Journal of Hazardous Materials 107 (2004) 3–9

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Comparison of hypothetical LNG and fuel oil fires on water

William Lehr*, Debra Simecek-Beatty

National Oceanic and Atmospheric Administration, Office of Response and Restoration, 7600 Sand Point Way NE, Seattle, WA 98115, USA

Abstract

Large spills of refined petroleum products have been an occasional occurrence over the past few decades. This has not been true for large spills of liquefied natural gas (LNG). This paper compares the likely similarities and differences between accidental releases from a ship of sizable quantities of these different hydrocarbon fuels, their subsequent spreading, and possible pool-fire behavior. Quantitative estimates are made of the spread rate and maximum slick size, burn rate, and duration; effective thermal radiation; and subsequent soot generation.
Published by Elsevier B.V.

Keywords: LNG fires; Fuel oil fires; Pool-fires; Modeling fires; Smoke generation

1. Introduction

Most unconfined oil spills do not provide suitable conditions for a pool-fire because the oil slick forms a thin film and rapidly weathers, losing its volatile and more flammable components. Occasionally [1], an accident will occur with spill leakage, accompanied by fire and explosion and causing a pool-fire near the ship. Response procedures, based on previous case histories, have been developed to handle such situations. Case histories for liquefied natural gas (LNG) vessel accidents are more rare. Moreover, important differences exist between LNG and refined oil fires that can affect response tactics. This paper compares the likely similarities and differences between vessel accidental releases of sizable quantities of these different hydrocarbon fuels, their subsequent spreading, and possible pool-fire behavior.

2. Slick spreading

When a buoyant petroleum product is spilled on the water it begins to spread. The Fay formulas [2] and other early spreading algorithms examined the properties of idealized spreading on calm water of a floating insoluble chemical such as oil. When the slick is relatively thick, gravity causes the oil to spread laterally. Later, interfacial tension at the periphery will be the dominant spreading force. The main retarding force is initially inertia, followed by the viscous drag of the water. Fay, therefore, separated spreading into three phases: gravity–inertial, gravity–viscous, and surface tension–viscous. Jeffery [3] did not observe the three separate phases and Lehr et al. [4] noted that the results of the Fay model differed considerably from measured values of experimental spills. However, versions of the Fay spreading algorithms are used to model LNG spreading in most existing models. Hence, it will be used in this comparison between fuel oil and LNG fires on water.

Defining g' as the reduced gravitational constant,

$$g' = g\left(1 - \frac{\rho_l}{\rho_w}\right) \tag{1}$$

where ρ_l (ρ_w) is the oil (water) density. We will use the standard assumptions made for inertial spreading [5]. The slick spreads radially, and the slick thickness gradient from the center to the leading edge is small. If r is the leading edge and h is the center thickness, then the radial acceleration of the edge, neglecting mass loss due to burn rate and evaporation, is [6,7]

$$\frac{d^2r}{dt^2} = -\varepsilon g' \frac{h}{r} \tag{2}$$

Here, ε is a parameter that is usually empirically determined for each particular oil. Dimensionless values range from 1.33 to 2 (see Conrado and Vesovic [8] for a discussion of appropriate choices for this parameter). Serag-Eldin [9] adds an extra term to the right side of this equation for continu-

* Corresponding author. Tel.: +1-206-526-6310; fax: +1-206-526-6329.
E-mail address: bill.lehr@noaa.gov (W. Lehr).

0304-3894/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.jhazmat.2003.11.006

ous spills to account for the direct effects of the source on spreading. Eq. (2) can be integrated [7] to yield

$$\frac{dr}{dt} = \sqrt{\varepsilon g' h} \quad (3)$$

This equation can be integrated to yield the standard Fay gravity-inertial formulas for an instantaneous release of volume, V_0, of

$$r = \sqrt{t\sqrt{k_1 \varepsilon g' V_0}} \quad (4)$$

and for a continuous spill of rate $\dot{V}_0$

$$r = \sqrt[4]{t\sqrt{k_2 \varepsilon g' \dot{V}_0}} \quad (5)$$

Based on geometrical considerations, Briscoe and Shaw [7] used the constants $k_1 = 4/\pi$ and $k_2 = 9/16\pi$.

