~5 kW/m^2. This value would be representative of a simple radiation heat transfer value. In considering both a participating media heat transfer analysis and a free convection heat transfer analysis for a Moss LNG cargo tank, the analyses support maximum heat flux estimates of up to 10 kW/m². Based on the fire modeling information, these heat flux values can be assumed to occur during free convection over the full tank surface area, including the area of the cargo tank below the main deck of the LNG vessel.

From the analyses, a heat flux of 5 kW/m² will result in an average pressure equivalent to the normal operating pressure of the cargo tank (~1.3 psig). A heat flux of 10 kW/m² will result in an average pressure of ~2.8 psig, and for the free convection case, a pressure of ~14.7 psig. Moss LNG cargo tanks are constructed to a design pressure which significantly exceeds the highest estimated pressure from the above scenarios. While the increased heat flux will cause some vaporization of the LNG in the vessel's cargo tanks, the cargo tank pressure relief valves are adequately sized to handle the resulting vapor production rates. Due to the combination of adequately sized cargo tank pressure relief valves and cargo tank design standards, there is a minimal likelihood of a Moss LNG cargo tank being damaged from a fire due to vapor over pressurization.

This approach was compared to an analysis performed by the Society of International Gas Tanker and Terminal Operators (SIGTTO) in 2009. This was an industry-wide study conducted to assess LNG cargo tank safety relief valve performance in the face of a large pool fire. The SIGTTO approach used standard handbook sizing algorithms and simplifying assumptions on fire/vessel interactions and cargo tank insulation damage rates, but reached similar conclusions. Overall, the testing and analyses suggest that the Moss LNG cargo tank insulation materials currently used can provide protection of the cargo tanks in a fire, and LNG vaporization would not increase to a level that would exceed the pressure safety relief valve capacity or damage the LNG vessel's cargo tanks. These analyses are presented in greater detail in Morrow, 2011.

LNG Vaporization and Deflagration Analysis

During an LNG spill, as the cryogenic LNG flows over the relatively warm structural steel within an LNG vessel, the LNG will begin to vaporize. Likewise, if a breach is at, near, or below the waterline, the LNG will also vaporize when it comes in contact with the relatively warm water. In both cases, the methane generated is flammable within a certain concentration range by volume in air (5 to 15 percent). Below five percent concentration, the vapor is too lean to burn, and above 15 percent concentration there is not enough air to sustain combustion.

During the spill flow analyses conducted, LNG vaporization and concentrations were also calculated. This provided an estimate of the amount and timing of the vapor generated and the likelihood of ignition, especially between the double hulls. In evaluating the calculated vaporization data, the combustible vapor concentrations varied spatially and temporally in each compartment and the ignitable concentrations in any region only lasted a few to ten seconds. Therefore, it is unlikely that ignition of methane vapors would occur inside the double hull compartments.

LNG Spill on Water Rapid Phase Transition Damage Analysis

A Rapid Phase Transition (RPT) is a phenomenon observed when two liquids of very different temperatures come into contact. LNG spilled onto water and undergoing a series of RPTs can create localized overpressures that look, sound, and behave like a small explosions. Where the explosive pressure is confined or where it is near structural elements, severe structural damage can occur.

In a review of the existing RPT information and data from LNG spills on water, the primary observation is that RPTs generally occur when LNG is either poured at high velocity onto water, or when water is sprayed at high velocity onto LNG. Therefore, we used the LNG flow results to identify and evaluate events with high LNG mixing rates. The results show that only a few events cause significant mixing. Those events that create the most mixing, and therefore the greatest likelihood of RPTs, occur relatively far away from an LNG vessel's outer hull. Therefore, the direct or additional damage of an RPT or a series of RPTs on the LNG vessel's outer hull is possible, but would likely cause minimal additional damage to the vessel.

VII. Large LNG Pool Fire Hazard Analyses

In this section we provide summarized thermal hazard distances resulting from large LNG spills and pool fires on water using solid flame models while the information is presented in detail in Luketa, 2011. The LNG pool fire hazard analysis parameters used in the 2004 and 2008 Sandia LNG reports (Hightower, et al. 2004) (Luketa, 2008) were based on LNG pool fire data of much smaller scale. In keeping with the principle of using the best available data, the parameters in those reports have been updated to reflect the newly acquired LNG pool fire and cascading damage data from this study. The former and updated fire parameter values are noted in Table 5 and are appropriate for use with common Solid Flame Fire Models. These types of models are suggested for their ease of use in estimating general hazard distances for a range of spills (Luketa, 2011).

