Large LNG Fire Thermal Radiation –
Modeling Issues & Hazard Criteria Revisited

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Abstract

Current models for evaluating the exclusion (hazard) zones around LNG fires in both US Regulations and NFPA-59A standard are prescriptive and require the consideration of large LNG releases. These models do not consider the effects of the combustion dynamics associated with large size pool burning. Oxygen starvation in the core of LNG fires of diameters larger than about 35 m leads to the formation of non-luminous, cold soot (smoke) resulting in a reduction of thermal energy radiated by the fire to the surroundings. The net effect is a smaller (calculated) thermal hazard distances for people exposure (by factors of 2 or 3 compared to results ignoring this phenomenon). Available large scale LNG fire test information is reviewed to quantify the effect of this phenomenon. This paper also discusses the common mistakes made in calculating the thermal radiation hazard distances around large fires by using, for the energy radiated from the fire, a constant percent of energy generated by combustion. The criteria for setting thermal radiation hazard zones around large hydrocarbon fires are also reviewed.

Introduction

In the past three years there has been considerable interest among regulatory agencies and the general public in Liquefied Natural Gas (LNG) fires, thanks to a number of applications submitted to the regulatory agencies to develop and operate LNG import terminals in the US [FERC, 2005]. The public is concerned about the potential consequences of release of a large quantity of LNG, either by accidents or due to acts of terrorism. While the public concern has been expressed for releases from both terminals and LNG ships, significantly more attention has been focused on large quantity releases from ships [Fay, 2003; ABS, 2004; Sandia, 2004] and public safety assessments have been performed. In many of these evaluations, the principal hazard scenario postulated is the occurrence of a LNG pool fire on water caused by releases from ships, and thermal radiation from such fires. Calculations have been performed using simplified descriptions of the geometry, physics of the fire and the effects of thermal radiation on people (and structures). Results presented by some researchers indicating that thermal hazard zone radii extending to 1,500 meters or greater have alarmed the public and the emergency response personnel. Unfortunately, these researchers have not considered many physical phenomena that occur in large fires, which tend to reduce the intensity of thermal radiation emission. Also, they have ignored many of the mitigating factors of short-term exposure of an urban population to fire thermal radiation.

This paper presents a summary review of data from most recent large scale LNG fire tests and discusses the many important phenomena that occur in large fires and the parameters that need to be considered in evaluating the hazard potential of LNG fires. Data from large LNG fire tests that have not been published in the literature are identified. Also, an approach to considering these data in a newer generation LNG fire models is discussed. The focus of the paper is limited to LNG pool fires.

LNG Experiments & Results

A number of organizations, worldwide, conducted LNG fire experiments in the 1970s and 1980s. These tests have included LNG spill tests on land (contained within a dike) and a limited number on water. Tests ranged from immediate ignition upon release, delayed ignition of dispersed vapor, dispersion without ignition of vapors generated by the boiling LNG, and in some cases, energetic ignition of stoichiometric concentrations of LNG vapor and air in large volume balloons (simulating unconfined energetic ignitions). Details of LNG fire field tests and their results have been published by May & McQueen [1973], AGA [1974], JGA [1976], Raj, et al., [1979], Raj [1982], Mizner and Eyre [1982], Nedelka, et al., [1989]. Some general information on the experimental parameters and results from these tests are indicated in Table 1.

The set of experiments conducted in China Lake, CA in mid 1970s remains as the only one designed and conducted to understand the characteristics of unconfined LNG (pool fire) burning on water and to measure the thermal radiation field external to the fire [Raj, et al, 1979]. The volume of LNG spilled varied from 3 m^3 to 5.7 m^3 with spill rates varying from 0.02 m^3/s to 0.11 m^3/s. The observed fire base diameters (averaged over the near steady burning duration) varied 8.5 m to 16.8 m. The observed duration of steady state burning diameters ranged from 42 s to 195 s. The best-fit correlation of the observed steady state fire base diameter and the spill rate indicated an average LNG pool regression rate of 5.7 x 10^{-4} m/s (corresponding to a mass loss rate of 0.242 kg/m^2s, or 12.1 MW/m^2 thermal release rate). The least square curve fit of the plot of the ratio of photographically measured average height of visible fire plumes (with the error bars connecting the maximum and minimum heights) to steady state diameters of the fires indicated a linear variation with 2/3 power of the dimensionless burning rate (also termed "modified Froude number"), similar to the correlations of Thomas (1963, 1965); see later discussions on the flame height correlations. Plate 1 shows a typical fire plume during the mid part of the steady state burning period. The fire was very columnar and generally yellow in color. The flame height variation relative to the mean height was about $\pm$20%. Narrow angle radiometers were directed at 4.6 m and 6.2 m above the base of the fire (location of very radiative part of the fire). The narrow angle radiometer data indicated the atmospheric absorption corrected flame emissive power of 220 $\pm$30 kW/m^2. The wide-angle radiometer readings showed considerable scatter over the duration of burning. The computed mean emissive powers computed from measured radiometer readings and applying correction for both the view of the radiometers and the atmospheric absorption ranged from 200 kW/m^2 for initial stages of fires to 225 kW/m^2 for later stages. This computation of emissive power was prone to significant calculation uncertainties because of difficulties in evaluating the atmospheric absorption, instantaneous flame heights and shapes and corrections for radiometer field of view.