Larger slicks can transition from gravity–inertial to gravity–viscous spreading. For an instantaneous spill, this time is given as [10]

$$t = k_3 \left(\frac{V_0}{g' \nu_w} \right)^{1/3} \quad (6)$$

where ν_w is the kinematic viscosity of water. Dodge et al. [10] sets $k_3 = 2.6$, if the other terms are expressed in MKS units. For a typical diesel fuel oil, a 500 m^3 spill would theoretically make the transition in 30 min (Fig. 1). The time is only slightly smaller for an LNG spill.

These times are longer than expected burn times for instantaneous spills [11]. Thus, if either a fuel oil or an LNG spill is immediately accompanied by a sufficient ignition source and subsequent pool-fire, it is doubtful that the slick will transition from gravity–inertial spreading to gravity–viscous spreading. This may not be the case if ignition is delayed. The slick may continue spreading, either until it transitions into surface tension–viscous spreading or reaches some practical minimum thickness. Dodge [10] suggests that an oil slick stops spreading when the thick part of the slick reaches a thickness of 0.1 mm.

Opschoor [6], based on earlier studies, recommends a larger minimum average thickness of 0.17 cm for an LNG slick. Based on Eqs. (4) and (6), an instantaneous LNG spill will reach minimum thickness around the time of transition if the initial volume is approximately 200 m^3. This, of course, does not take into account the mass loss due to evaporation, a much more significant factor for LNG than for the average fuel oil. The transition time to gravity–viscous spreading increases as the cube root of the initial volume, whereas the time to reach minimum thickness, based on Eq. (4), increases as the square root of the initial volume. For very large spills this suggests that if the Fay assumptions are valid, LNG spills on water may transition to gravity–viscous spreading. The reason existing models do not consider this transition may relate to the much smaller experimental volumes utilized compared to those necessary to reach the transition before minimum thickness is achieved. Thus, far, the scant experimental data [8,12] do not indicate any transition in spreading mechanism.

If the spill of LNG or fuel oil is accompanied by an immediate ignition of the spilled product, then the volume, V, of the slick will vary over time according to the equation

$$\frac{dV}{dt} \equiv \dot{V} = \dot{V}_0 - \dot{h} A \quad (7)$$

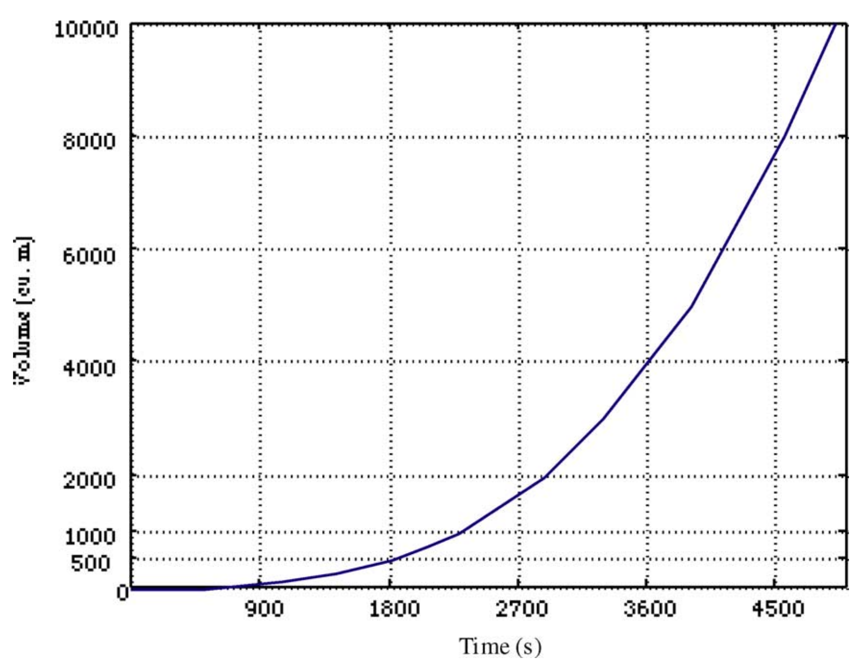

Fig. 1. Initial spill volume vs. time for the transition from gravity–inertial to gravity–viscous spreading for a large diesel spill.

with A as the spill area and $\dot{h}$ as the burn regression rate. Instantaneous spills can be included by expressing $\dot{V}_0$ as a delta function. Experiments of LNG pool-fires on water indicate that the burn regression rates vary from 0.4 to 1.0 mm/s [13]. For larger continuous releases, the LNG burn regression rate has been estimated as 0.25 mm/s [14]. The reason for a decrease in the regression rate for these larger spills may be due to incomplete mixing with the air. The burn regression rate for fuel oils varies with the product and the weathering state. For large experimental spills of fresh gasoline and diesel, Chatris et al. [15] found that the burn regression rate varied from 0.03 to 0.1 mm/s. Although the LNG slick will continue to burn at any thickness, fuel oil slicks thinner than 2–3 mm will not support combustion [16].

