The Phoenix Series Large-Scale Methane Gas Burner Experiments and Liquid Methane Pool Fires Experiments on Water

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Abstract

This paper summarizes a series of large-scale outdoor and indoor LNG pool fire experiments conducted at Sandia National Laboratories in Albuquerque, New Mexico. Two outdoor LNG spills on water with resulting pool fires of 21 m and 56 m in diameter were conducted to improve hazard predictions by obtaining measurements of flame height, smoke production, and burn rate. The experimental data indicates that LNG pool fires on water display different behavior than those on land by producing less smoke. Surface emissive powers of up to 286 kW/m^2 , flames heights of up to 146 m, and burn rates of about $0.147 \text{ kg/m}^2\text{s}$ were measured. Discussion is provided on the observed behavior of the two outdoor tests with regards to smoke production, wind effects, and hydrate production. The large-scale indoor experiments used a 3-m diameter gas burner with methane fuel to assess flame height to fire diameter ratios as a function of non-dimensional heat release rates for extrapolation to large-scale LNG fires. A flame height correlation was developed from this data.

1. Introduction

Liquefied Natural Gas (LNG) is imported and exported at ports across the U.S. in ships with capacities ranging from about $150,000 \text{ m}^3$ to $250,000 \text{ m}^3$. Due to the extremely large capacity of these carrier ships, there are concerns over the impact that accidental spills could have on public safety and property. In the early 2000's, as LNG imports started to increase in the U.S., a number of LNG 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 analyses [1] [2] highlighted some primary knowledge gaps that were limiting the fidelity of site-specific risk assessments due primarily to the lack of large-scale LNG fire data. Experimental data used by the early 2000's studies were taken from pool fires 10 to 100 times smaller in scale than that anticipated from LNG ship incidents (~100s meters)[3]. The greatest uncertainty regarded the surface emissive power and the amount of smoke production. There were some studies speculating that a 100 meter diameter pool

fire would have significant smoke shielding, similar to other hydrocarbons, to result in significantly reduced predicted thermal hazard distances. It was uncertain if this was the case.

Thus, in order to reduce uncertainties, two large-scale tests were conducted at Sandia National Laboratories (SNL) in 2009, resulting in pool fire diameters of 21 m and 56 m. The parameters pertinent to empirical models used to calculate thermal hazard distances are the burn rate, flame height, and surface emissive power (SEP). Thus, these measurements were obtained in order to improve the accuracy of thermal hazard evaluations. The 56 m test is the largest LNG pool fire performed on water or land to date. The details of the test series and recommendations for hazard analysis are provided in Sandia reports [4] [5]. In addition to the outdoor tests, an indoor test series was performed utilizing a 3-m diameter gas burner in order to develop a flame height correlation. The following first provides a summary description of the experimental facilities and instrumentation. Then the data from the outdoor and indoor tests is presented as well as discussion of the behavior of LNG pool fires on water.

2. Large Scale LNG Pool Fire Experiments on Water

2.1 Site and Infrastructure

Conducting cost-efficient tests at the required scale of around 100 meters posed several challenges, such as, designing a containment system for the LNG that prevents complete evaporation and leakage before test execution, provision of a suitable water reservoir, and design of a delivery and diffuser system.

The most cost effective design for the containment system or reservoir consisted of an above-ground, dome-covered, truncated cone structure constructed with compacted soil (Figure 1a). The LNG in the reservoir was gravity driven through a pipe that delivered the fuel to the center of a water pool (Figure 1b). A diffuser was constructed at the end of the pipe for uniform dispersal.

The reservoir is approximately 7 m tall, with a base diameter of approximately 73 m and a top diameter of approximately 44 m. The cavity of the reservoir is an inverted truncated cone, designed to contain a maximum of 1172 m³ of LNG. Since LNG is a cryogenic fluid with a saturation temperature of -160°C, the cavity wall was insulated with four inches of sprayed polyurethane foam to reduce boil-off and LNG usage. The foam was covered with two inches of “shotcrete” concrete with carbon mesh reinforcement (Figure 2a).

Figure 1: Large-scale LNG facility, a) side view and, b) top view.

The body of water which LNG spilled onto was created by excavating nearby soil to construct a water pool with a diameter of ~ 120 m, a depth of approximately 2 m at the center 43 m radius, and an upward slope to the pool edge (Figure 2b). The depth of the pool was chosen to prevent significant freezing, so that the water could maintain a constant supply of heat to the LNG.

Figure 2: Reservoir construction (a) and water pool excavation (b).

The delivery and diffuser system consisted of three concrete pipes with diameters of 0.38, 0.61, and 0.91 m. The pipes had matching mating plugs, designed to achieve the desired LNG pool spread. The plugs were lifted using SS wire rope and sheaves on a SS A-frame attached to a concrete thrust block (Figure 3).

Figure 3: Lifting of plugs at drainage junction between reservoir and concrete pipes.

Reinforced concrete pipe (2.44 m sections) was used to construct pipe runs (~1% slope) approximately 91.5 m long, with the first 30.5 m under the reservoir and the last 61 m inside a dirt berm constructed during the water pool excavation. The three reinforced concrete pipes terminated in a mating stainless steel Y-connector inside a diffuser near the center of the water pool. The diffuser converted the horizontal momentum of the LNG liquid discharge to a near uniform radial spread onto the water pool. The diffuser was 1.83 m tall and had an inner diameter of 2.44 m.

Three igniters, two of which were propane flares, and one a highway emergency flare, were installed on top of the diffuser located at the center of the water pool. The igniters were used to remotely ignite the methane exiting the LNG discharge pipe at the start of the spill.

A concrete slab, transport container, and thermal shield located at ground level outside the reservoir comprised the pool Data Acquisition System (DAS) station. This station housed a majority of the support systems – winches and batteries for lifting the LNG discharge plugs, propane and flare igniter systems at the diffuser, reservoir and discharge pipe gas sampling systems, gas bubbler systems for LNG liquid level, and the DAS for the pool and reservoir instrumentation.

2.2 Measurements and Instrumentation

Measurement locations were along four cardinal axes or spokes, where the North spoke (also called the 0 spoke) has a magnetic heading of 340 degrees. Three heat flux instrument towers on each spoke were located approximately 110 m, 160 m, and 210 m from pool center. Cameras located on the end of each spoke (~226 m) focused on the pool vertical centerline. Some spokes contained additional instrumentation, such as IR cameras, spectrometers, and meteorological instrumentation. The heat flux instruments were water-cooled and the towers were thermally insulated.

The instrument towers, approximately 1.5 m tall, were embedded in concrete slabs to provide a stable platform. Tower 1 of each quadrant was the primary tower, supporting five narrow-angle (also called narrow-view or NV) radiometers for spot intensity measurements and one wide-angle (also called wide-view or WV) radiometer for computing overall flame surface emissive power (SEP). Towers 2 and 3 each supported one narrow-angle radiometer and one wide-angle radiometer, which were used to determine heat flux variation with distance. Note that the spot diameter for the 5.5° narrow-angle gauges at a distance of 110 m (to pool centerline) is about 10.6 m, at 160 m is 15.4 m, and at 219 m is 20.2 m.

The data acquisition system (DAS) consisted of five PCs (one on each spoke and 1 pool/reservoir) with 16-bit data acquisition cards connected to a National Instruments (NI) SCXI-1001 chassis. LabView® software interfaced with the NI cards to both control systems and record data. During pretest and post-test periods, data from all 5 field computers was monitored and recorded at 1 Hz. Immediately before ignition, the field computers were programmed to record individual spoke and pool high-speed data locally at 200 Hz.

Twenty eight (28) narrow-angle radiometers measured the spot incident heat flux at various heights of the flame plume surface (Medtherm Schmidt-Boelter sensors, 12 mV nominal at 300 kW/m², 5.5° view angle, with zinc selenide window, water cooled, 63.2% time constant is 35 ms). Note that narrow-angle heat flux can be considered as a spot-average surface emissive power if the relatively small spot is completely filled with flame. The relative angle of the narrow-angle gauges (to the ground plane) was adjusted to measure the flame plume heat flux at different heights (approximately equal spacing) with the line of sight for each gauge passing through the vertical centerline of the pool.

Twelve (12) wide-angle radiometers measured the radiant heat flux, where each tower had one gauge. The wide-angle radiometers were water-cooled, Medtherm Schmidt-Boelter sensors, with a view angle of 150°, a zinc selenide window, and a 63.2% time constant below 500 ms. In order to increase signal intensity and reduce measurement uncertainty, different gauge spans were used. The gauge ranges were: Tower 1 – 100 kW/m², Tower 2 – 50 kW/m², and Tower 3 – 30 kW/m². To support the wide-angle radiometer analysis, four video cameras (one at each location) were positioned to have nearly the same view as the wide-angle radiometer in order to capture the flame plume shape and allow converting the incident heat flux to a “flame-average” SEP. Uncertainty of the radiometers, per the manufacturer, is ±3% of the responsivity, corresponding to a measurement uncertainty of ±3% of the measurement across the calibration ranges [Nakos 2005]. MODTRAN (with a custom desert aerosol atmosphere model) was used to determine the radiant attenuation by atmospheric species to correct the radiometer SEP data.