Table 1
Summary of LNG Fire Experiments

#	Year	Sponsored by	Conducted in	Type of Tests	# of Tests	Fire Dimensions	Liquid Regression Rate (m/s)	Wide-angle Radiometer based, Mean Emissive Power (kW/m^2)	Avg fraction of combustion energy radiated (%)	Technical Reference(s)
		Details of Field Tests						Principal Results		
1	1962	US Bureau of Mines	Lake Charles, LA	LNG spill on diked ground	NA					Burgess, and Zabetakis (1962)
2	1969	Esso	Libya	LNG fire in a land diked area (trench): Continuous LNG feed	6	70 m long x 25 m widest x 5 m depth (avg). Eq diam = 18 m	1.6×10^{-4}	92	12 - 16	May and McQueen (1973)
3	1973	AGA	San Clemente, CA	Diked pool on land	7	Diameter = 1.8 m	1.5×10^{-4}	100	20	AGA (1974)
					8	Diameter = 6.1 m	2.2×10^{-4}	143 – 178 (max)	25	Raj & Atallah (1974)
4	1974 - 76	USCG	China Lake, CA	Unconfined pool on water: Continuous spill	5	Steady state fire diameters from 8.5 m to 15 m	4×10^{-4} to 10×10^{-4} with a mean of 5.7×10^{-4}	185 to 224	12 to 32 (depending on spill rate)	Raj, et al (1979)
5	1976	JGA	Japan	Diked pool on land	3	2 m x 2 m square	NA	58	13	JGA (1976)
6	1980	British Gas	England	Diked pool on land	29	Square and rectangular (2.5:1) dikes. Equivalent diameters 6.9 m to 15.4 m	NA		NA	Moorhouse (1982)
7	1980	Shell Research	Maplin Sands, England	Diked pool on land	1	Diameter = 20 m	2×10^{-4}	150 to 220	NA	Mizner and Eyre (1983)
				Unconfined pool on water		Mostly vapor fires resulting from delayed ignition	NA	NA		
8	1981	Tokyo Gas	Japan	Diked pool on land	8	Square pools of 2.5 m x 2.5 m	NA		NA	Kataoka (1981)
9	1987	Gaz de France	Montoir, France	Diked pool on land	3 of dia 35 m	1.8, 6.1, 10.2, 20 and 35 m diameter shallow dikes	3.3×10^{-4}	257-273	NA	Nedelka, Moorhouse & Tucker (1989)

Source: Raj, et al (1979)
Plate1: LNG pool fire (d= 15 m) on Water in a pond (50 m x 50 m x 1 m)

Source: Gaz de France (2004)

Plate 2: Snap shot of a 35 m dia LNG
Fire on insulated concrete dike

Source: AP Photo, 9th June 2004, Iraq.
(© *The Associated Press; Reprinted with permission*)

Plate 3: Fire on an oil spill from a
pipeline rupture

A series of three tests conducted in Montoir, France in 1987 involving LNG spill on to an insulated concrete floor dike of 1000 m^2 area (35.7 m diameter) and its ignition constitute the largest land spill fire tests to date. Nedelka, et al. (1989) have presented limited information on these tests; the bulk of data remains unpublished.

The Montoir tests show that large LNG fires burn with the production of copious amounts of black soot (smoke), contrary to the conventional assumption that LNG fires burn clean. The effect of smoke is to obscure the inner burning core of the fire thereby reducing the amount of total radiation that is emitted by the fire. In addition, the fire displays considerable similarity in its dynamics with other hydrocarbon fires of the same size, including the "puffing" type of burning in which large fireball puffs are released at a frequency determined by the fire size. Plate 2 is a clip from a video film of one of the Montoir tests showing the fireball type burning and considerable smoke production in the lower layers of the fire. Plate 3 is from a news clip of an oil pool fire resulting from a pipeline rupture[1].

The results provided by Nedelka, et al., can be summarized as follows: The average burning rate is 0.14 kg/m^{2}s (i.e., liquid regression rate of 3.3 x 10^{-4} m/s or 7.1 MW/m^2), spot emissive powers measured by narrow-angle radio meters ranged from 290 to 320 kW/m^2, the average surface emissive power (computed from the wide-angle radiometer data corrected for atmospheric absorption and the projected view of a specific area of fire as seen by the radiometer) ranged from 230 to 305 kW/m^2. The projected image of fire seen by the radiometer was smaller than the projected image of the average dimensions of the visible fire. The equivalent surface emissive power, calculated using the entire visible fire area, is shown to be between 257 kW/m^2 and 273 kW/m^2.

LNG Fire Hazard (Evaluation) Models

Two general approaches have been in use to determine the distance to specified level of heat flux hazard from fires (Raj, 1977; Raj 1979; Considine, 1984; Moorehouse & Pritchard, 1982; McGrattan, et al., 2000). These are the so-called "solid flame" model and the "point source" model. The application of each of these models and the modifications/enhancements needed in the models, in the light of data from large-scale LNG fire experiments, are discussed below.