Although the thickness of the slick will not be uniform, the variation in thickness will be small in comparison to the horizontal scale of the slick. If circular spreading is assumed, $V = hA = h\pi r^2$, and Eq. (3) can be expressed in terms of area change rather than radius change. Differentiating Eq. (7), then matching the area growth rate term in the two resulting equations provides a second order equation in the slick volume

$$\frac{d^2V}{dt^2} = -2\dot{h}\sqrt{\varepsilon\pi g' V} + \ddot{V}_0 \qquad (8)$$

Here, $\ddot{V}_0$ is the rate of change of the leak source, which we will take to be negligible. This would be true for an instantaneous spill at times greater than zero or for long continuous spills (e.g. a large tank with a small puncture). Eq. (8) can then be integrated to yield

$$\dot{V}_0^2 - \dot{V}^2 = \tfrac{8}{3}\dot{h}\sqrt{\varepsilon\pi g'}(V^{3/2} - V_0^{3/2}) \qquad (9)$$

For an instantaneous spill, the largest amount of oil or LNG on the water would obviously be right after the spill event. If the release is long and continuous, the volume of oil or LNG on the water will increase until the amount being burned equals the amount being spilled. The maximum volume of product on the water for a continuous spill is found when $\dot{V} = 0$ in Eq. (9). This yields a maximum volume, V_{max}, of

$$V_{max} = \left(\frac{3}{8\dot{h}\sqrt{\varepsilon\pi g'}}\dot{V}_0^2\right)^{2/3} \qquad (10)$$

Fig. 2 shows the expected maximum volume versus spill rate for an LNG continuous spill.

The maximum area of the slick, except for very small leak rates, does not coincide with the area of the slick at maximum volume, since the slick will continue to spread until it reaches minimum thickness. Opschoor [6] provides an approximate formula for maximum area for an instantaneous spill. By equating $\dot{V}$ in Eqs. (7) and (9), it is possible to solve for maximum slick area as a function of minimum thickness, h_{min}, burn regression rate, and source leak rate

$$A_{max} = \frac{1}{9\dot{h}^2}\left[\sqrt{16\,\varepsilon\pi g' h_{min}^3 + 18\dot{h}\dot{V}_0} - 4\sqrt{\varepsilon\pi g' h_{min}^3}\right]^2 \qquad (11)$$

This is approximately twice the size of the area that can be sustained by a source of strength $\dot{V}_0$ and hence should be reconsidered a mathematical artifact. The slick will break up and shrink until its area is just enough to balance the volume removed by burning with the volume added by the leakage. For a leaking source that is long compared to the