The fuel regression rate, sometimes referred to as the burn rate, is driven by heat transferred from both the higher temperature water below and the flame above. The combined fuel regression rate is a calculated parameter determined by dividing the

measured transient mass flow rate from the reservoir by the measured transient liquid pool area and this represents an average value over the whole area of the pool.

Change in reservoir liquid level versus time, in conjunction with as-built reservoir interior dimensions, was used to determine mass flow rate from the reservoir. The as-built volume of the LNG reservoir cavity as a function of liquid height was obtained by interpolation of a set of 2305 laser measurements. A dip tube system employing two independent pressure-based liquid level sensors was used to measure the height of LNG in the reservoir. A slow, constant flow rate purge of dry argon gas in the dip tubes was regulated, metered, and monitored. The pressure in the dip tube required to displace the head of liquid in the tube was sensed using a pressure tap downstream of the metering valve, leading to a sensitive pressure transducer scaled for 2.54 m of water column. Calibrations of the dip tubes were carried out prior to each experiment using known depths of water.

Overhead video was used to determine the real-time extent of the spreading pool fire. The overhead video utilized manned four-axis LSG-2 gyro-stabilized mounts by Aerial Exposures™. They were flown in two Kirtland AFB 58th/SOW UH-1N helicopters hovering opposite each other to obtain video from a near directly overhead view (457 m horizontal, 305 m vertical from pool centerline). Attached to the stabilized mounts were two primary Sony™ HDW-750 high definition video camcorders. These cameras are 3 CCD, 2/3" color format and used Fujinon™ HA22-7.3 BERM telephoto lenses. Additionally, one still photographer per aircraft acquired high resolution pictures using Nikon still cameras with image stabilized optics. One still camera captured wide view and the other camera was zoomed to high magnification for LNG-water interface and other detail. In order to calibrate the camera images to yield accurate measurement of the pool area as a function of time, a grid of uniformly spaced markers (0.152 m diameter stainless steel floats, 5 m spacing, at 4 radii from the diffuser to the pool edge,) was placed within the pool. Eight fire resistant, 0.61 m quad stadia boards were placed pool-side to provide additional dimensional measurement calibration for the aerial view.

One HD real-time camera (Canon Vixia HD MiniDV real time camcorders (30 Hz)) was installed on each spoke (~225 m from the pool center). The 6.1-61 mm zoom lenses were identically adjusted for anticipated flame height. A 0.7x Panasonic wide angle lens was attached to each camera to accommodate for the expected 100 m base width of the LNG fire. These cameras, paired with the wide-angle radiometers on each spoke, were used to determine the average surface emissive power of the fires.

Infrared data was acquired using remotely-triggered FLIR Systems™ model S-60 and SC-660 infra-red cameras with uncooled microbolometer detectors, utilizing 450 FOV lens. The S-660 (640 x 480 pixel array) was located on the 90 spoke and the S-60 (320 x 240 pixel array) was located on the 180 spoke, both at a distance of 214 m from pool center. These cameras are sensitive to the wavelength band of 7.5-13 micrometers.

To calibrate the vertical axis of the spoke and long range cameras, a tethered linear array of helium balloons was deployed prior to reservoir fill operations. The array consisted of a 2.44 m diameter balloon at a height of 140 m above the diffuser with 0.66 m diameter

marker balloons at 30.5 m spacing on the tether (starting at 15.2 m below the 2.44 m diameter balloon). A Meggaflash bulb located at the diffuser, was remotely fired to provide a visual frame-synchronization of all cameras and fiducial signals to the control room DAS, the pool DAS, and all four spoke DASs.

Mid-infrared spectral radiation intensity measurements were taken by an imaging spectrometer located on the 180 spoke (226 meters to the center of the pool). The ES-200 measures spectral radiation intensity at 390 Hz in the 1.3 to 4.8 micron wavelength range and each of the pixels looks at a wavelength of 22 nm. The total wavelength range accounts for 75% of the emitted radiation energy from a blackbody source at 1420K, which is approximately the effective radiation temperature from a large hydrocarbon fuel fire as determined by [6]. The view angle of the stationary spectrometer is ± 0.27 degrees. The ES200 spectrometer is equipped with a 1D scanner. The scanner is capable of measuring a line with 128 pixel resolution in just 0.32 seconds. When referenced with calibrations obtained using a black body, the data provides the absolute values of radiation intensities recorded by the detector array. The scan angle, and the corresponding vertical scan distance and width were 12.2° , 48 m, and 2.2 m, respectively. The manufacturer's stated uncertainty for the Spectraline ES-200 spectrometer is $\pm 0.5\%$ of full range of the signal (0 to 10 Volts), which corresponds to the random error in the measurement. The accuracy of the intensity measurement is then a function of the accuracy and appropriateness of the calibration. A linear calibration is employed. A sensitivity of $5000 \text{ W/m}^2/\text{sr}/\mu\text{m}/\text{V}$ is typical, corresponding to a typical uncertainty of $250 \text{ W/m}^2/\text{sr}/\mu\text{m}$ due to random error in the voltage measurement. With expected typical voltage signals of 0.1 V to 1.5 V for the minimum and maximum intensities, respectively, the uncertainty due to the random measurement error is $\pm 4\%$ to $\pm 50\%$ of the measured intensity. If the uncertainty in the calibration is assumed to be $\pm 5\%$, the overall uncertainties rise to $\pm 6\%$ and $\pm 50\%$ for the maximum and minimum recorded intensities, respectively.

Three separate optical instruments were fielded by the Sandia remote sensing group. The main instrument is a single element Fourier Transform Infrared (FTIR) Spectrometer. The other two instruments were fielded to provide contextual and ancillary information to support the spectrometer. They included a fast framing visible camera and a video rate thermal camera. These instruments were in a data acquisition trailer located $\sim 30^\circ$ North of the East spoke and at a range of ~ 1100 meters from the center of the pool fire.

The FTIR is a Fourier Transform Interferometer manufactured by ABB – Bomem capable of measuring the spectral region from 1.0 to $15.0 \mu\text{m}$ with a spectral resolution of up to 1 cm^{-1} . The instrument was used with the narrow angle telescope to have a field of view (FOV) of 4.9 mrad . The nearest focusing range for the narrow angle telescope is 30 meters and the range for the field collect was over 1 km. The instrument is capable of collecting anywhere from 10 to 107 scans per second depending on the spectral resolution selected.

The thermal imager is a microbolometer based camera that has a broadband response from $8\text{-}12 \mu\text{m}$. The field-of-view of the instrument is approximately 26° by 19.6° . The

camera can output images at a rate of 30 frames per second. A moderate speed visible imager with an extended focal length lens is exactly co-boresighted with the FTIR (using the FTIR beam splitter). The camera model is a Pike and is manufactured by AVT.

The FTIR was calibrated with a blackbody source with and without the narrow angle telescope in place to evaluate the telescope-induced radiometric losses. Based on the calibration routine, the maximum error associated with the FTIR field measurements is $\pm 21\%$. The calibration measurements were not used to correct the hyperspectral data collected by the FTIR but rather provide a maximum error bar on the measurements taken in the field.

Wind direction and velocity, temperature, relative humidity and barometric pressure were measured and recorded with near-field instruments. Wind speed and direction were measured at 2 m, 5 m, and 10 m heights on the North tower and at 10 m on the East tower using YOUNG 81000 Ultrasonic Anemometers. Wind speed measurement accuracy is $\pm 1\%$ rms ± 0.05 m/s for a range of 0 to 30 m/s. Wind direction measurement resolution is 0.1 degree with accuracy of $\pm 2^\circ$ for a range of 1 to 30 m/s. Barometric pressure was measured using a Setra Model 278 Barometric Pressure Sensor. The accuracy of the Model 278 is specified over the full temperature range of -40° to $+60^\circ\text{C}$, rather than as a percent of full scale, with accuracies to within ± 0.3 kPa/Mb of the full scale pressure range (500-1100 Mb). Relative humidity (RH) was measured using a CS HMP45C Temperature and RH probe with an integral radiation shield. The instrument has a measurement range of 0.8 to 100% RH, accuracy of $\pm 1\%$ RH at 20°C , temperature dependence of $\pm 0.05\%$ RH/ $^\circ\text{C}$, and temperature accuracy of $\pm 0.5^\circ$.

The temperature of the pool water was measured using 36 1.59 mm diameter mineral-insulated metal-sheathed (MIMS) type-K thermocouples (TCs) at twelve locations; at each location temperature is measured at 6 inches below the water surface, 6 inches above the pool bottom, and at water midline.

The temperature of the liquid LNG and reservoir gas was measured using 1.59 mm diameter type-T MIMS thermocouples. Thermocouples were also embedded in the shotcrete and attached to various structures inside the reservoir.

The large-scale pool fire tests were performed with liquid methane ($>99.5\%$) as a surrogate for LNG. The purpose of using this grade was two-fold; 1) minimize the potential for explosive rapid phase transitions (RPTs) that could damage or destroy the experimental setup and 2) minimize the parameter variations to reduce uncertainty in the analysis of the test data. It is recognized that LNG can have a wide range in composition (depending on the source), from almost pure methane to mixtures composed primarily of methane (typically, at least 90 percent), but may also contain ethane, propane and heavier hydrocarbons and small quantities of nitrogen, oxygen, carbon dioxide, sulfur compounds, and water. However, previous historic experiments performed with typical LNG have shown that the methane burns off first, with little participation by the heavier hydrocarbons until late in the test[7].