The **Solid Flame Model** is based on the equation

$$\dot{q}'' = E\,F\,\tau \qquad\qquad\qquad (1)$$

where, $\dot{q}''$ is the radiative heat flux received by an object located at a specified distance from and oriented in a specified angle to the fire, E is an average value of thermal radiation flux emitted by the fire over a defined surface of a specified geometrical fire shape (generally referred to as the "surface emissive power – SEP"), F is the geometrical view factor between the radiation receiving object and the radiation emitting parts of the fire and τ is the transmissivity of the atmosphere to thermal radiation from the fire over a mean distance between the object and the geometrical shape of the fire (Fτ can also be evaluated by dividing

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[1]   The diameter of the fire is unknown but guesstimated to be between 30 and 50 m.

the fire surface that can be "seen" from the object into smaller areas and summing each sub-area's view factor x atmospheric transmissivity product value).

Fire Shape: In most "solid flame" models the shape of the fire is chosen to be a circular cylinder of diameter equal to the base diameter of the fire and axial length representing the visible plume of the fire. The axis of this cylinder is assumed vertical in low wind speeds (wind velocity below a critical value) and tilted in the wind-direction by an angle wrt the vertical, which depends on the wind speed, the diameter of the fire and the burning rate. (In some models, the drag of the base of the fire at ground level due to the wind is also considered. Other modifications include considering the horizontal cross section of the tilted cylinder to be elliptical rather than circular).

Fire Plume Length (L): Correlations of the following type due originally to Thomas (1963, 1965) have been used in the models to calculate the fire plume length for a fire of diameter D.

$$\frac{L}{D} \quad = \quad A \, F_C^{\,p} \, (U^*)^q \tag{2}$$

where, A, p and q are correlation constants,

$$F_C = \frac{\dot{m}''}{\rho_a \sqrt{g\,D}} = Combustion \; Froude \; Number = Dimensionless \; burning \; rate \tag{3}$$

and
$$U^* = \frac{U_{wind}}{\left[\frac{\dot{m}''}{\rho_a} g D\right]^{\frac{1}{3}}} \quad = Dimensionless \; wind \; speed \tag{4}$$

Thomas (1963) proposed a value A=42, p=0.61 and q=0, which was modified in a later report (Thomas, 1965) to A=55, p=2/3 and q = -0.21. Many models, including the models required by regulations (LNGFIRE3, 2004) use a constant correlation (A=42, p=0.61, q=0, with a wind tilt angle that depends upon U*). Using a single value for the exponent on the combustion Froude number to determine the fire plume length over all values of F_C is incorrect. For large LNG fires (D>30 m) the correlations used in such models as LNGFIRE3 over predict the length of flame and, hence, the radiation hazard distance. In fact, Thomas (1963) has provided data that indicate different values for the exponent (p) in different value ranges of F_C; p = 0.4 for F>10^{-1}; p= 0.61 for 10^{-2}<F<10^{-1} and p= 2/3 for F<10^{-2}. In fact, it can be shown from a simple analysis of air entrainment (Raj, 2005) that p = 2/3, if the fire length (L) is defined as the location by which the fuel is completely consumed within the plume by burning. The same p=2/3 correlation has also been indicated in a book by Murgai (1976) based on analysis of forest fire data. Moorhouse (1982) has proposed a correlation with p=0.254. Heskestad (1983) shows data for a large span of F (10^{-3}<F<10^{0}) indicating varying values for the exponent (p). The experimental results of Cox and Chitty (1985) indicate that p=1 for 10^{-4}<F<10^{-3} and p = 2 for 10^{-5}<F<10^{-4}.