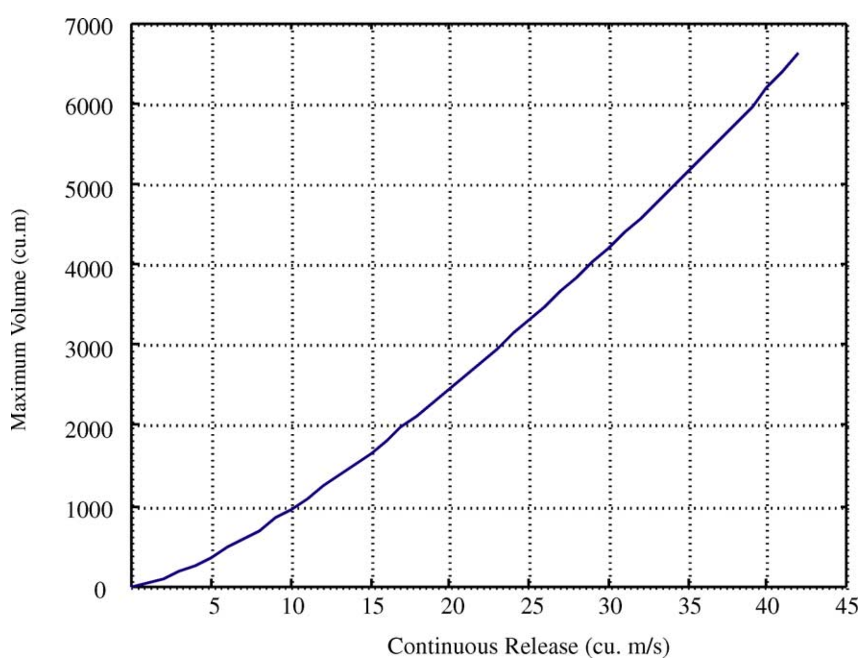

Fig. 2. Maximum volume of LNG on the water vs. spill rate for a burning pool-fire.

time of the burn, the final area, A_f, is

$$A_f = \frac{\dot{V}_0}{\dot{h}} \tag{12}$$

which represents a practical estimate for the size of the slick.

3. Evaporation

Even if the spilled oil or LNG does not ignite immediately, the liquids will still be subject to removal by evaporation. LNG is typically composed of approximately 95% methane, with the remaining percentage a mixture of ethane and other higher hydrocarbons. Since methane has a boiling point of 112 K, it will flash boil when it comes in contact with water. Assuming that the water body is adequately large to act as a vast heat source, the interfacial turbulence between the LNG and water should be sufficient to keep the water–LNG temperature difference approximately constant. The mass evaporation rate per unit area, $\dot{m}_{\text{evap}}$, is given by

$$\dot{m}_{\text{evap}} = \frac{h_e \, \Delta T}{L} \tag{13}$$

where L is the specific latent heat of vaporization, h_e is a heat transfer coefficient, and ΔT is the temperature difference between the LNG and water. Opschoor [6] suggests a typical mass evaporation rate of about 0.05 kg/(m^2 s). The NG vapors will form a flammable cloud above the LNG slick. Dilution of this cloud will depend on specific atmospheric conditions. The remaining liquid will continue to be fractionally enriched by the non-methane hydrocarbons. Conrado and Vesovic [8] point out that eventually the slick will transition from a methane-dominated, film boiling regime to an ethane-dominated, metastable, transitional regime. This will reduce the evaporation rate. Nevertheless, the vapor above such a slick should still be considered a fire risk.

The fire risk from fuel oil spills is another matter. The evaporation rate is much less than LNG and the proportionally higher evaporative loss of the volatile components over other components can play a factor in assessing the flammability risk. While the results of evaporation are well known, the dominant physical mechanisms are still a matter of discussion among experts in the field [17,18]. Nevertheless, it is generally agreed that the volatile components are more rapidly depleted than others in the hydrocarbon mixture that comprises a typical fuel oil.

The US *Code of Federal Regulations* grades transported liquid fuels according to their flash point. Any liquid with a flash point greater than 80 °F (26.7 °C) is considered non-flammable. Diesel and heavier fuel oils have initial flash points higher than this value. However, according to a study by Jones [19], about 85% of a gasoline spill must evaporate before it weathers to a nonflammable liquid. Therefore, it seems prudent to consider gasoline spills, particular confined spills, as a potential fire risk.

4. Emissive power and smoke generation

For the large fires discussed in this paper, the solid-flame radiation model is the most widely used. This model assumes a cylindrical flame equal in area to the circular slick. The flame is assumed to radiate uniformly over the cylinder's entire surface, mostly in the visible range. Because of their size, fires from large spills are considered to be optically thick. The incident thermal radiation, I, is a product of the average emissive power at the flame surface, E_{av}; an atmospheric transmissivity factor, τ; and a geometric view factor, F.

$$I = E_{\text{av}} F \tau \tag{14}$$

When LNG burns, it produces minimal amounts of smoke, although large LNG fires, such as those discussed in this paper, will show some smoke dampening [20]. The maximum emissive power of LNG is reported to be in the range of 200–270 kW/m^2 [11,21]. Due to the smoke dampening, the actual surface emissive power falls off as the burning slick size grows larger, thus the lower emissive power value is probably more appropriate for large fires.