Table 5: Recommended Nominal Values for Solid Flame Model

Nominal value	***2004 and 2008 Sandia LNG reports***	***Current report***
Burn rate (m/s)	3.0×10^{-4}	3.5×10^{-4}
Flame height (m)	Moorhouse correlation	Sandia correlation
SEP (kW/m^2)	220	286
Transmissivity	0.8	Wayne formula

As in the 2004 and 2008 Sandia reports, it must be emphasized that hazard distances from an LNG spill and fire will change depending on site-specific environmental conditions and breach scenarios, and site-specific analyses should be considered when appropriate.

Table 6 provides predicted thermal hazard distances for intentional events using the updated parameters and the same scenario matrix for hole sizes and tanks breached as presented in the 2004 Sandia report, which are contained in Table 7. The average pool size is calculated using the same approach as in the 2004 report, and the discharge coefficients also have not changed. Note the calculated pool diameter for the nominal cases are representative of pool diameters of 180 m to 350 m calculated for the spill and flow analyses conducted for this study.

The updated parameter values suggest the use of a higher heat flux, lower flame height, and the same pool diameters previously used, which result in about a two percent decrease in the thermal hazard distances relative to those predicted in the 2004 Sandia report for spills from smaller LNG vessels. Using the same approach, the hazard distances are reduced by about 7 to 8 percent relative to the 2008 Sandia report for larger vessels and larger spills.

From a cascading damage viewpoint, the analyses presented suggest that significant LNG vessel damage is likely from a large spill, but the major damage occurs about 15-30 minutes after an initial breach and spill. This is about the same time that a fire from an initial breach will begin to die out from a large spill. Therefore, it is expected that if cascading damage occurs, it will likely be a sequential, but not simultaneous, breach of other LNG cargo tanks, and suggests that evaluating hazard distances based on a nominal one-tank spill, with a maximum of a three-tank spill, as has been recommended in the 2004 Sandia report, is still appropriate for estimating hazard distances.

Table 6: Thermal hazard distances using parameters from the 2009 large pool fire test data

HOLE SIZE (m^2)	TANKS BREACHED	DISCHARGE COEFFICIENT	BURN RATE (m/s)	SURFACE EMISSIVE POWER (kW/m^2)	τ	POOL DIAMETER (m)	BURN TIME (min)	DISTANCE TO 37.5 kW/m^2 (m)	DISTANCE TO 5 kW/m^2 (m)
INTENTIONAL EVENTS									
2	3	0.6	3.3×10^{-4}	286	nom	199	20	299	895
5	3	0.6	3.3×10^{-4}	286	nom	546	8.1	697	1894
5*	1	0.6	3.3×10^{-4}	286	nom	315	8.1	433	1266
5	1	0.3	3.3×10^{-4}	286	nom	223	16	329	974
5	1	0.6	1.9×10^{-4}	286	nom	415	8.1	471	1180
5	1	0.6	5.1×10^{-4}	286	nom	253	8.1	393	1252
5	1	0.6	3.3×10^{-4}	286	low	315	8.1	320	922
5	1	0.6	3.3×10^{-4}	248	nom	315	8.1	404	1183
5	1	0.6	3.3×10^{-4}	326	nom	315	8.1	479	1347
12	1	0.6	3.3×10^{-4}	286	nom	488	3.4	636	1748

*nominal case

Table 7: Thermal hazard distances in the 2004 Sandia LNG report

HOLE SIZE (m^2)	TANKS BREACHED	DISCHARGE COEFFICIENT	BURN RATE (m/s)	SURFACE EMISSIVE POWER (kW/m^2)	τ	POOL DIAMETER (m)	BURN TIME (min)	DISTANCE TO 37.5 kW/m^2 (m)	DISTANCE TO 5 kW/m^2 (m)
INTENTIONAL EVENTS									
2	3	.6	3×10^{-4}	220	.8	209	20	250	784
5	3	.6	3×10^{-4}	220	.8	572	8.1	630	2118
5*	1	.6	3×10^{-4}	220	.8	330	8.1	391	1305
5	1	.3	3×10^{-4}	220	.8	233	16	263	911
5	1	.6	2×10^{-4}	220	.8	395	8.1	454	1438
5	1	.6	8×10^{-4}	220	.8	202	8.1	253	810
5	1	.6	3×10^{-4}	220	.5	330	8.1	297	958
5	1	.6	3×10^{-4}	175	.8	330	8.1	314	1156
5	1	.6	3×10^{-4}	350	.8	330	8.1	529	1652
12	1	.6	3×10^{-4}	220	.8	512	3.4	602	1920