2.3 Data Reduction and Analysis

2.3.1 Regression Rate

The regression rate was determined by dividing the estimated liquid spill rate at the diffuser by the spreading LNG pool area. A 2-phase flow model was used to estimate the time-dependent liquid volume discharge from the reservoir and also the vapor fraction of the liquid being discharged at the diffuser (also time-dependent due to flowing in the initially uncooled discharge pipe) to yield the liquid flow rate from the diffuser. The spreading pool area was determined using frames extracted from the overhead high-resolution video. Adobe Photoshop CS3 extended, a graphics editing program developed and published by Adobe Systems, was used for the purpose of quantitative data extraction and image analysis. An uncertainty analysis for regression rate measurements included the reservoir volume measurement, the reservoir liquid and diffuser vapor discharge rates, liquid methane density, and the spreading methane pool area. The uncertainty in the regression rate, using the root-sum-square method, is estimated to be ~21%.

2.3.2 Plume Parameters

Extensive MatLab® programs were developed to reduce the video data (to include camera calibration and image scaling) to determine fire morphology (width, height, flame area, etc.). In addition, the video analyses provided information to allow corrections of radiometer data for atmospheric transmission effects, inform on the narrow-view radiometer “spot” results, and determine a time-dependent flame-average surface emissive power (SEP) from the wide-range radiometer data.

The flame plume horizontal center-of-gravity (CG) was used to determine a time-dependent path length and shift from the pool centerline for use in later analyses, for correction of transmission losses for the narrow view angle radiometers and for correction of wide view angle radiometer data to obtain average flame SEP results. The CG (a term commonly used in video analysis to denote the center of area of an image) was calculated based on the calibrated video data from the cameras at each spoke.

A color intensity threshold (pixels with red intensity $>230 \pm 5$, depending on camera view) determined those pixels for each video frame (1 s intervals) that indicate the flame region, shown by green pixels. The flame plume area was determined simply by summing the area of each green pixel identified as the flame region in each image (after first calculating the length and width of the pixel given by the camera calibration).

The video analysis routines also determined a time-dependent fill fraction for each narrow-view radiometer, based on the nominal gauge parameters (gauge height, view angle, inclination angle, and the distance to fire CG) in order to determine validity of the gauge data. This information determined a location and area on the flame surface (a spot) that provided the field of view for each narrow view radiometer. Each video frame was then interrogated to count the number of pixels indicating the flame region that lay within this spot.

2.3.3 Radiative Measurements

MODTRAN [8], with a custom desert aerosol atmosphere model, was used to estimate the effects of atmospheric absorption on the radiometer measurements. The input parameters for MODTRAN (altitude, temperature, relative humidity, and pressure) were measured just before the test with a local weather station. An estimate of the in-band average transmission was determined by first weighting the MODTRAN transmission by the spectral source radiance (using an appropriate blackbody curve). Next, the apparent radiance (the source radiance times the MODTRAN path transmission) as a function of distance was calculated for each blackbody temperature. Finally, the in-band average transmission as a function of path length and source temperature was determined by summing up the apparent radiance and dividing by the sum of the source radiance.

The integrated average transmission as a function of path length for Test 1 is given in Figure 4 for the three blackbody source temperatures at eight specified path lengths. Spectral analyses determined that the LNG fire temperatures are in the range of ~1400-1700K. A fit of the transmission at 1400K was performed for use in correcting measured heat flux data. The distance from the flame CG to the instruments, combined with the MODTRAN atmospheric transmission curve, provided the energy transmission fractions for each gauge.

Figure 4: Integrated transmission versus horizontal path length for LNG Test 1.

2.3.4 Flame Surface Emissive Power

The video data was used in conjunction with the wide-view radiometers to determine a time-dependent flame surface emissive power (SEP). The data reduction requires that the pixels from each video frame be mapped to a plane roughly at the location of the high-temperature source, that the pixels within the high-temperature source region are identified for each image, that the radiometer is located at a known distance from the plane, that the orientation of the radiometer relative to the image plane is known, and that

the location of the projection of the sensing element's surface normal onto the image plane is known. Equation 1 relates the emissive power of the high-temperature source to the gauge output at a particular time. The full derivation of Eq. 1 is provided in the comprehensive report of these experiments[4].

$$E_{source} = E_{environment} \left[\frac{\pi (1 - \cos^2 \theta_{max})}{\sum_{pixels in source} \cos \theta \frac{\cos \phi dA_{pixel}}{S^2}} \right] \quad (1)$$

where E_{source} is the average emissive power of the high-temperature source, $E_{environment}$ is the gauge output via its calibration, dA_{pixel} is the area of each pixel on the image plane, S is the distance from the radiometer to the pixel, θ is the angle between the radiometer's surface normal and the ray from the radiometer to the pixel, and ϕ is the angle between the image plane's surface normal and the ray from the pixel to the radiometer (refer to Figure 5b). The scaling factor (the term in brackets) was applied on a frame-by-frame basis using the video images and the radiometer output corresponding to the image. The view factor is the reciprocal of scaling factor. The circles in Figure 5a indicate the seven narrow-view radiometers approximate view area and location. The three increasing size middle circles are for the radiometers located at a distance of 110 m (to pool centerline), 160 m, and 219 m.

Figure 5:a) Test 2 fire image and b) sketch of Eq. 1 geometry for pixel analysis.

2.4 Results

2.4.1 Reservoir Discharge Flow Rate and Mass Regression Rate

A 2-phase LNG flow model was used to calculate the vapor fraction of the liquid being discharged at the diffuser. The measured flow rate from the reservoir was multiplied by the time-dependent liquid fraction (1 minus the vapor fraction at diffuser) to provide the liquid flow rate at the diffuser. The mass regression rate is determined by dividing the estimated liquid spill rate at the diffuser by the pool area. The predicted vapor fraction at the diffuser was 3% during the interval from 390-510 s for Test 1. A root-mean-squares regression analysis that included uncertainty in reservoir volume discharge rate, diffuser discharge rate, pool area, and time, the relative uncertainty in the regression rate under the conditions of Test 1 estimated the overall uncertainty to be 20.4%. Table 1 provides results for flow rates, intervals, pool size, and mass regression rates for each test.

Table 1: Flow rate, interval, pool diameter, and mass regression rate for each test.

Test	Average volume flow rate from reservoir (m^3/s)	Average mass discharge rate at diffuser (kg/s)	steady-state interval (s)	equivalent circular diameter (m)	mass regression rate ($\text{kg/m}^2\text{s}$)
1	0.121 ± 0.001	49.4 ± 0.9	390-510	20.7 ± 0.4	0.147 ± 0.01
2	1.91 ± 0.84	~ 802	250-300	82.8 ± 4.0	NA

The mass regression rate could not be accurately determined for Test 2 since the reservoir emptied before the steady-state pool area was reached. In addition, a large portion of the spreading LNG pool did not ignite, which leaves the question as to exactly what area should be used in the regression rate calculation. It is worth noting that dividing the measured release rate of 802 kg/s by the regression rate of 0.147 kg/m²s determined in Test 1 provides an equivalent circular diameter of 83.3 m, very close to the measured 82.8 m. All calculations use 420 kg/m³ for the liquid methane density.

Since the burn rate is a function of the heat transfer from the flame and from the water, the range of burn rates for LNG pool fires on water can be estimated by combining data from pool fire experiments on land and un-ignited spill tests on water. The Montoir tests measured an average mass burn rate of 0.14 kg/m²s with no uncertainties reported. Note that the tests were performed in wind speeds ranging from about 3 – 10 m/s [7]. It is anticipated that if these tests were performed under calm conditions the measured mass burn rate would be lower[9]. The mass burn rate was calculated from dip tube measurements assuming a liquid density of 500 kg/m³. This indicates a burn rate of 2.8×10^{-4} m/s for an LNG pool fire on land. The range of values for regression rates derived from un-ignited LNG pools on water range from 0.64×10^{-4} to 4.3×10^{-4} m/s with no uncertainty values reported [3]. If these values are added to the Montoir data, the range of

burn rate values for pool fires on water would be 3.4×10^{-4} to 7.1×10^{-4} m/s. The SNL burn rate is 3.5×10^{-4} m/s which is within this range.

2.4.2 Flame Plume Characteristics

As previously mentioned, extensive MatLab® programs were developed to reduce the video data to determine fire morphology (width, height, flame area, etc.). Figures 6a and 6b show flame heights for Test 1 and Test 2, respectively, as determined from the analysis of the four spoke cameras. Table 2 presents the average and standard deviation of the height fluctuations over the steady-state time intervals listed.

Figure 6: Flame peak height for a) Test 1 and b) Test 2.

Table 2: Flame height fluctuations and average height.

	<i>Test 1</i>	<i>Test 2</i>
	Height (m)	Height (m)
	390-500 s	250-300 s
N camera	36.0 ± 6.5	140.4 ± 19.6
E camera	31.8 ± 5.8	139.7 ± 20.0
S camera	38.0 ± 8.1	156.3 ± 24.3
W camera	34.6 ± 6.0	148.3 ± 22.5
average	35.1 ± 2.6	146.2 ± 7.8

During Test 1 there was an appreciable wind speed, causing the flame to tilt 50 degrees as shown in Figure 7. In Test 2, there was very little flame tilt; however, the wind did appear to drag the plume toward the south where the flame attached somewhat to the pipe berm. 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 wind speed and direction (magnetic north) at various heights is provided in Table 3. Table 4 provides effective plume diameter (at 15 m above pool), flame length, length/diameter, and flame tilt.