Mudan [20] determined that smoke generation rapidly increases when the carbon to hydrogen ratio exceeds 0.3. This would not be the case for fresh LNG but certainly would be for fuel oils, particularly for intermediate and heavy fuel oils. The burn regression rate for such oils was discussed earlier. Some controversy exists over the mass fraction of oil, Y, which is turned into smoke. Fraser et al. [22] noted that the fraction increases with increasing slick size and suggested the correlation (MKS units)

$$Y = 0.1 + 0.03 \log_{10}(2\,r) \tag{15}$$

However, results from an experimental burn off the coast of Newfoundland showed a slightly larger smoke yield than predicted by Eq. (15) [23].

The smoke emission rate can be determined by calculating the burn volume rate of oil times the emission fraction. The resulting plume will be driven by two factors, the smoke generation process itself and the heat produced by the fire, which provides buoyant lift to the smoke plume and determines, along with atmospheric stability and wind speed, the terminal height of the smoke. Two common models used to predict smoke plume trajectories are the Brigg's bent-over plume model [24,25] which provides an analytical estimate, and the ALOFT model [26], which uses a numerical approach. Both models often show that the smoke plume generates a minimal health risk except very near the burn site, although individual circumstances vary. Barnea et al. [27] note that monitoring of planned oil slick burns for smoke concentrations is feasible if health risks are a factor.

The smoke from burning oil will dampen the radiation effects of the fire since the thermal radiation from black smoke is low, around 20 kW/m^2. This dampening is intermittent, as the generated smoke may sometimes clear, allowing radiation from the flames to escape. Mudan [20] suggests fractionally combining the thermal radiation from the luminous spots and the black smoke to get an average emissive power estimate. The SFPE Handbook [11] combined liquid pool-fire data for gasoline, kerosene, and JP-5 and suggests the following correlation to determine average emissive power, E_{av}, of large, sooty hydrocarbon fires:

$$E_{av} = E_m e^{-2Sr} + E_s(1 - e^{-2Sr}) \quad (16)$$

where the maximum emissive power of the luminous spots, E_m, is 140 kW/m^2, the emissive power of smoke, E_s, is 20 kW/m^2, the pool radius is r, and a parameter determined from experimental data, S, is 0.12 m^{-1}. For the large pool-fire considered in this paper, this method yields an emissive power estimate considerably lower than the LNG results.

While virtually all of the LNG slick will be consumed in the pool-fire, the fuel oil slick will cease combustion before all the oil is burned, leaving a residue of mostly unburned oil with some of the more volatile fractions removed [28]. In some instances, this residue is reported to become negatively buoyant and sink. The factors that would make this happen for certain fuel oil fires and not for others are not completely understood [28].

5. Flame geometry and atmospheric transmissivity

The view factor, F, is calculated assuming the pool-fire's flame is shaped as a vertical placed cylinder [29] with the flame height L_f representing the cylinder height. Flame height for such a fire is often estimated using some form of the Thomas equation [30]

$$L_f = C_T r \left(\frac{\dot{h} \rho_l}{\rho_{air} \sqrt{2gr}} \right)^{0.61} \quad (17)$$

Table 1
Relationship between visibility, atmospheric condition, and absorption coefficient

Reference	Visibility (km)	Atmospheric condition	k
[31]	40–80	Clear to very clear	0.1–0.003
[31,32]	20	Clear	0.2–0.4
[21]	10	Light haze	0.4
[21,31,32]	4–5	Haze	1.0
[21,31,33]	<2	Foggy, smoky, thin fog	0.4–2.0

where ρ_{air} is the air density. The correlation term, C_T, is sometimes expressed as a weak function of the wind speed. However, it must be noted that the correlation in Eq. (17) is based on small-scale pool-fires. Extrapolating to larger burns, as discussed in this paper, increases uncertainty in the model predictions.

Thermal radiation transmitted from a pool-fire to an object can be reduced considerably due to absorption and scattering from the atmosphere. Based on work of thermal radiation transmitted from a nuclear bomb explosion, Glasstone and Dolan [31] indicate the attenuation by the atmosphere, τ, due to absorption, is given by

$$\tau = \exp(-kx) \quad (18)$$

where x is the distance from the pool-fire to an object, and k is the absorption coefficient. Lees [21] provides a literature review of values for attenuation coefficients based on atmospheric conditions (Table 1).