Figure 1 shows the plot of measured visible flame length to diameter ratios from a number of LNG experiments. The Moorhouse correlation is unacceptable on the grounds that it is not physically justifiable (it has the wrong slope of L/D ratio variation with Froude number), and the Cox & Chitty correlation is not applicable in the range of experimental combustion Froude numbers. For postulated LNG fire diameters (330 to 512 m) due releases from ships from acts of terror ([Sandia, 2004) the estimated combustion Froude number (F_C) is in the range 1.83×10^{-3} to 1.47×10^{-3}. The values for the flame height-to-diameter ratios (L/D) used by Hightower, et al., (based on Moorhouse correlation) for the above ranges of Froude numbers are 1.28 and 1.35, respectively. These are considerably higher than those predicted by Thomas' correlation (viz, L/D = 0.71 and 0.822). All other things being equal the radiation hazard distances predicted by Hightower, et al. are, therefore, higher than what should be the case based on Thomas' correlation for flame heights which are based on physical principles and experimental measurements.
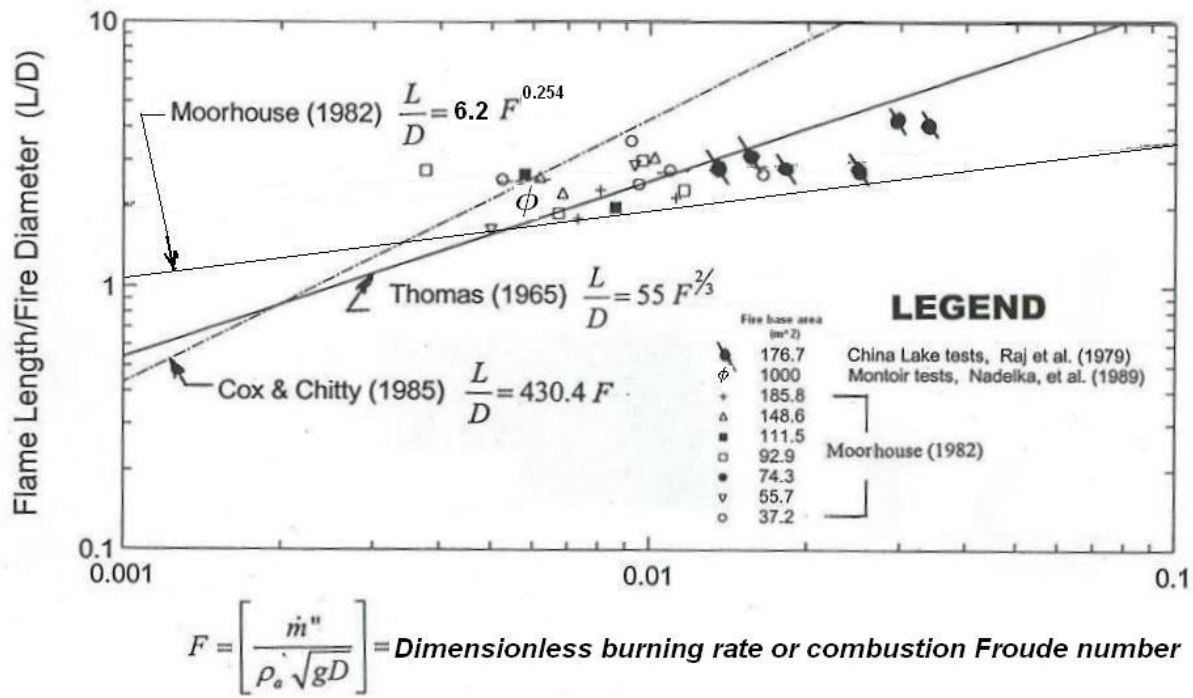

Figure 1: Fire height to diameter ratio data from LNG fire experiments

The models to calculate the fire radiation hazard should also consider the different regimes of combustion within the height of the visible flame. Current generation models do not take these into consideration. It has been recognized in the fire literature that as the fire diameter increases the burning region is no longer represented by a columnar, cylindrical plume but consists of distinct zones. This can be seen in photographs in Plate 1 and Plate 2. McCaffrey (1983) proposed a three-zone model for a turbulent diffusion fire. The first zone consists of a fuel rich core region. In the second zone the flame is still anchored to the base but pulsates in size both radially and axially due to the effects of large scale eddies in the entrained air. The third zone, termed "the intermittency region" is where peeled off blobs of fuel

burn in irregular clumps. This model for burning is shown schematically in Figure 2. While no specific calculation procedures are available to determine the heights of each zone, it is known that the first zone generally extends to about 10% of the visible flame height, the second zone varying between 10% and 40% of the flame height.

Plate 2 and Plate 3 also show the distinct "puff" type of burning as the diameter of the fire increases. A large diffusion fire can be considered to be made of a series of connected starting thermals, which exhibit the classic mushroom formation. Malalsekera, et. al., (1996) have described the physics of formation of such burning puffs. It is obvious that the "top" of the burning flame ("flame height") is not a unique position in space but changes with time. Heskestad's (1983) data indicates a correlation for the length of the intermittent zone (L_l) with the combustion Froude number F_C (for $7.5 \times 10^{-4} < F < 2.5 \times 10^{-1}$) as follows:

$$\frac{L_l}{L} = 0.167 - \log_{10}(F_C^{\frac{1}{4}}) \qquad (5)$$
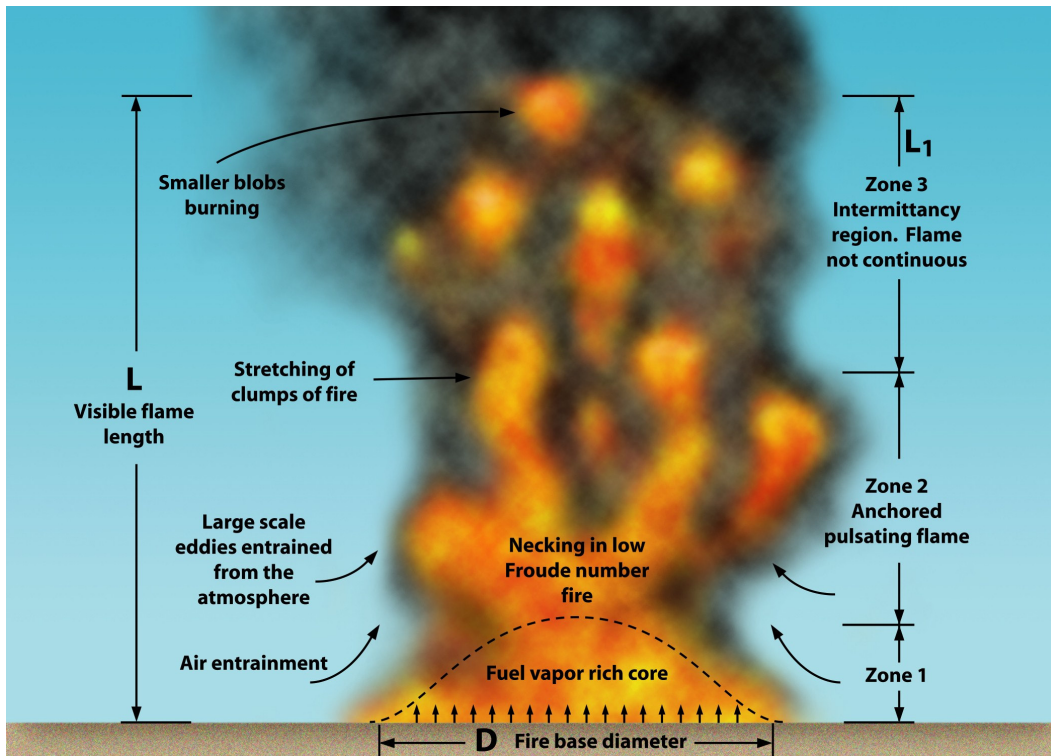

Figure 2: Schematic representation of the intermittency in buoyant diffusion flame height

In the intermittent fire region the flame is not coherent and, therefore, cannot be considered as a continuous emitter of radiation over the entire length of the intermittency region. New generation of LNG fire models must consider the effect of this phenomenon. It may be appropriate to consider different values for the surface emissive power for the three regions. McGrattan, et. al.,(2000) have used a variation of this theme based on assumptions of the percent of combustion energy released, where all of the energy released is assigned to the first zone (and from which an effective height of uniform emissive power fire is determined). The application of the approach of McGrattan, et al., to LNG fire radiation assessment is questionable.

Surface Emissive Power-SEP (E): Several values for the parameter E (or SEP) have been reported in the literature for LNG fires based on calculations from heat fluxes measured by radiometers. (Some of these results, obtained by using Thomas' correlation for flame heights are indicated in Table 1). These results show considerable scatter. The increase in the value of E with fire diameter is noticed. However, for the largest size, 35 m diameter, tested to date (Nedelka, et al., 1989) the trend shows E leveling off or even decreasing with increase in diameter of the fire. Unfortunately, the data scatter is too high and amount of data too low to make definitive predictions.

It should be noted that SEP is a derived quantity and its value depends upon the geometry of the fire used (especially the value used for the "height" of fire plume), assumptions made in calculating the atmospheric transmissivity and the general experimental errors. In fact, Nedelka, et al. (1989) have pointed out that in the Montoir tests (35 m diameter fire) when the results for E are calculated based on the actually observed flame radiating surfaces, one set of values is obtained (E=275 kW/m^2) whereas the same radiometer data gives a value of 175 kW/m^2 for SEP when the Thomas' flame height correlation is used for the radiating surface calculation! Therefore, when a fire thermal hazard calculation is made using equation 1, the value of E and the geometry used to obtain the value of E must be used in exactly the same way as it was originally calculated from test data. Recently, for example, Hightower et al, (2004) have used a value of E=220 kW/m^2 to 350 kW/m^2 for large LNG pool fires (without indicating the source for these numbers), and using them with Moorhouse correlation for flame height. As already stated, Moorhouse correlation cannot be applied to large fires.

Smoke production in fires. Large diameter LNG fires seem to produce a significant amount of smoke (see Plate 2). This is similar to those observed in the burning of other higher hydrocarbon liquids (propane, butane, heavier oils, etc – see Plate 3). Two physical phenomena may contribute to the production of smoke, even in "clean burning" fuels such as LNG. The first is the lack of enough oxygen in the core of large diameter fires to burn the carbon produced by the pyrolysis of fuel vapor. This not only produces soot (carbon particles) but also lowers the overall heat release –and hence the temperature- resulting in the promotion of smoke production. The second phenomenon may be due to the lowering of the effective concentration of fuel and vapor in the core from the recirculation of burnt gases by the toroidal vortex that is prevalent in all large fires. The effect of smoke is to shield the emission of thermal radiation from the fire reducing, significantly, the thermal radiation hazard distance around large LNG or other fires. In addition, the formation (and recirculation) of smoke could result in less efficient combustion of the fuel and result in the lowering of the effective flame temperature. However, the reduction in the radiant emission out of the fire tends to increase the temperature of the gases; which one of the two effects dominates depends on the chemical properties of the fuel, chemistry of combustion, the physical dimensions and the hydrodynamics of gas flow within the fire. No model exists that considers all of these phenomena.