Table 3: Wind speed and direction

Height (m)	<i>Test 1</i>		<i>Test 2</i>	
	speed (m/s)	direction (degrees)	speed (m/s)	direction (degrees)
2	4.27 ± 0.67	334 ± 25	1.5 ± 0.3	324 ± 8.5
5	4.69 ± 0.67	336 ± 22	1.6 ± 0.2	328 ± 5.9
10	4.77 ± 0.69	336 ± 11	1.6 ± 0.2	334 ± 5.7

Figure 7: Flame tilt in Test 1.

Table 4: Flame plume diameter, flame length, length/diameter, and flame tilt.

Test	equivalent diameter of flame plume at elevation of 15 m (m)	flame length (Test 1) or height (Test 2) (m)	length/diameter	flame tilt (degrees)
1	21.7 ± 2.9	~ 70	3.2	~ 50
2	56.1 ± 12.1	146.2 ± 7.8	2.6	negligible

2.4.3 Flame Temperature and Emissivity

Figure 8 shows peak IR-camera reduced temperature data using a camera emissivity setting of 1 for Test 1 and Test 2. Pictures from the East spoke IR camera at 300 s into the fire are also presented. Table 5 provides the IR-reduced average peak temperatures over the time interval during approximate steady-state flow from the reservoir.

Figure 8: IR-camera peak temperatures in Test 1 and Test 2.

Table 5: IR-reduced average peak flame temperatures for Test 1 and Test 2.

Test	time interval (s)	average peak temperature (C)
1	300-520	1179±33°C (east spoke) 1181±41°C (south spoke)
2	240-300	1386±29°C (east spoke) (south spoke camera stopped at 100 s)

The ES-200 spectrometer located on the 180° spoke acquired data throughout the fire. The spectral intensity data were then further analyzed to determine the approximate temperature and emissivity at each location in the fire. Similar to the method of [10], wavelength bands that were free of gas band emission and atmospheric absorption (1.48-1.75 and 2.08-2.34 micron bands) were assumed to only contain emission from soot radiation. A two parameter fit of the Planck function was performed to determine an approximate soot temperature and emissivity. It was assumed that the soot was gray (i.e., emissivity did not vary with wavelength).

The results of the temperature and emissivity fits as a function of height at four scan times during the steady-state portion of the Test 1 fire are shown in Figures 9a and 9b, respectively. The temperature in the fire appears to vary from approximately 1100°C to 1600°C. Note that the average flame height was ~34 m; puffing or lack of the fire above this height would have had an impact on the spectrometer measurements. Table 6 presents the average and standard deviation of the spectrometer-derived temperature and emissivity between heights of 1.2-34.5 m at the 4 scan times. The overall average temperature and emissivity is 1262°C and 0.68, respectively.

Figure 9:a) Temperature and b) emissivity fit as a function of height in LNG Test 1.

Table 6: Average temperature and emissivity from the ES-200 data in Test 1.

<i>Scan time (s)</i>	<i>Height range (m)</i>	Temperature (C)		Emissivity	
		<i>average</i>	<i>st. dev.</i>	<i>average</i>	<i>st. dev.</i>
322	1.2 - 34.5	1197	52	0.67	0.22
350	1.2 - 34.5	1354	107	0.53	0.36
382	1.2 - 34.5	1289	54	0.60	0.21
468	1.2 - 34.5	1209	28	0.92	0.13
average		1262	73	0.68	0.17

In both tests, the spectrometer was positioned on a tilt table to acquire two sequential vertical scans (nominally 1-50 m and 50-100 m and ~15 s between scans). The 50-100 m scan (tilt angle #2) was able to collect data throughout the Test 2 fire which was not the case with the much smaller Test 1 fire.

Temperature and emissivity of the Test 2 fire were calculated using the method employing a two parameter fit of the Plank function as described earlier. The results as a function of height (scans 7, 8, 9, and 10) are shown in Figures 10a and 10b, respectively, and Table 6. For Test 2, at low heights the calculated fire temperatures were highest and the emissivity was lowest. With increasing height, the temperature decreased and the emissivity increased. From a height of about 40 m to the top of the measurement region (~100 m) the temperature and emissivity are approximately constant.

(a) (b)

Figure 10: Estimate of temperature and emissivity vs. height ((a) 0-10m, (b) 50-105 m) from LNG Test 2 spectra.

It is suspected that these derived results at lower elevations are not accurate due to the entrainment of water vapor at the base of the fire. During Test 2, a very prominent white cloud formed on the water and surrounding ground, somewhat visible near the fire base in Figure 11. Figure 11 also shows the spectrometer scan width and height. The portion of the water not covered by LNG or hydrates was being evaporated from the fire and consequently entrained. As the water vapor encountered the ice/hydrate portion of the pool it condensed to form a white cloud that obscured part of the spectrometer field-of-view. Water vapor scatters rather than absorbs radiation and consequently blocks the flame radiation coming from the base of the fire. The scattering is much greater for radiation having smaller wavelengths - that is why it appears white. This scattering explains the reduced intensity of the spectra (not shown) at the lower heights that likely compromised the temperature/emissivity fits for data near the base of the fire.

Table 7 provides average temperature and emissivity values at the four scans plotted in Figures 10a and 10b for low and high elevations, respectively. The data in scans 7 and 9 for heights less than 40.2 m is not included in the averages, as discussed above. The overall average temperature and emissivity is 1600°C and 0.29, respectively.

Table 7: Average temperature and emissivity from the ES-200 data in Test 2.

<i>Scan# / time (s)</i>	<i>Height range (m)</i>	Temperature (C)		Emissivity	
		<i>average</i>	<i>st. dev.</i>	<i>average</i>	<i>st. dev.</i>
7 / 243	40.2 – 49.8	1702	45	0.20	0.02
8 / 258	49.8 – 103.1	1566	69	0.33	0.05
9 / 274	40.2 – 49.8	1589	32	0.31	0.02
10 / 288	49.8 – 103.1	1542	61	0.33	0.09
average		1600	71	0.29	0.06

Figure 11: LNG Test 2 at ~236 s with spectrometer field-of-view overlay.

The ABB Bomem MR Series 304 spectrometer collected on the central region of the flame at a rate of 10 scans per second, scanning from the short-wave infrared ($1.0\ \mu\text{m}$) all the way out to the long-wave infrared ($15.0\ \mu\text{m}$). The FLAMES code was used to simulate the source fire intensity and predict the spectral output from combustion [11]. The molecular emission bands supported by the current version of FLAMES are: Soot, H_2O , CO_2 , CO , HCl , HF , OH and NO . The FLAMES code calculates soot emission with spectrally varying emissivity and constant temperature. The FLAMES code only predicts the spectral radiant exitance of the target. The spectral radiant exitance is the radiant flux emitted by a surface per unit area per unit frequency or wavelength. In order to predict the apparent radiance reaching the aperture of the FTIR, the source radiance has to propagate through the atmosphere to the instrument. In order to accomplish this, the path transmission was predicted by MODTRAN.

To more closely approximate the spectral signature, a two temperature linear mixing model was used to combine two separate FLAMES simulations. This allows for the simultaneous simulation of a hotter cleaner burning portion of the flame along with a cooler more soot filled portion. There was very good agreement of the two-temperature model to the measurement.

For Test 1, the FLAME code input and mixing parameters used with the 2-temperature model are given in Table 8. Thus far, only data at 465 s has been analyzed. Based on user-specified (chosen to give the best fit) fractional weights of 40% for high-temperature, more complete combustion and 60% for low-temperature, soot-rich combustion; the model determined a weighted-average flame temperature of 1250°C with an emissivity of 0.46 for Test 1.

Table 8: List of the FLAME code 2-temperature model inputs for LNG Test 1

FLAME Code Input (data at 465 s)	High Temperature More Complete Combustion	Low Temperature Soot Rich Combustion	Weighted Average
Fractional Weight of Total Flame Temperature	40% 1670°C	60% 970°C	1250°C
Emissivity at 4 microns	0.18	0.65	0.462
H ₂ O Mole Fraction	0.05	0.05	0.05
CO ₂ Mole Fraction	0.001	0.005	0.003
CO Mole Fraction	0.002	0.05	0.031

For Test 2, as in Test 1, the ABB Bomem MR Series 304 spectrometer collected at the central region of the flame and the FLAMES code was again used to predict the source radiance which was reduced by the predicted path radiance. The two temperature linear mixing model was also used. Five different times were chosen to evaluate the flame properties from the spectral FTIR data. The height of the bore sight ranged from 10 m to 20 m above the pool surface. In order to get the modeled radiance to fit the measured data better, a short path of CH₄ was modeled to account for some absorption that was observed but otherwise unaccounted for. A much better fit of the data was determined when assuming a 1 meter path of a few percent methane just outside of the flame.