6. Example 500 m^3 instantaneous spill

An idealized example of a 500 m^3 instantaneous spill with accompanying ignition source illustrates some of the ex-

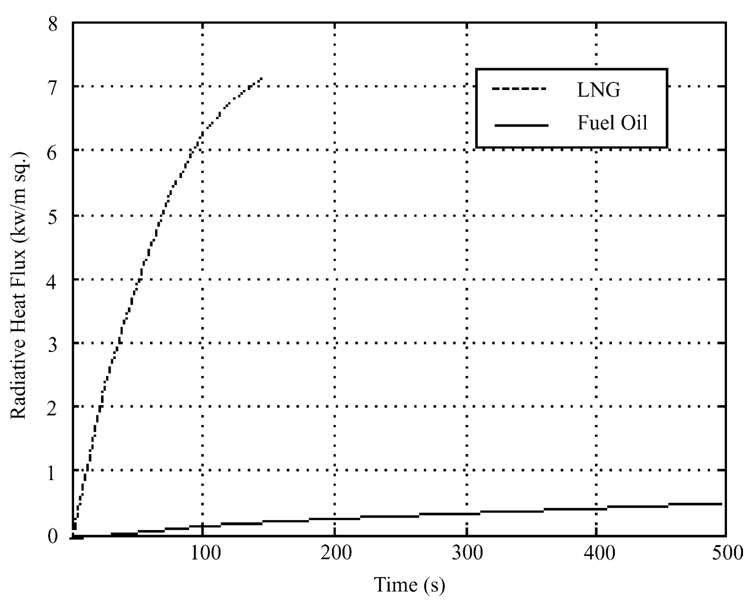

Fig. 3. Average radiative heat flux at 500 m from pool edge for a 500 m^3 release of LNG and fuel oil.

pected differences between pool-fires of LNG or a light fuel oil (API = 32). The volume of $500\,m^3$ is large but not unreasonable for an LNG vessel, in which a single tank can contain as much as $25{,}000\,m^3$. Assuming that the liquid is released instantaneously is, of course, an idealization. Some leakage time would be involved no matter how large the hole in the damaged container.

Calculation of the radial spread velocity for either LNG or the fuel oil shows a velocity after a few seconds of less than 1 m/s, followed by a rapid deceleration as the slick continues to spread, but at a slower rate. This rate compares with a horizontal flame spread rate for LNG of several times this speed [13]. Presumably, a similar case would hold for the fuel oil fire. Therefore, we can assume a cylindrical flame equal in area to the circular spreading slick.

The maximum burn time of the LNG would be around 2–3 min, leaving little residue on the water. The fuel oil fire would burn more slowly, on the order of 8 min, leaving a residue of approximately 6–7 percent of the initial volume, assuming a 1-mm-residue thickness. Fig. 3 shows the average emissive power for a hypothetical instantaneous release of $500\,m^3$ of LNG and fuel oil under clear atmospheric conditions.

We must stress that this calculation is based on the idealizations of instantaneous release and uniform thickness. Actual fuel oil spills would spread out on the edges to a thin sheen, which would not burn but would evaporate. The LNG pool-fire would have a somewhat smaller radius and would not form an idealized flame cylinder. The model output values are probably too high, reflecting the simplifications used in the model. For example, at maximum radius and flame height, the radiation fraction of combustion energy for the LNG pool-fire is calculated as 0.21. Based upon experimental results [13], we would anticipate a somewhat smaller value for a real fire. However, the qualitative difference in radiative output between the LNG and fuel oil fire remains.

7. Final comparisons and conclusion

The preceding analysis demonstrates the likely similarities and differences between vessel accidental releases of sizable quantities of different hydrocarbon fuels, their subsequent spreading, and possible pool-fire behavior. If there is no immediate ignition source, both LNG and fuel oil spills will spread and evaporate. If the initial spill is large enough, there may be a transition to gravity–viscous spreading. Unlike the typical oil spill, the LNG will evaporate rapidly, creating a flammable atmosphere above the slick, and stop spreading while the LNG slick is relatively thick. Oil will spread thinner and is not likely to create a fire hazard except for very light fuel oils such as gasoline.

