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SUMMARY OF THE PHOENIX SERIES LARGE SCALE LNG POOL FIRE EXPERIMENTS

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The increasing demand for natural gas is expected to increase the number and frequency of Liquefied Natural Gas (LNG) tanker deliveries to ports across the U.S. Because of the increasing number of shipments and facility siting applications, concerns about the potential for an accidental spill or release of LNG have increased. In addition, since the incidents surrounding September 11, 2001, concerns have increased over the impact that accidents and other events on hazardous or flammable cargoes, such as those carried by LNG ships, could have on public safety and property. The risks and hazards from an LNG spill will vary depending on the size of the spill, environmental conditions, and the site at which the spill occurs. Risks could include injuries or fatalities to people, property damage to both the LNG ship and equipment and onshore property, and economic impacts due to long-term interruptions in the LNG supply or closure of a harbor. With the growing use of imported LNG to meet increasing U.S. and regional natural gas demands, damage or disruption from a spill to LNG import terminals or harbor facilities could curtail LNG deliveries and impact natural gas supplies. Therefore, methods to ensure the safety, security, and reliability of current or future LNG terminals and LNG shipments are important from both public safety and property perspectives, as well as from a national and regional energy reliability standpoint.

As LNG imports started to increase in the U.S. in the early 2000's, a number of hazard studies were conducted that resulted in widely varying consequence and hazard estimates resulting in broad public concern over the adequacy of current hazard and consequence analysis techniques. Subsequent Sandia analysis [Hightower et al., 2004] highlighted some primary knowledge gaps that were limiting the fidelity of site-specific risk assessments due primarily to the lack of large-scale LNG spill, fire, and damage data. Experimental studies used to justify current hazard analyses were 10 to 100 times smaller in scale than potential incidents. The limiting factor in conducting the needed larger-scale experiments was that they were thought to be cost prohibitive.

While much progress has been made in LNG threat, consequence and vulnerability assessment; for example, a general approach to risk evaluation has been developed and used as a basis in site-specific risk assessments [Hightower et al., 2004]; there are still knowledge gaps for very large scale LNG pool fires [Luketa et al., 20008] that limit the fidelity of site-specific risk assessments and remain a focal point of concern. These knowledge gaps result in the need to make assumptions in hazard analysis that may or may not be warranted and could lead to over predicting or underestimating both direct and latent hazards and impacts to the public, property, the economy, or energy reliability.

To address these concerns, Congress funded the Department of Energy (DOE) in 2008 to conduct a series of laboratory and large-scale LNG pool fire experiments at Sandia National Laboratories (Sandia) in Albuquerque, New Mexico. The focus of the LNG pool fire testing efforts were to improve the understanding of the physics and hazards of large LNG spills and fires by conducting laboratory experiments and fire tests of LNG spills on water of up to 100 m in diameter. These tests were expected to better represent the fire behavior of spills postulated from current and future LNG carriers.

Due to its unique chemistry, methane fires behave differently compared to other hydrocarbon fuel fires, but are expected to follow the trend of heavy hydrocarbon fuel fires, where the surface emissive power (SEP) of a pool fire increases to reach a maximum value then decreases to reach a limiting value with increasing diameter. For LNG, the limiting SEP value is unknown and verifying the actual values required the improved laboratory and large-scale experiments funded by Congress. These large scale spreading LNG pool fire experimental datasets, combined with small scale gas burner experiments, will support pool fire model development and validation for extrapolation to a scale of an potential LNG spill of 300-500 m or larger in diameter.

Laboratory-Scale Experiments

The reduced-scale experiments, burning methane gas in the FLAME test cell at the Thermal Test Complex, measured flame height at various flow rates to provide data for flame height correlations in fully turbulent fires burning lightly sooting fuels. One of the deficiencies of historical data with gas burners is that due to the small size of burners used (< 1 m) the fires were not fully turbulent. Turbulence affects flame height and thus it is important to capture this physics. The Sandia tests utilized the largest gas burner to date (3 m diameter) and are fully in the turbulent regime. Four separate methane experiments yielded twenty two sets of flame height vs. fuel flow rate data. A flame height correlation as a function of a dimensionless heat release rate (e.g., Q*) was developed to support recommendations on flame height for very large LNG pool fires (~1000 m diameter). The correlation estimates the H/D for a 300-500 m diameter LNG fire to be approximately 1.3-1.0 (with decreasing H/D for increasing diameter).