The average source temperature and emissivity based on mixture fractions as derived from fitting the FLAMES model to the data is provided in Table 9 for the selected times and bore sight heights above the pool. The average CH₄% is the percent methane assumed in the 1 meter path just outside of the flame, chosen to achieve the best fit. The emissivity is calculated with Eq. (2) using the soot optical density (OD).

$$\varepsilon = 1 - e^{-OD} \quad (2)$$

Table 9: Test 2 derived temperature, emissivity, and CH₄ path concentration

Time (s)	Boresight Height (m)	Average Temperature (C)	Average Emissivity	Average CH ₄ (%)	Average OD
257	10	1377	0.42	6.40	0.55
312	15	1327	0.34	6.40	0.42
351	10	1307	0.30	3.20	0.35
405	10	1237	0.36	6.40	0.44
460	20	1287	0.51	0.00	0.72
average	13	1307	0.386	4.48	0.50

Summarizing, flame temperature and emissivity data are provided from multiple instruments that have probed the two fires at different locations and at different times. Not surprising, these different instruments and associated data reduction methodologies

have provided a range of results with uncertainty. Overall, it does appear that Test 2 had higher flame temperatures and lower emissivity values than in Test 1. The reader is encouraged to review the LNG test report [4] for complete details of data collection and reduction methodologies.

2.4.4 Radiant Fraction

The radiant fraction, χ_{rad} , can be estimated using

$$\chi_{rad} = \frac{4\pi r^2(q''/\tau)}{m_b h_c} \quad (3)$$

where r is the CG distance (m) from the fire, q''/τ is the wide-view heat flux (kW/m²) corrected for the transmission loss (τ), and $m_b h_c$ is the average total heat release by combustion (m_b is the mass burning rate (kg/s), assumed equal to the reservoir mass flow rate) and h_c is methane heat of combustion (55,687 kJ/kg)). The average radiant fraction from all measurements and one standard deviation are provided Table 10.

The following section provides the flame surface emissive power (SEP). For the SEP to be of practical use, it is desirable to know the emitting surface area from which this power originates. The flame area (average of the four camera views) is also provided in Table 10.

Table 10: LNG Test 1 and Test 2 radiant fraction and flame area

Test	Time Interval (s)	Average Radiant Fraction	Average Flame Plume Area (m ²)
1	390-500	0.21±0.04	546±63
2	250-300	0.24±0.08	5054±743

2.4.5 Flame Surface Emissive Power

2.4.5.1 Wide Angle Radiometers

Table 11 and Table 12 provide the average and standard deviations of the wide-angle incident heat flux (corrected for the atmospheric transmission loss), the view factor, and the flame SEP for Test 1 and Test 2, respectively. For Test 1, the average overall SEP is 277 ± 60 kW/m² (2 sigma), which is based on the average of the 11 individual SEP data points, discounting the suspect N Tower 2 gauge as it did not return to zero at test end. For Test 2, the average overall SEP is 286 ± 20 kW/m² (2 sigma), which is the average of the 11 individual SEP data points.

Table 11: LNG Test 1 heat flux, view factor, and flame SEP.

Time Interval 390-500 (s)	Wide-View Heat Flux (kW/m ²)		Scaling Factor (Eq. 1, term in brackets)		Surface Emissive Power (kW/m ²)	
	average	st. dev.	average	st. dev.	average	st. dev.
N Tower						
1	2.4	0.3	106	15	247	19
2*	NA	NA	NA	NA	NA	NA
3	0.8	0.1	363	54	303	29
S Tower						
1	6.2	0.9	47	8	286	32
2	2.4	0.3	105	18	252	26
3	1.3	0.1	189	32	239	28
E Tower						
1	4.2	0.6	75	11	305	22
2	1.8	0.2	167	25	293	22
3	1.2	0.2	260	39	312	25
W Tower						
1	4.5	0.5	69	8	310	21
2	1.9	0.2	137	16	260	27
3	1.0	0.2	230	27	236	32
	average				277± 60	

*Gauge did not return to zero at ten of test.

Table 12: LNG Test 2 heat flux, view factor, and flame SEP.

Time Interval 250-300 (s)	Wide-View Heat Flux (kW/m ²)		Scaling Factor (Eq. 1, term in brackets)		Surface Emissive Power (kW/m ²)	
	average	st. dev.	average	st. dev.	average	st. dev.
N Tower						
1	20.9	1.6	13.6	1.1	283.4	11.8
2	12.6	0.9	22.4	2.0	280.6	13.7
3	8.4	0.6	33.9	3.1	284.3	15.5
S Tower						
1	39.4	3.4	7.2	0.5	283.8	22.1
2	20.8	1.8	13.3	1.0	276.0	19.8
3	13.3	1.2	21.8	1.9	287.9	20.6
E Tower						
1	NA*	NA	13.1	1.1	NA	NA
2	13.3	1.2	22.6	2.0	298.6	19.5
3	8.6	0.7	35.7	3.5	305.8	20.9
W Tower						
1	20.6	1.9	14.3	1.3	292.6	25.8
2	12.1	1.4	23.4	2.3	283.4	32.1
3	7.7	0.8	35.5	3.8	271.4	23.8
	average				286 ± 20	

*Gauge failed prior to test.

2.4.5.2 Narrow Angle Radiometers

The video analysis routines determined a time-dependent fill fraction for each narrow-view radiometer, based on the nominal gauge parameters (gauge height, view angle, inclination angle, and the distance to fire CG) in order to determine validity of the gauge data. This information determined a location and area on the flame surface that provided the field of view for each narrow view radiometer. The incident heat flux values and derived average surface emissive power values (incident heat flux/fill fraction) for both tests are provided in Table 13.

For Test 1, heat flux gauge 1 on the North spoke tower 1 and heat flux gauges 1 and 2 on the South spoke tower 1 were the only gauges with their field of views essentially filled during the entire averaging interval. The North spoke NV provided an SEP of 222kW/m² and the South spoke NV gauges provided an average SEP of 239 ± 68 kW/m².

For Test 2, the North spoke NV gauges provided an average SEP of 316 ± 62 kW/m² (2 sd). The South spoke NV gauges provided an average SEP of 239 ± 67 kW/m² (2 sd). These gauges had fill fractions greater than 0.9. The North heat flux gauge 3 recorded peak fluxes in the range of 350 kW/m² for short periods of time during the steady-state

interval. Due to the size of the fire, it was anticipated that significant smoke production would occur such that a smoke mantle would partially cover the flame envelope, but this did not occur for either test. Further discussion of this behavior is provided in section 4.1.

Table 13: Narrow gauge heat flux measurements for Test 1 and Test 2

Test	Time Interval (s)	Gauge	Time Averaged Incident Flux* (kW/m ²)	Average SEP(kW/m ²)
1	390 - 500	North		
		1	216.1 ± 7.40	222.4
		South		
		1	236.3 ± 20.6	238.0
		2	203.1 ± 50.9	252.3
		average		238 ± 30 (2 sd)
2	250 - 300	North		
		1	275.2 ± 19.9	277.4
		2	283.4 ± 37.5	290.8
		3	306.4 ± 43.8	323.3
		7	326.7 ± 47.5	344.8
		9	324.5 ± 30.5	344.0
		South		
		1	187.6 ± 24.4	198.5
		2	225.8 ± 28.4	228.3
		3	250.5 ± 29.6	251.4
		4	271.0 ± 43.1	277.4
		average		282 ± 101 (2 sd)

*transmittance corrected

Figure 12 displays the comparison of the surface emissive power derived from the spectrometer and South spoke NV radiometer measurements (symbols slightly shifted from their nominal heights for easier viewing) for Test 2. SEPs are low near the ground level, with approximate values of 100 kW/m². The SEP then increased steadily from 0 to 40 m and reached peak values approaching 275 kW/m². Note that the spectrometer was not able to scan past the top of the flame zone; thus, the SEP values do not begin to decline at some height.

The agreement in the SEPs from both diagnostics is acceptable. Error bars on the radiometer measurements are an indication of the temporal variability of the heat fluxes measured by the radiometers. The data points represent a three second average of the high speed data and the error bars are one standard deviation. The extent of the error bars increases with height due to the fluctuations of the fire. These increased fluctuations are

also evident in the spectrometer data above 50 m as the puffing of the fire is more pronounced at these higher elevations.

Figure 12: Test 2 SEPs derived from spectrometer and radiometer measurements.

3. Large-Scale Gas Burner Experiments

An additional objective of this work was to develop a flame height correlation by utilizing a 3-m diameter gas burner, the largest burner obtaining such data to date. These tests acquired data on flame height for particular Q^* values which is a dimensionless heat release rate parameter that has been found to correlate with flame height, that is, $H/D \sim Q^*$. This form of scaling is based on the Froude number which is the ratio of momentum versus buoyancy forces. Thus, radiation aspects are not considered. This scaling form is considered here to enable comparison with other researchers who have similarly used this scaling form. Q^* is of the following form

$$Q^* = \frac{\dot{m}\Delta H}{\rho_a T_a C_{pa} \sqrt{g} D^{5/2}} \quad (4)$$

where $\dot{m}$ is the fuel mass loss rate in units of kg/s, ΔH is the heat of combustion (50 MJ/kg for methane), and the thermal properties, ρ_a , C_{pa} , and T_a are evaluated at ambient conditions.