Soot is carbon particles (with diameters in the 3 nm to 30 nm) in a fire that are being oxidized and are "glowing"; in fact, the visibility of a fire is caused by the emission of radiation in the visible spectrum by the burning soot. When the carbon produced by pyrolysis is either partially oxidized or is not oxidized at all because of lower local temperature, carbon particles agglomerate to form long chain molecules of carbon or "smoke." Soot formation studies are

extensively reported in the literature (see Narasimhan & Foster, 1965; Glassman, 1979; Hura & Glassman, 1988, Mrakstein, 1988; Fowler, 1988; McCaffrey & Harkleroad, 1988). However, there is very little work on the measurement of smoke production rates in large turbulent diffusion fires. Notarianni, et al (1993) measured the smoke production in crude oil fires of diameters from 0.085 m to 17.2 m and found that smoke yield (mass % of burnt fuel that is emitted as smoke) increases as the diameter of the fire increases. The data for the mass fraction smoke yield (Y in %) vs. fire diameter (D in meters) presented by these researchers can be correlated for crude oil fires as,

$$Y = 9.412 + 2.758 * \log_{10}(D) \tag{6}$$

It is anticipated that the constants in the equation will depend very critically on the fuel chemical composition and pyrolysis properties. Unfortunately, such data do not exist for LNG fires. Considine (1984) has discussed one approach to determining the effect of smoke in reducing the radiation by assuming an effective emissivity of the fire (in the regions of smoke production) to be about 0.3. This would typically make the LNG fire surface emissive power in the smoke regions to be about 65 kW/m^2. Delichatsios & Orloff (1988) are able to correlate measured radiation from _optically thin flames_ with burner size and fuel flow rate by postulating the soot concentration to be proportional to a fuel residence time scale (which depends upon the intensity of turbulence) and the reciprocal of the chemical formation time scale. This method is not applicable to large fires, which are optically thick and radiate in the H_2O and CO_2 bands. McCaffrey & Harkleroad (1988) have presented soot data from small-scale experiments for a number of hydrocarbon fires in the form of specific extinction area (SEA) for soot; for propane SEA is found to be 124 m^2/kg and for crude oil fires it is 1000 m^2/kg. No direct data for the smoke yield, as a function of fire diameter exists for large fires of different fuels.

Modeling smoke effects on radiation: The presence of smoke in a fire is to absorb thermal radiation emission and reduce the effective emissive power. The effective emissive power in the smoke obscured regions can be represented by,

$$E_{eff} = E_0\, \tau_s \tag{7}$$

and,

$$\tau_s \quad = \quad \text{Transmissivity of smoke} = e^{-(k_m C_s L_b)} \tag{8}$$

where, E_{eff} = Effective surface emissive power in the smoky regions of fire
  E_0 = Maximum surface emissive power (generally at lower regions of fire unaffected by smoke)
  k_m = Specific soot extinction area (m^2/kg)
  C_s = Mass concentration of smoke in the flame gases (kg smoke/m^3)
  L_b = Beam length = 0.63 D, for cylindrical fires (m)

A fire thermal radiation model for different diameter fires, which incorporates the results of correlations similar to those of Notarianni, et al (1993) and McCaffrey & Harkleroad (1988), the fire dynamics, smoke obscuration effects indicated above, and the intermittency of fire core exposure will be presented in a future publication (Raj, 2005). This model divides the fire radiation zone into two distinct zones (with height) and considers the pulsating nature of exposure in the second zone as a function of fire diameter and height. Equations to determine

the relative heights of each zone and the variation of surface emissive power with height will be presented. It is calculated that for very large fires the smoke obscuration averaged SEP over the height of the fire (calculated using Thomas' correlation) is about 50% of the SEP at the base!

Fractional Energy Radiated by a Fire: The heat flux to an object at a distance S from the center of a fire of diameter D is sometimes calculated using the point source model with the following equation

$$\dot{q}'' = \chi_R \frac{\left[\dfrac{\pi}{4} D^2 \dot{m}'' \Delta H_C \right]}{4 \pi S^2} \tag{9}$$

where,

$\dot{q}''$ = Radiative heat flux received by an object at distance S

χ_R = Fraction of combustion energy released that is radiated

$\dot{m}''$ = Mass burning rate per unit area

ΔH_C = Heat of combustion (lower) of the fuel burning

Based on radiation measurements in a limited number of field experiments with LNG fires of diameters less than 15 m, the value of χ_R is shown to vary between 12% and 32% (see Table 1). It is anticipated that for larger diameter fires the fraction radiated will decrease due to smoke obscuration effects, and simple geometry effects (ie, the heat generation rate is proportional to fire base area whereas the emitting surface area increases as $d^{1.7}$). Data presented by McGrattan, et al (2000), for heavier hydrocarbon fuels (other than LNG), shows the following correlation for the fraction radiated with fire diameter,

$$\chi_R = 0.35 e^{-(D/20)} \qquad ; \qquad D = \text{fire diameter in meters} \tag{10}$$

This correlation, if applied to a 15 m diameter LNG fire, predicts $\chi_R = 0.17$, a value tantalizingly close to a measured value (in the China Lake experiments) of 0.125. However, this can only be considered as a coincidence; the application of the above correlation to a 35 m diameter fire (Montoir tests) yields $\chi_R = 0.06$ and application to a 100 m diameter fire results in $\chi_R = 2.36$ x 10^{-3}. Of course, such predictions are unsubstantiated.