Large-Scale LNG Pool Fire Experiments

Cost estimates to build a facility to conduct large-scale LNG pool fire tests were prohibitive. This forced Sandia to assess ways to develop a safe, low-fabrication-cost experimental setup that could be constructed. The solution selected necessitated significant operational safety considerations including unprecedented cooperation between numerous Sandia organizations, the DOE Sandia Site Office, and Kirtland AFB agencies (including flight-operations and emergency fire-response). By focusing on the experimental objectives, and using experience in conducting large-scale experiments, the team came up with a simple, low-cost experimental approach. The experimental design concept (Figure 1) included: 1) use the soil excavated from the creation of a shallow 120-m diameter pond to create a deep, 310,000 gallon reservoir to hold the LNG while filling, 2) insulate and cover the reservoir to minimize vaporization losses, 3) use industry standard prefabricated reinforced concrete pipes to transport the LNG from the base of the reservoir to the center of the pool, and 4) use a simple, liftable plug to allow gravity to control the flow rate.

Figure 1 The Large Scale LNG Pool Fire Experimental Site

This approach enabled high LNG spill rates onto water representative of potential large spills, while minimizing the need for cryogenic rated high-flow rate pumps and hardware. This novel approach required significant environment, safety, and health analysis to provide confidence that the design and operations would be safe. Safety issues examined included reservoir integrity, thermal (cryogenic to fire fluxes) impacts, asphyxiation, explosion, drowning, and aviation operations (helicopter and airport traffic) issues. Advanced transient, three-dimensional transport simulations were used to estimate both the thermal performance of the reservoir and components, the transport of gaseous boil-off during the cool-down process, and in the design of the diffuser in the middle of the pool needed to translate the linear momentum of the LNG in the discharge pipes into a radially spreading pool.

Two experiments were completed obtaining fires from LNG spills with spreading pool diameters of approximately 21 m and 81 m. Extensive sets of fire data were collected for each test. Numerous cameras, spectroscopic diagnostics, and heat flux sensors were used to obtain heat flux data from the resulting fires. The spreading pool fire area was photographed with the aid of gyroscopically stabilized cameras deployed in U.S. Air Force helicopters. While three tests were proposed (to achieve spreading pool diameters at ~35 m, 70 m, and 100 m), it is believed that the data collected from the two completed tests is sufficient to allow spill and fire model development and validation for use in estimating hazards and consequences for LNG pool fires up to projected spills of 300-500 m.

The data collected showed some unique and unexpected results specifically that the fire diameter was not the same as the spreading pool diameter as had been assumed by all analyses to date. Previous studies with stagnant pools in pans had resulted in fires the same size as the pool. However, in all such studies, the pans have edges that can result in flame stabilization that would not be available on the open water. 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 that the ship itself will act as a flame anchor.

In LNG Test 1, 58.0 m^3 (~15,340 gal) were discharged in ~510 s through a 15-inch discharge pipe. The flow rate initially was about 0.061 m^3/s (970 gpm) and increased throughout the test, reaching 0.123 m^3/s (1960 gpm) at the end of the test. During the steady-state fire interval of 300-510 s, the average flow rate from the reservoir was 0.119 m^3/s (1890 gpm), yielding an average mass discharge rate of 50.0 kg/s from the reservoir. The liquid mass flow rate from the diffuser was slightly less at 48.4 kg/s due 2-phase flow and the generation of methane vapor. The steady-state pool area yielded an equivalent circular diameter of 21.4 m. At steady-state, the regression rate was 0.14 kg/m^2s. Note that this mass loss rate was approximately 66% of the value used for the reservoir design criteria (0.212 kg/m^2s).

In LNG Test 1, the average wind speed was 4.8 m/s at 331 degrees, tilting the flame plume to the South. The average length was ~60-70 m (as compared to an average height of ~34 m). The average tilt angle was ~50°, yielding an L/D ratio of ~2.8-3.3. Narrow view (spot) radiometers corrected for transmission losses measured a spot-average steady-state surface emissive power (SEP) of 228 kW/m^2. A flame-average SEP was determined by correlating view factor information from video analysis with the wide-angle radiometer data, yielding an average overall SEP of 270 kW/m^2.