The burner is housed in a controlled environment in the Fire Laboratory for Accreditation of Models and Experiments (FLAME) / Radiant Heat (FRH) test cell in the Thermal Test

Complex at Sandia National Laboratories. Figures 13a and 13b show a representation and interior of the FRH test cell, respectively. The main test chamber of the FRH cell is cylindrical in shape, 18.3 m inner diameter with a height around the perimeter of 12.2 m. The ceiling slopes upwards ($\sim 18^\circ$) from the perimeter walls to a height of 14.6 m over the center of the facility. A round hole at the top of the facility 4.9 m diameter transitions to a 3.0 m by 3.7 m chimney duct. A large electrostatic precipitator downstream of FLAME collects soot prior to combustion products being sent to the exhaust stack. The outer walls are made of steel channel sections welded together and are filled with water for cooling during tests. The FRH cell is functionally airtight.

Figure 13: A cutaway view (a) and interior view (b) of the FRH facility at Sandia.

The ground level of FRH can be divided into three concentric sections. At the center of the facility is a fuel pan or gas burner. The facility can operate a gas burner (He , H_2 , CH_4 , etc.) or a liquid fuel pool (JP-8, methanol, etc.) from 1 m to 3 m in diameter. The second section is a steel spill plate, which extends to a diameter of 12.7 m. The floor of the outer section is made of a steel grating, through which air is supplied to the FRH chamber during fire experiments.

Combustion air is supplied from the forced draft (FD) fan in a central utility building (not shown) through a large underground pipe (3.66 m diameter) to a plenum that feeds 18 radial pipes (0.91 m diameter) to a 1.22 m by 1.22 m annular ring in the FLAME basement. Air exits the grated top of the annular ring and enters the ground level steel grating. An induced draft (ID) fan just before the exhaust stack automatically adjusts speed to maintain the differential pressure (to ambient) across the FLAME wall to near zero.

The gas burner consisted of an outer tub of mild steel 3 m in diameter and 1 m tall. An inlet pipe 0.15 m in diameter at the center of the base of the tub piped the fuel into the burner. The fuel first passed through a conical diffuser at the base of the tub which was designed to direct the fuel flow outward in all directions from the inlet pipe. The diffuser was a conical section containing 8,986 holes 1.7 mm in diameter; the total open area ratio

of the diffuser is 11%. The fuel then passed through three layers of horizontal stainless steel baffle plates which served to flatten the velocity profile across the burner. Each baffle plate contained 32,345 holes of 1/8 inch (3.2 mm) diameter for a total open area ratio of 4%. The final burner layer, nearly flush with the top surface of the tub, was a layer of small crushed glass pebbles ~2 inches deep intended to diffuse the gas leaving the last baffle plate. The gas burner was mounted at the center of the FRH test cell with the top of the burner surface ~1-2 inches below the ground plane of the FRH cell.

3.1 Test Description and Results

The fire was ignited with a propane igniter and allowed to burn for approximately 5 minutes before data was taken to allow the fire and air flow in the cell to stabilize. The ID fan was set to maintain 33 m³/s air flow into the cell for all of the methane tests. A test represents a series of flow rates in which the flow rate of the fuel was varied in a controlled manner during each test. Sufficient data was collected to obtain an average at steady-state conditions. Ambient air temperature ranged between 15-25°C, ambient pressure for all tests was ~830 kPa, and the ambient air relative humidity ranged from 7-18%.

Five separate experiments using methane gas as the fuel were performed providing twenty eight sets of flame height vs. fuel flow rate data. Each data set correlates steady-state average gas flow rate data with video analysis to determine medium flame height data over a 30 second interval.

3.1.1 Median Flame Height – Visual Data

The median flame height was determined from visual data from a video camera, which prior to the test each camera view was calibrated using vertical stadia placed at the pool centerline. The flame height was assumed to be the height at which the flame is visible at least 50% of the time. Uncertainty in the actual height of the visible flame in an individual image is estimated to be approximately 5 cm. Uncertainty in determination of the median flame height was assumed to be equal to the uncertainty in determining the height of the flame within the frame.

For each selected averaging period within a test, thirty seconds of video data were analyzed to determine the median flame height and the puffing frequency. The puffing frequency for all of the methane fires ranges from ~0.9 Hz at the highest flow rates to ~0.8 Hz at the lower flow rates.

To automate the process, imaging analyses software (ImagePro®) was used to provide the average pixel intensity at each horizontal row of a 1/3 burner diameter wide vertical line drawn through the burner centerline. A Fortran routine was used to process the vertical line profile intensity of the 900 frame dataset, varying the threshold intensity from 0 to 255 and determining the average flame height at each intensity.

3.1.2 H/D vs. Q^* - Data Reduction and Analysis

Figure 14 shows the median flame height/diameter ratio as a function of the estimated Q^* , along with several other correlations obtained with smaller burners (up to 0.5 m diameter) by other researchers which indicate agreement with the SNL data.

Figure 14: Flame height/diameter ratio vs. dimensionless heat release rate Q^* .

Three additional data points from a previous study [12] utilizing constant level liquid hydrocarbon (methanol, ethanol, JP8) pool fires were included with the methane gas data in the SNL fit shown in Figure 14, along with other correlations for comparison [13] [14] [15] [16] [17] [18]. The SNL H/D data and correlation shown in Figure 14 are bracketed by the correlations determined by Zukoski [13] and Heskestad [15].

The SNL data can be fit with the curve

$$H/D = 4.196Q^{*0.539} - 0.930. \quad (5)$$

The uncertainty on the flow measurements is 8% (2 sd) and the uncertainty on the flame height data is 10%. The correlation is valid for Q^* values ranging from 0.1 to 1. For the large scale experiments, Test 1 and Test 2, the corresponding Q^* values are 1.34 and 0.81, respectively. For Test 1, the measured height to diameter ratio ranged between 2.84 and 3.72, and the predicted ratio is 3.98. Note that the Q^* value for Test 1 falls outside the valid range of the SNL correlation and was performed under wind conditions, while the Q^* value for Test 2 is within the range and was performed under relatively calm conditions. Using the Q^* value for Test 2, the predicted H/D is 2.8 versus 2.6 as measured from the large scale experiment, indicating fairly good agreement. Note, that for hydrocarbons with high smoke production the measurement of flame height becomes very difficult due to obscuration. However, Test 2 did not have significant smoke

shielding, thus identification of a flame height was fairly straightforward. The flame height is strongly correlated with entrainment and is ultimately a function of the energy balance of the flame which controls the strength of the buoyancy. Thus, the emitted radiation will alter the flame temperature and hence the buoyancy. The effect of a smoke mantle will be to cause an increase in flame temperature. Thus, the effect of a smoke mantle should be taken into account in a scaling law, but this is beyond the current scope of this work.

This correlation can be used to predict the ratio of flame height to diameter for very large pool fires by using Eq. (5) and a corresponding burn rate, diameter, and appropriate atmospheric conditions to determine a value of Q^* . Based upon data from the LNG pool fire Test 1 it is anticipated that a regression rate of $0.147 \text{ kg/m}^2\text{s}$ would result for very large LNG pool fires. The H/D value for a given Q^* value can then be determined using the SNL correlation. For reference, if Q^* is calculated from standard atmospheric properties of $T_a=288 \text{ K}$, $\rho_a=1.2 \text{ kg/m}^3$, $c_{pa}=1006 \text{ J/kg K}$, and a regression rate of $0.147 \text{ kg/m}^2\text{s}$ is used, a pool diameter of 300 m corresponds to a Q^* value of 0.30 and an H/D ratio of about 1.3.

Note that several researchers have theorized that there is a pool diameter limit at which the flame envelope breaks up into multiple fires or flamelets, defined as a mass fire. The heights of these flamelets are much less than the fuel bed diameter[19][20]. The break up into flamelets would result in a much shorter flame height than the assumption of a single coherent plume in which height correlations are used. Heskestad, based upon experiments involving fires on horizontal 7.3 m x 7.3 m wood-fiber boards that had a very low mass flux, developed a correlation predicting the pool diameter at which break up occurs[21]. He observed that break up began around an H/D value of 0.5. The diameter at which H/D is 0.5 for LNG would be 1,200 m using his correlation and the value he used for the mass burn rate of $0.1 \text{ kg/m}^2\text{s}$. He predicted that H/D would be zero for a pool diameter of 8,900 m for LNG spills using this value of mass burn rate. Using the SNL correlation, Eq. (5), and mass burn rate of $0.147 \text{ kg/m}^2\text{s}$, the predicted diameter for H/D values of 0.5 and zero is approximately 4,400 m and 7,200 m, respectively. These values are far beyond what is anticipated from spills from an LNG ship where pool diameters are on the order of 100s of meters.

4. Discussion of Observed Behavior of LNG Large-Scale Tests

4.1 Soot Production

One of the most interesting aspects of the large-scale experiment, Test 2, is the less smoke production than the Montoir experiments, which were 35 m diameter LNG pool fire experiments conducted on land in 1987 [7]. This is contrary to the trend that smoke production should increase with larger diameters. As observed with most other hydrocarbons, the average SEP over the flame will first increase with increasing fire

diameter due to reaching the optically thick limit then decrease with further increases in diameter due to the increasing smoke layer coverage of the flame envelope. While smoke was produced during the SNL tests, it mostly formed in small amounts at lower elevations and rolled up to accumulate near the tip then exited the flame as shown in Figures 15a and 15b for Tests 1 and 2, respectively. Thus, no significant smoke shielding was observed during the SNL tests. Smoke shielding was quite evident in the upper half of the flame during the Montoir tests based on viewing video footage by the authors and also a description provided in reference [7]. As noted from reference [7], “These 35 m diameter fires exhibited a pronounced tendency for smoke shielding in the upper parts of the fire and this is consistent with the previously observed behavior of fires of higher hydrocarbons fuels.”