The relationship between the fraction of the combustion energy that is radiated by a fire of diameter D and its mean emissive power is calculated below, subject to the following assumptions:

- The average surface emissive power (E) of LNG fire does not change with fire diameter (which as we have discussed earlier is not true and, in fact, decreases with increase in diameter).
- The fire can be represented by a vertical axis cylinder.
- The fuel burning rate per unit area of the fire base is independent of diameter,

- The visible flame surface represents the radiating surface and the height (L) of the fire is related to the fire diameter (D) and the burning mass flux ($\dot{m}''$) by Thomas' equation,

$$\frac{L}{D} = 55\left[\frac{\dot{m}''}{\rho_a\sqrt{gD}}\right]^{\frac{2}{3}}$$

It can be shown that,

$$\chi_R = \frac{Rate\ of\ heat\ radiation\ from\ the\ cylindrical\ fire\ surface}{Rate\ of\ heat\ production\ by\ fuel\ combustion} \tag{11a}$$

$$\chi_R = \frac{\pi\,D\,L\,E}{(\pi/4)\,D^2\,\dot{m}''\,\Delta H_C} = 220\left(\frac{E}{\dot{m}''\,\Delta H_C}\right)\left[\frac{\dot{m}''}{\rho_a\sqrt{g\,D}}\right]^{\frac{2}{3}} \tag{11b}$$

Fay (2003) has used the point source model to calculate LNG fire hazards. He assumed 15% for the fraction of energy radiated from a 340 m diameter LNG fire on water caused by release of 14500 m^3 of LNG from a ship and calculated the hazard distance to 5 kW/m^2 heat flux to be 1900 m. The assumed value of 15% energy radiated from a 340 m size fire is incorrect and unsupportable on any measured data[2]. Using the China Lake test data of 12.5 % for the fraction of energy radiated by a 15 m fire together with the inverse cube root of diameter relationship from equation 11b, it is calculated that for a 340 m diameter fire the fraction of combustion energy radiated is 4.4%. With this value for the fraction radiated, absent all other radiation reduction mechanisms for large fires discussed in this paper and neglecting atmospheric absorption, the hazard distance calculated by Fay would be reduced by a factor of 1.85 or hazard distance would become 1030 m. Consideration of smokiness of large LNG fires, atmospheric absorption (by about a factor of 0.6 for this distance) results in a hazard distance of the order of 600 m, a reduction by a factor of 3 compared to Fay's predictions. Hence, caution should be exercised in using the point source model to estimate any fire hazard zones.

Thermal Hazard Heat Flux : NFPA 59A Standard stipulates 5 kW/m^2 (1,600 Btu/hr ft^2) as a safe level of exposure at a property line that can be built upon next to a LNG storage facility. Also, this level has been set as (tolerable risk) threshold level for thermal exposure in the regulations of several other countries. Exposure of a bare human skin to this level of thermal radiation results in 2nd degree blisters in 30 seconds. A recent work (Raj, 2004) has compared this exposure level with exposures to thermal radiation in industrial and residential settings and finds that for an accident situation, this level may be acceptable. There is information in the literature that indicates that ordinary clothing worn by people affords an enhanced level of protection to 5 kW/m^2 radiation flux; in fact, even the basic fabric reduces thermal intensity on the skin by a factor of about 5 and the exposure time for 2nd degree burns is correspondingly increased by at least an order of magnitude. In addition, the buildings and indoor occupancies provide significant level of safety from exposure to an urban population; Considine (1988), McGrattan, et al (2000) have considered the effect of tallness of buildings and other deliberately constructed obstruction panels in minimizing thermal radiation impact in

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[2] On the basis of this number for the fraction of combustion energy emanating over the "nominal" surface of a cylindrical fire of diameter 340 m and flame height predicted by Thomas' equation, the SEP would be 750 kW/m^2.

areas surrounding fuel storage plants. A realistic hazard criterion should be based on the likelihood of exposing larger than *an priori* specified fraction of the population to the threshold heat flux level. Such a calculation should consider the effects of mitigating parameters such as clothing protection, shadows of buildings, ability of people to seek shelter within 30 s, etc.; that is, a probit based model should be used for hazard area calculations instead of assessments based on a single number for the hazard heat flux level.

CFD Approach to Simulating Fire Dynamics & Radiation

A number of researchers and institutions [Smith, et al. (2003), Malalasekara, et al. (1996), Hostikka, et al. (2003)] are investigating the feasibility of modeling and simulating the characteristics of large fires through the use of Computational Fluid Dynamics codes. These codes are attempting to simulate the combined effects of turbulence (which influences the mixing of fuel, oxidizer and the products of combustion and determines the local reactant concentrations), reaction chemistry and the generation of different products of combustion including the formation of soot precursors (Polycyclic Aromatic Hydrocarbons-PAH), soot precipitation, agglomeration and soot particle growth, and the effects of thermal radiation both to the burning fuel substrate (ex., liquid pool) and to the environment. The success in mimicking real fires to date has been limited and computationally very expensive both in cost and computer time.