*nominal case

VIII. LNG Spill Prevention and Risk Management

As noted in both the 2004 and 2008 Sandia LNG reports, risk prevention and mitigation techniques can be important tools in reducing both the potential for a spill and the hazards from a spill, especially in locations where the potential impact on public safety and property can be high. However, what might be applicable for cost-effective risk reduction in one location might not be appropriate at another location. Therefore, coordination of risk prevention and management approaches with local and regional emergency response and public safety officials is important in providing a comprehensive, efficient, and cost-effective approach to protect the public and property at a given LNG import or export location.

From an LNG vessel damage viewpoint, the analyses conducted and presented in this report suggest that significant damage is likely to LNG vessels from medium and large breach events and spills. Therefore, a large breach and spill could have both short-term and long-term impacts on public safety, energy security and reliability, and harbor and waterway commerce at some sites. For this reason, significantly more attention and proactive measures should be considered for preventing the possibility of larger breach and spill events or for mitigating the cryogenic and fire impacts of larger spills on LNG vessels.

Risk management options should be focused on approaches that can be used to actively prevent or mitigate larger spills. Some risk management approaches that can be considered to help reduce the possibility of an event occurring, or reduce the hazards to the vessel and the public should an event occur include:

- Implementation of enhanced operational security measures, to include:
  - Positive control of other vessel movements during LNG vessel transits and operations;
  - Review of LNG vessel escort protocols and operations to improve the ability to enforce exclusion zones through enhanced standoff and active interdiction approaches;
- Review of port operational contingency plans to ensure procedures are in place to address larger spills, to include options for moving the vessel to a safe anchorage to monitor, inspect, and assess damage, and for longer-term response options, including vessel lightering;
- Review of emergency response coordination and procedures for the LNG vessel, terminal or port, port authority, and emergency response groups to reduce the overall impacts and consequences of larger spills; and
- Review LNG vessel design, equipment, and operational protocols for improved fire protection to the LNG vessel, terminals, and vessel personnel from a large LNG fire.

IX. Conclusions

The major findings for smaller breach events include:

- For the very small breach events, which could occur from a number of credible accidental or intentional events, the spill rates are more than a 1,000 times less than that of potential larger breach events.
- This puts smaller spills into a regime that would typically fall within current spill detection and safety systems on LNG vessels such that it is extremely likely there would be sufficient time to move the vessel to a safe anchorage to monitor, inspect, and assess damage and long-term response options.

The major findings for medium and larger breach events:

- Large-scale fracture testing, cryogenic flow analyses, and fire modeling indicated that LNG vessels would be disabled, severely damaged, and at risk of sinking.
- For these events, LNG vessels would not be capable of movement to a safe anchorage, and would require longer periods to monitor, inspect, assess, and establish long-term response and remediation measures.

The major findings for Cascading Damage Hazards:

- Current LNG vessel and cargo tank design, materials, and construction practices are such that simultaneous multi-cargo tank cascading damage spill scenarios are extremely unlikely, though sequential multi-cargo tank cascading damage spill scenarios are possible.

- Should sequential cargo tank spills occur, they are not expected to increase hazard distances resulting from an initial spill and pool fire, but could increase the duration of the fire hazards.
- Based on the data collected from the large-scale LNG pool fire tests conducted, thermal (fire) hazard distances to the public from a large LNG pool fire will decrease by at least 2 to 7 percent compared to results obtained from previous studies.
- Risk management strategies to reduce potential LNG vessel vulnerability and damage from breach events which can result in large spills and fires should be considered for implementation as a means to eliminate or reduce both short-term and long-term impacts on public safety, energy security and reliability, and harbor and waterways commerce.

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