The two main differences between the Montoir and SNL tests are elevation and water. There is also the difference of fuel composition. The Montoir tests used LNG mixed with heavier hydrocarbons while the SNL tests used fairly pure LNG (>99% methane). The fuel composition difference is not considered to be a factor because gas composition measurements in the Montoir tests indicate that for the duration of measurements there was at least 99-mol% methane boiling from the pool. Thus, measurements from a methane fire were obtained, similar to the SNL tests.

Figure 15: SNL experiments of LNG pool fires of diameters (a) 21m, and (b) 56m.

Due to the elevation of Albuquerque, N.M. the SNL tests were conducted in an ambient pressure 17% lower than that of sea level while the Montoir tests were conducted at sea level. The extent that atmospheric pressure affects soot production for optically-thick turbulent pool fires has yet to be substantiated in the fire science community.

One approach traditionally taken to predict the influence of pressure is pressure scaling modeling which is based upon dimensionless arguments. The idea behind pressure scaling is to gain understanding about larger fires from smaller scale tests which has the obvious advantage of lower cost and increased safety. The scaling involves altering the

pressure such that a test performed under elevated pressure is equivalent to a larger test performed under a lower pressure. Thus, the SNL test at lower pressure is equivalent to performing a smaller scale test at a higher pressure such as that of sea-level. Pressure scaling is effective for pool diameters under around 1 m and for certain physical quantities such as fuel regression rate and upward flame spread[22], but for larger optically-thick fires where radiation becomes dominant over convective heat transfer, convection/diffusion and radiation cannot be scaled simultaneously using only pressure scaling[23]. For any scaling relation there must be validation by comparing to pool fires that are in the fully turbulent regime since heat and mass transfer characteristics are very different than laminar flames. Thus, the scaling rule should be able to predict information about 'large-scale' turbulent fires from information obtained at 'small-scale' performed under elevated pressure. For optically-thick, fully-turbulent pool fires this has not been achieved for the prediction of soot production and oxidation using pressure scaling modeling. Even for laminar flames, pressure scaling dependence has shown not to be independent of fuel type and similar throughout a flame regarding soot volume fraction [24]. Note that even if the scaling found from the laminar tests for local peak values of soot volume fraction were considered valid for optically-thick turbulent pool fires, a $p^{1.2}$ scaling would mean that the SNL test is equivalent to a 40 m diameter fire, still larger than the Montoir, but with significantly less smoke production. This pressure scaling dependence does not explain the difference observed between the two tests. Thus, additional effects are likely present to explain the contrary trend observed in smoke production.

Beyond the difference in ambient pressure between the Montoir and SNL tests, there is also the presence of water. The Montoir tests had the LNG contained in a berm whereas for the SNL test the LNG was spilled over water. Water vapor entrainment on the oxidizer side of the flame is quite evident as observed during Test 2. This test resulted in an 83 m diameter spill that surrounded the fire. Thus, there was a significant portion of the pool not burning. The non-burning region was made up of hydrates and will be discussed in section 4.3. The very cold non-burning region allowed for clear visualization of water vapor entrainment due to condensation. Water vapor is also most likely entrained on the fuel side due to vigorous boiling at the LNG/water interface. Water addition has been used to control combustion systems such as internal combustion engine performance [25], gas turbine systems [26], and steam-assisted flares [27], with several studies demonstrating thermal/physical and chemical effects of water addition on flames. A few pertinent studies are detailed in the following.

Zhang, et al. obtained measurements of temperature, soot volume fraction, number density, species, and polyaromatic hydrocarbons for a methane counter-flow diffusion flame with various combinations of non-heated and preheated reactants and product diluents [28]. One of the diluents was water vapor, added in one case to the oxidizer side and another to the fuel side. The results indicate that the addition of water vapor either on the oxidizer or fuel side reduced soot volume fraction values by a factor of about 2 with a slightly greater reduction when water vapor was added to the oxidizer side. The inlet

CH₄ and O₂ concentrations, flow rates and flame temperature were maintained constant, thus the effect of water vapor addition can be attributed to a chemical rather than a thermal effect. The authors believe that the chemical effect is mainly due to the reaction $\text{H}_2\text{O} + \text{H} \rightarrow \text{OH}\cdot + \text{H}_2$ producing the hydroxyl radical, OH $\cdot$, which lowers soot precursor concentrations and oxidizes soot. The fuel side does not have oxygen that can oxidize soot, thus OH $\cdot$ production through water addition on the fuel side is a likely cause of oxidation. It was further found that CO₂ addition has less effect on inhibiting soot formation than water vapor. To explain this they cite the work by Smyth, et al. regarding concentration measurements of the OH $\cdot$ radical in a laminar, co-flowing methane-air diffusion flame [29]. Smyth, et al. found that the reaction $\text{H}_2\text{O} + \text{H} \rightarrow \text{OH}\cdot + \text{H}_2$ is 14 times faster than the reaction $\text{CO}_2 + \text{H} \rightarrow \text{CO} + \text{OH}\cdot$ which indicates that H₂O is much more effective than CO₂ in forming OH $\cdot$. Note that these chemical reactions are highly temperature dependent and as such, would be applicable to the SNL tests if they had similar temperatures to Smyth's experiments, but due to the lack of data the applicability cannot be determined.

Atreya, et al. also experimentally and numerically studied a counter-flow methane diffusion flame [30]. One of their objectives was to determine if water has a chemical effect, and not just a physical or thermal effect on a flame. Different levels of O₂ and water in either liquid or vapor form introduced in the oxidizer stream were tested. By varying the O₂ concentration in the oxidizer stream different levels of soot production could be produced. The results show that for a 12% O₂ oxidizer stream, water as liquid droplets has a physical suppressive effect and decreases CO₂ and increases CO production with increasing water application rate (2.12 mg/s to 13.3 mg/s). The opposite trend occurs for a 30% O₂ stream due to the higher flame temperature which allows for water to be more chemically active. A 15% O₂ stream results in CO and CO₂ either following the 12% or 30% O₂ trend depending on the application rate, thus indicating competing effects of chemical enhancement and physical dilution. Based on visual observation water can also reduce soot production.

Water in vapor form indicates a different trend as a function of increasing O₂ concentration. For O₂ oxidizer stream concentration levels from 15% to 25% the CO₂ increases and CO decreases as the water vapor concentration increases (tested range of 0 to 40%). The authors attribute this different behavior to volumetric expansion effects from the evaporation of liquid droplets that can alter the flow field as well as cooling effects as compared to water vapor. Note that oxidation of CO to CO₂ is an exothermic reaction that can offset up to a certain extent the cooling effect of water. The soot production also decreases based on visual observations and the flame temperature increases with increasing water vapor concentration in the flame zone. Numerical calculations investigating how flame structure is affected by flame radiation and strain rate indicate that an increase in water vapor concentration enhances flame radiation particularly at low strain rates. The authors note that water can suppress a flame due to cooling and dilution, enhance radiative heat loss due to increased water concentration,

enhance mixing due to evaporation, and decrease luminous flame radiation due to a reduction in the soot concentration.

Similar results have also been found for other hydrocarbons. Rao and Bardon [31] studied a laminar diffusion flame of 5 cm in diameter for emulsions of diesel oil, toluene and benzene with water up to a 95% mole fraction. Soot concentrations were measured by gas collection above the flame. It was found that the soot concentration decreases as the water in the fuel vapor increases for all emulsions tested. Muller-Dethlefs and Schlader [32] conducted experiments of propane and ethylene premixed flames using a Bunsen burner with steam addition. A critical air-fuel ratio at which flame luminosity is suppressed was defined by measuring the ratio of C/O, excluding the oxygen provided from the added steam. It was found that with increasing steam addition the critical C/O ratio increased. Thus, less air is required to suppress flame luminosity when water is added indicating inhibition of carbon formation. Richard, et al., [33] conducted experiments of 10 cm diameter heptane pool fires with water vapor addition from boiling water underneath the fuel layer. With water addition both the soot yield and CO decreased and CO₂ increased indicating the inhibition of soot formation.

These studies clearly demonstrate that water addition either on the fuel or oxidizer side has chemical and thermal effects. For optically-thin flames, where gas-band radiation dominates, the suppression of soot will reduce the net heat flux radiated to a distant object, but for optically-thick fires in which the flame is soot saturated the effect of water vapor will be to reduce smoke formation with the consequences of increasing the net heat flux radiated to an object outside the fire. Thus, water addition is a plausible explanation for the discrepancy seen between the optically-thick SNL and Montoir tests.

It should be stressed, however, that the above studies are of small scale diffusion flames, that is, they are not in the turbulent, optically-thick regime. Thus, none of these studies directly address the influence of water addition on soot production and oxidation on the scale of fires studied here. To determine if water has an effect, additional testing is needed. It would be valuable to obtain data on soot production and water entrainment for various hydrocarbon pools on water at scales from 1 to 10s of meters to investigate this issue.