Smith, et al., report the results of an investigation in which a 10 m diameter heptane pool fire is simulated using a 150 x 150 x150 node grid representing 50 m x 50 m x 50 m space. Radiation to the pool was not simulated but the burning rate was assumed constant and used as an input. Soot chemistry was simplified from the normal 100 degrees of freedom to one and optically thin radiation model was used. Even with these simplifications the simulation is reported to have taken 72 hours on a 500 parallel processor, SGI Origin 2000 server. The simulation results show the puffing type burning (a result of use of the Large Eddy Simulation code) agreeing both physically and in frequency domain with experimental results. The radial and axial velocities predicted for a 1 m diameter fire (for which experimental data were available), while agreeing in overall distributions, show deviations from measured values. The radiation predicted was far lower than actually measured in the experiments. A more recent publication (C-SAFE Annual Report 2004) of the University of Utah paints an even more pessimistic picture of the feasibility of using CFD codes to determine the thermal radiation emission from large fires. For example, to generate 8 s of simulation time for a 0.3 m heptane fire with a 181^3 mesh, the simulation ran on 120 processors on a Frost server for over a month and required 500 GB disk space to store the results! In addition, the difference between the measured and simulated values was outside the estimated error of the two measurements, which resulted in a relatively poor validation metric of 0.31 (1=perfect agreement, 0=poor agreement). None of the simulations took into account the effect of wind, either in enhancing the turbulence or in tilting the fire plume.

The state of the art in CFD applications to predicting the dynamics and radiation from a realistic, large pool fire is still in its infancy. Computational time, even with the fastest computers, seems to be measured in days/month rather than in minutes. Computational efficiency (both $ and crunch time) and ease of use of the program (in terms of the number and format of input variables) will be needed if CFD codes are to be useful for realistic applications. In addition, the accuracy of prediction, as of this date, is far from satisfactory for

use of this tool in hazard assessment, or for regulations to specify their use for the design of facilities storing liquefied gases such as LNG, LPG, etc. Semi empirical models based on field test data with realistic physics of fires included will have to suffice for a foreseeable future for use in fire hazard and risk assessment efforts.

Conclusions;

LNG fire thermal radiation hazard evaluation models currently used in regulations and those being used in several public presentations have been reviewed in the light of experimental data, both quantitative and qualitative. The following general conclusions are the result:

1   In general, large LNG pool fires exhibit burning characteristics very similar to those seen in large higher hydrocarbon fires (kerosene, LPG, crude oil, JP-4, etc), which burn very sooty and reduced radiation output to the surroundings.

2   It is not possible at this time to predict the "critical diameter" of LNG fires beyond which they behave similar to higher hydrocarbon liquid fires; however, it can be argued that this value is in the 35 to 50 m range.

3   Newer generation models should take into account the significant soot formation and the intermittent burning characteristics of large LNG liquid pool diffusion fires.

4   Current state of the art in simulating large outdoor diffusion pool fires is still in the realm of research. Optimized calculation procedures for realistic predictions with acceptable computer time and cost are not available, yet. CFD approaches are far from being at a stage for inclusion in regulations or for use in facility location analyses.

5   Hazard calculations should also consider the effect of mitigating parameters such as peoples' clothing, shadow of buildings and ability of persons to seek shelter quickly. The use of probit type equations, to take into account the probabilities of persons seeking shelter, having sufficient clothing and taking evasive action to reduce direct exposure to heat will constitute a more realistic and better approach than is used currently.

Nomenclature

C_S = Mass concentration of smoke (or soot) at any point in the fire (kg/m^3)
D = Diameter of the base of fire (m)
E = Surface emissive power of a flame (W/m^2)
F = Geometric view factor between an object and the fire
F_C = Combustion Froude number $= \dfrac{\dot{m}''}{\rho_a \sqrt{g\,D}}$
g = Acceleration due to gravity = 9.8 (m/s^2)

ΔH_C = Heat of combustion (lower heat) (J/kg)
k_m = Specific soot extinction area (m^2/kg)
L = Length of visible fire plume (m)

L_b	=	Mean beam length inside a fire plume = 0.63 D	(m)
$\dot{m}''$	=	Fuel burning rate per unit area	(kg/m^2 s)
$\dot{q}''$	=	Radiant heat flux received by an object	(W/m^2)
S	=	Distance from fire center to the radiation receiving object	(m)
U_{wind}	=	Wind speed	(m/s)
Y	=	Fraction by mass of burning fuel converted to smoke	
ρ_a	=	Density of air = 1.3	(kg/m^3)
ρ_s	=	density (intrinsic) of smoke particles ≈ 2000	(kg/m^3)
χ_R	=	Fraction of combustion energy that is radiated to surroundings	
τ	=	Transmissivity of the atmosphere for fire thermal radiation	
τ_S	=	Transmissivity of soot	

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