In LNG Test 2, about 198.5 m^3 (52,500 gallons) were discharged in ~144 s through the three discharge pipes. The average flow rate during the fully open period (130 s to 220 s) was 1.91 ± 0.84 m^3/s (30300 ± 13350 gpm), yielding a mass discharge rate of ~802 kg/s. The spreading LNG pool area continuously increased during the discharge interval, achieving an equivalent circular diameter of ~81 m at the end of the spill. Since the reservoir emptied prior to the pool achieving a constant area, a burn rate could not be calculated.

The test had unexpected results in that the fire did not attach to the leading edge of the spill, hence the effective fire diameter was smaller than the spreading LNG pool diameter. The average flame width at 15 m above the pool was ~50 m and the average flame height was ~146 m during the steady-state interval from 250-300 s. This yields an H/D ratio of ~1.7 and an H/W ratio of ~2.9. The average wind speed was 1.6 m/s at 324 degrees. There was very little flame tilt; however, the wind did appear to drag the plume toward the south.

Narrow view (spot) radiometers on the North and South data collection spokes yielded spot-average steady-state surface emissive power (SEP) of 316 kW/m^2 and 239 kW/m^2, respectively. The SEP on the South spoke is believed to be low due to the presence of smoke from grass fires partially obstructing the view of the instruments. The overall flame average SEP was 286±10 kW/m^2.

Thermal radiation spectra as a function of height and time were acquired using a scanning mid-infrared (1.3-4.8μm) spectrometer. For LNG test 2, data reduction efforts were concentrated on spectra acquired within the quasi-steady burning period (250-300 sec). The spectra from heights at approximately ground level to over 100 m yielded thermal radiation intensities lowest for elevations closest to the ground and then increased steadily to a maximum where they remained until the maximum scan height was achieved. There was no indication of declining intensities as the maximum scan height was approached (100 m).

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. At low heights it appears that the fire temperatures are highest (~2000°C) and the emissivity is lowest (~0.1). With increasing height, the temperature decreases and the emissivity increases. From a height of about 40 m to the top of the measurement region (~100 m) the temperature and emissivity are approximately constant with values of 1550°C and 0.33, respectively.

The agreement in the surface emissive power derived from the radiometer data and the spectrometer data is acceptable and within the experimental variability. Surface emissive power (from spectrometer data) is a minimum near the ground level, with approximate values of 100 kW/m^2. The heat fluxes then increase steadily from 0 to 40 m and reach peak values approaching 275 kW/m^2.

Additional spectrometer data was collected with an FTIR spectrometer, a high-speed visible camera, and a thermal imager. A two-temperature spectra fire model correlated extremely well to the measured spectra. It is postulated that the two temperature states more accurately depict the true nature of the fire by characterizing both the efficient combustion regions and those dominated by slow burning, absorbing soot.

Conclusions

Figure 2 plots SEP vs. LNG pool diameter for a variety of hydrocarbon fuels [Vela 2009], including the three SNL LNG pool spread tests on water (the 2005 10 m test is documented in a SNL classified report) and other major LNG tests (both land and water). SEP for hydrocarbon fuels all have similar behaviors in that the SEP starts low (due to burning in a laminar regime), increases as the burning transitions into a fully-turbulent regime), and then tails off due to smoke shielding as soot is quenched at the flame surface. Soot quenching starts at the flame mantle, and as the fire size increase, the smoke shield progressively moves down toward the base of the burning pool. LNG is expected to follow similar trends; however, due to its unique molecular bond structure, the shape of the curve is shifted toward the right as indicated by the test data.

Even though very little smoke shielding occurred in LNG Test 2 (Figure 3), the trend in the data does indicate that the SEP is leveling off, indicating that a SEP of ~286 kW/m^2 can be expected for spreading pools with diameters in the range of 100 m, and would be a reasonable value for use in hazard calculations for structures adjacent to or near the fire. Larger LNG fires are expected to have smoke shielding effects in the upper portions of the flame plume that will lower the *overall* SEP. This would impact hazard calculations for far-field objects but not for near-field objects relatively close to the base of the fire.