4.2 Wind Effects on Flame Stability

Observations from the large scale experiments, Test 1 and Test 2, indicate that the flame did not cover the entire pool surface as shown in Figures 16a and 16b, respectively. Extinction can be a result of both thermal effects, as will be discussed in section 4.3, and flow effects.

Figure 16: Occurrence of non-burning regions shown for the (a) 21 m, and (b) 56 m diameter SNL pool fires.

In addition to heat losses there are chemical and diffusive time scales to consider with regards to flame stability and extinction. The characteristic chemical reaction time, τ_c , and diffusion time, τ_d , depend on the particular flow configuration and reactants. The chemical reaction rate is typically much faster than the diffusion velocity of the gases but not for states near extinction. As the surrounding flow velocity increases the characteristic diffusion time decreases and a critical flow velocity can be reached where the chemical reaction cannot keep up with the supply of fuel and oxidant and extinction occurs. Thus, chemical reaction time limits the combustion rate in the case of extinction. When chemical times are on the order of diffusion time scales, finite rate chemistry must be considered. The Damkohler number, $Da = \tau_d / \tau_c$, is a dimensionless number used to represent the ratio of these two time scales, where a critical Da determines system-dependent flame extinction. Due to the large size of these fires and associated high entrainment velocities, extinction at the pool edges probably was a combination of attainment of critical Da numbers and thermal effects from water entrainment. With the current lack of data regarding entrainment velocities and temperature measurements at the pool edges for these tests, their contributions cannot be quantified. Further research is required to fully understand their effects for the test configuration studied here. Such research could potentially involve experiments at smaller scales and the utilization of computational fluid dynamic based simulations to evaluate flow times at larger scales.

In conditions of wind and where the pool is not contained such that a lip does not surround the pool there is a high probability for a critical Da number to be reached. In this instance the fuel does not burn at the upwind edge of the pool surface. The extent of the non-burning region will increase with increasing wind speeds. Even without wind the entrainment induced by the fire can potentially create critical Da number regions where burning does not occur. In the case where there is a pool lip by virtue of containment, the presence of such an obstacle provides regions of reduced velocities as in the leeward side of a bluff body. This locally reduces the flow velocity thereby allowing for the chemical reaction to keep pace with the supply of reactants in these regions. In addition, the hot products collected in the recirculation zone of the downwind region of the obstacle provide a suitable ignition source for reactants. During Test 2, it was observed that the flame anchored to the berm. It is well envisioned that since wind conditions are prevalent

in scenario environments there will be a mixture of non-burning and burning pool regions due to flow-induced extinction with the fire principally anchored to the LNG ship. It is difficult to predict the partition of these regions since it depends upon the wind and spill conditions. The scenario affording the most potential regarding fire size is anticipated to be a spill on the downwind side of a ship.

4.3 Water Conditions

As mentioned previously, Test 2 resulted in an 83 m diameter methane hydrate layer that encompassed the 56 m diameter pool fire. Methane hydrates are ice-like compounds where water molecules interstitially encage CH_4 gas molecules and is comprised of $\text{CH}_4 \cdot n\text{H}_2\text{O}$ ($n \geq 5.75$). Methane hydrates typically are found to occur in high-pressure low-temperature environments. They can however be found at 1 atmosphere under low temperatures near and below the freezing temperature of water, but they are not stable. This state is termed metastable and dissociation to H_2O ice + CH_4 gas at 0.1 MPa can be on the order of minutes to hours between the temperatures of 242 – 273 K [34]. Stern, et al. found that dissociation behavior is dependent on the pressure-temperature-time path taken to create a metastable state. Rapid depressurization of methane hydrate at isothermal conditions results in an anomalous region where the dissociation rate is non-monotonic with temperature and the stability is greater between 242 and 271 K than below 240 K, whereas slow-warming does not result in this anomalous behavior [34]. For equilibrium stability at atmospheric pressure methane gas hydrate must be at a temperature of 193 K or below. Mixtures of methane, ethane, and propane representative of natural gas does not show this anomalous behavior, though they have displayed stable behavior up to 256 hours at 1 atmosphere for the temperature range of 268.2 - 270.2 K when achieved through certain pressure-temperature paths [35]. These studies demonstrate that there are methods to achieve metastable states at 1 atmosphere near water-freezing temperatures such as through rapid depressurization. The methods used are different than the dynamics of the SNL tests in that very cold liquid methane is being mixed with much higher temperature water. It can be anticipated that ice and/or hydrates will form particularly when the water temperature is near 273 K and even at warmer temperatures, though their stability will significantly decrease with warmer water and with surrounding agitation, such as, from the spill itself and/or ocean conditions.

Expectation are that the heat flux from the flame would melt the ice/hydrate layer or prevent its formation even in near water-freezing temperatures. During the test, burning was prevented due to the previously mentioned extinction mechanism and the presence of water vapor that attenuated the radiation from the flame to prevent melting. The level of attenuation was significant given that the flame ignited scrub grass near the south pool edge approximately 20 m to 30 m away but could not melt the adjacent hydrate layer. The very cold hydrate layer provided a suitable environment for a thick layer of water vapor from the pool and environment to condense and form above it. The water vapor was continually transported across this layer due to entrainment. Evidence of hydrates is shown in Figure 17 which shows that near the end of the test the fire significantly

decreased then spread, extending beyond the tip of the diffuser and subsequently burned in isolated regions across the pool area indicating the presence of fuel. With the occurrence of a smaller fire near the end of the test, the entrainment and the consequent protective water vapor layer above the pool decreased thereby allowing the warming of the hydrate and ignition of the released fuel.

Figure 17: Sequence of late-time burning of the hydrates during the 83-m SNL test resulting in a 56 m fire.

The amount of LNG encased in the hydrate is uncertain but there are indications that it was mostly comprised of ice since the duration of late-time burning was relatively short and the burn area was very limited. Assuming a hydrate thickness of approximately 0.01 m and surface area of roughly 3,700 m² it can be estimated that about 10 m³ (2640 gallons) of equivalent LNG was encased in the hydrate layer which is about 5% of the LNG spilled. This most likely is an upper bound estimate.

A hydrate layer formed during Test 1, but not nearly of the same magnitude as occurred during Test 2, shown in Figures 18a and 18b, respectively. Beyond the amount spilled, the difference between the Test 1 and Test 2 is the temperature of the water where temperatures of 277 K and 274 K were measured, respectively. Since the water temperature was near freezing (274 K) for Test 2, the propensity to form hydrates was enhanced. The amount of hydrate formation for Test 1 was considerably less relative to the burning region than Test 2, which is most likely due to the higher water temperature.

(a)

(b)

Figure 18: Post-test hydrate layer in (a) Test 1 and (b) Test 2.

With regards to the locations of LNG ports, formation of hydrates may be an issue for certain locations that have water temperatures near freezing. If a hydrate layer does form its effect will be to reduce the burning region to result in a smaller pool fire. Thus, a conservative assumption for ports in near-freezing locations is no hydrate formation. For most port locations however the water is at a temperature that will not sustain hydrates for a significant duration. Additionally, in ocean environments the presence of salinity and waves will reduce the probability of formation [36]. Additional research is required on hydrate formation as a function of water temperature, salinity concentration, and wave condition.

5. Conclusions

LNG pool fires on water display different behavior than most other hydrocarbons at similar scale. The surface emissive power can be a factor of three to five greater depending on the diameter. The burn rate can be a factor of up to approximately six greater depending on the surface terrain. The flame height due to the higher burn rate is also greater by about a factor of two to three. Consequently, for a given diameter the thermal hazard distance for an LNG fire will be greater than most other hydrocarbons.

Several factors can influence the behavior of pool fires such as the presence of obstacles which promotes flame anchoring. Wind has several effects such as extinction at the upwind leading edge of the pool, increase in burn rate with wind speed, smoke shedding, and the formation of counter rotating vortices that enhance surface emissive power at the downwind side of the pool. Methane hydrates have the potential to form in locations that have environmental conditions to provide metastable states such as water temperatures near freezing. The hydrate sheet that potentially forms can limit the size of the pool. However, with salinity and turbulent mixing present in an ocean environment it is more difficult and most likely will not support a metastable state.

Several studies have demonstrated that water entrainment can affect a diffusion flame by altering the production of soot as well as product species. It is anticipated that heavier hydrocarbons also would display similar behavior. It would be of interest to conduct a series of experiments with various hydrocarbons over a span of scales ascertaining the effect of water entrainment on soot production. The hydrogen content of a fuel has been correlated with the propensity for soot production similar to the smoke point [37]. It is interesting to note that the stoichiometric balance of the ratio of water to fuel and the laminar smoke point can be correlated. The effect of water may be an explanation for the hydrogen content indicator. Note also that methane which does not display a laminar smoke point produces much more water for a given amount of fuel than other hydrocarbons.

In accordance with experimental observations of hydrocarbons and LNG, smoke production should increase with increasing pool diameter for LNG pool fires. Thus, smoke shielding is expected for LNG pool fires on the order of 100s of meters in

diameter, however the extent is uncertain. From a scientific perspective, highly accurate prediction of soot for large scales is currently beyond computational capabilities and a full understanding is an active area of research for members of the fire science community. From an engineering perspective, more development and assessment is required concerning soot models in order to provide better estimates. From a public safety perspective, a conservative approach is to utilize the measured surface emissive power from the SNL tests since these are the largest tests to date.

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