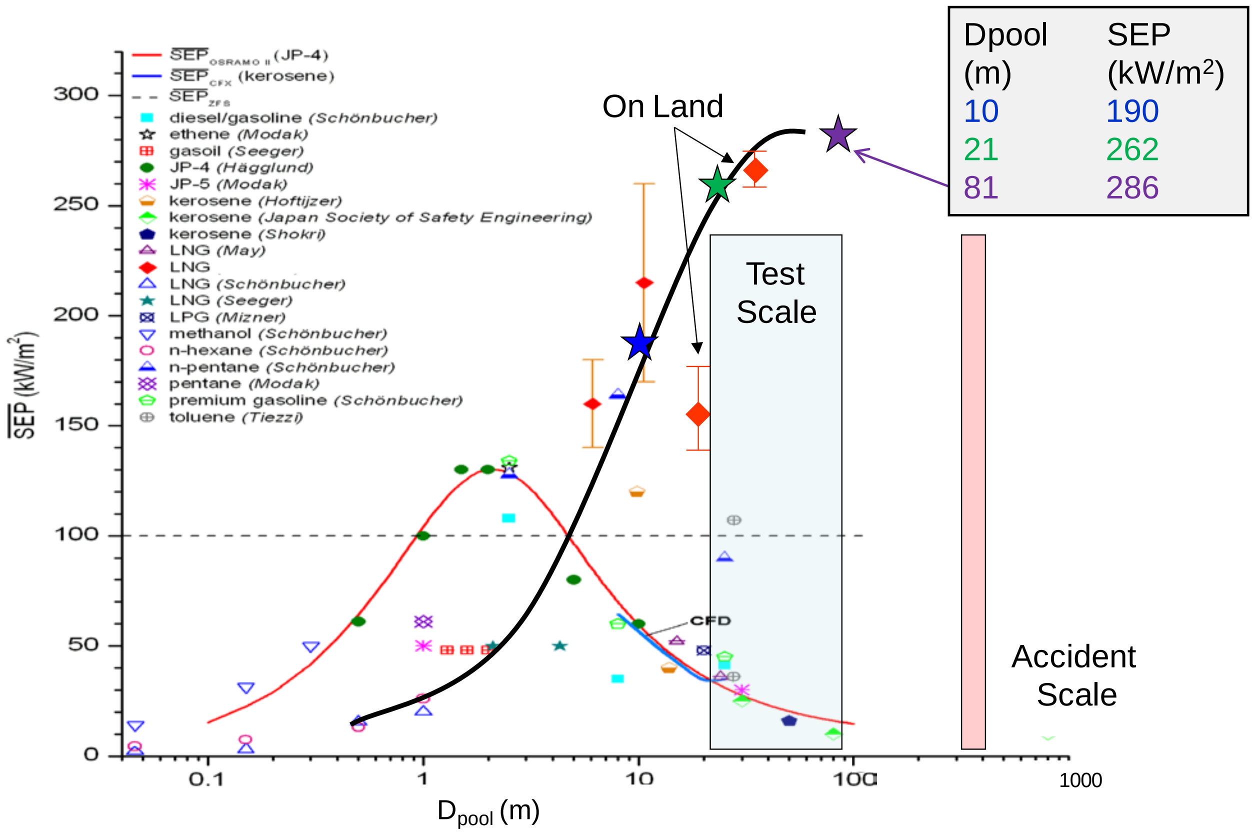

Figure 2 SEP vs. pool diameter for various hydrocarbon fuels.

Smoke mantles were not evident in either test, i.e., smoke shielding was nonexistent. 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, as can be seen in Figure 3.

The results from LNG Test 2 identified a number of pool fire dynamics that should be considered when modeling flame spread, flame geometry, and smoke production for use in hazard predictions. They include 1) water entrainment and condensation in the cold region above the pool acting as a suppressant, 2) entrapment of methane in hydrates that limits fuel supply rate, 3) fluid velocities opposing flame spread from air entrainment and wind created by the intense fire, 4) de-coupled LNG pool spreading and fire spreading, and 5) lack of flame anchoring over the water pool. The LNG pool fire size, soot production, and SEP could vary depending on the size of a harbor and the relative congestion. Flame anchoring could change fire dynamics, behavior, and hazards. The de-coupling of the flame spread with the pool spread, i.e., lack of flame anchoring to the leading edge of the spreading LNG pool over the water pool was evident in all three spreading LNG pool fire tests performed at Sandia, shown in Figure 3. Fire models that capture the above dynamics will be needed to better understand LNG fire physics and behavior over water.

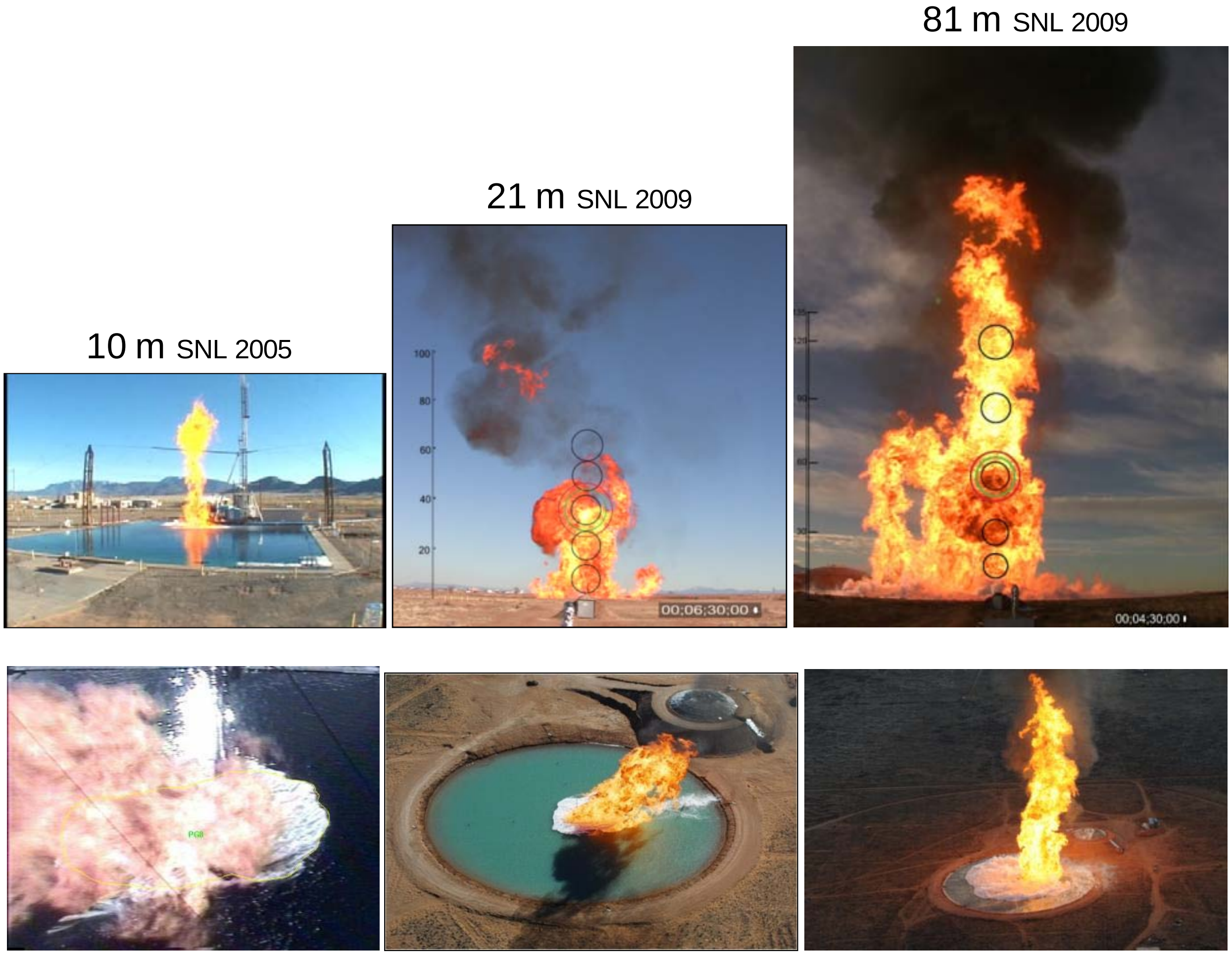

Figure 3 LNG fire dynamics at large scale.

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