If there is an ignition source at the beginning of the spill, neither fuel oil nor LNG will spread beyond the gravity–inertial phase. For a long continuous leak, the maximum volume on the water will not coincide with the maximum slick area. For operational purposes, the estimated area of the slick will be such that the amount burned equals the amount leaking. LNG will burn quicker and hotter than a fuel oil fire [11]. While LNG pool-fires are relatively smoke-free, fuel oil fires typically produce enough smoke to reduce the radiation effects from the fire. Thus, an LNG pool-fire will likely have a somewhat smaller area and burn quicker, cleaner, and with considerably more thermal radiation than a comparable volume of fuel oil.

Disclaimer

The conclusions and results of this paper do not necessarily reflect the official views of the National Oceanic and Atmospheric Administration or any other agency of the US Government.

References

[1] P. Bao-Kang, Analysis of significant oil spill incidents from ships, 1976–1985, in: Proceedings of the 1987 Oil Spill Conference, American Petroleum Institute, Washington, DC, 1987, pp. 43–47.
[2] J.A. Fay, The Spread of Oil slicks on a Calm Sea, Fluid Mechanics Laboratory Report, Department of Mechanical Engineering, MIT, Cambridge, Mass., 1969.
[3] P.G. Jeffery, Large scale experiments on the spreading of oil at sea and disappearance by natural factors, in: Proceedings of the Joint Conference on Prevention and Control of Oil Spills, American Petroleum Institute, Washington, DC, 1973, pp. 469–474.
[4] W.J. Lehr, H.M. Cekirge, R.J. Fraga, M.S. Belen, Empirical studies of the spreading of oil spills, Oil Petrochem. Pollut. 2 (1984) 7–12.
[5] D.P. Hoult, Oil spreading on the sea, Ann. Rev. Fluid Mech. 4 (1972) 341–368.
[6] G. Opschoor, Investigations into spreading and evaporation of LNG spilled on water, Cryogenics (1977) 629–633.
[7] F. Briscoe, P. Shaw, Spread and evaporation of liquid, Progr. Energy Combust. Sci. 6 (1980) 127–140.
[8] C. Conrado, V. Vesovic, The influence of chemical composition on vaporization of LNG and LPG on unconfined water surfaces, Chem. Eng. Sci. 55 (2000) 4549–4562.
[9] M.A. Serag-Eldin, Computation of NG spread following very large LNG spills from ship tankers, Appl. Math. Model. 12 (1988) 238–248.
[10] F.T. Dodge, J.T. Park, J.C. Buckingham, R.J. Magott, Revision and Experimental Verification of the Hazard Assessment Computer System Models for Spreading, Movement, Dissolution, and Dissipation of Insoluble Chemicals Spilled onto Water, Report No. 06–6285, Southwest Research Institute, San Antonio, TX, USA, 1983, 190 pp.
[11] SFPE Handbook of Fire Protection Engineering, second ed., National Fire Protection Association, Quincy, MA, USA, 1995, pp. 3/197–240.
[12] B. Otterman, Analysis of large LNG spills on water, Cryogenics (1975) 455–460.
[13] P.K. Raj, K.S. Mudan, A.N. Moussa, Experiments Involving Pool and Vapor Fires from Spills of LNG on Water, Report # CG-D-55–79, NTIS AD077073, US Coast Guard, 1979.
[14] National Oceanic and Atmospheric Administration, Hazardous Materials Response Division, unpublished internal note, 2001.
[15] J.M. Chatris, J. Quintela, J. Folch, E. Planas, J. Arnaldos, J. Casal, Experimental study of burning rate in hydrocarbon pool fires, Combust. Flame 126 (2001) 1373–1383.

[16] ExxonMobile, Oil Spill Response Field Manual, ExxonMobile Research and Engineering Company, USA, 2002.
[17] W.J. Lehr, Review of modeling procedures for oil spill weathering behavior, in: C.A. Brebbia (Ed.), Oil Spill Modeling and Processes, WIT Press, Southampton, UK, 2001, pp. 51–90.
[18] National Research Council, Committee on Oil in the Sea, Chapter 4, Oil in The Sea III: Inputs, Fates, and Effects, National Academy Press, Washington, DC, 2002.
[19] R. Jones, Effects of Weathering on the Flammability of Oils, Report No. CG-04000, United States Coast Guard Research and Development Center, Groton, CT, USA, 1999, 25 pp.
[20] K.S. Mudan, Thermal radiation hazards from hydrocarbon pool fires, Progr. Energy Combust. Sci. 10 (1984) 59–79.
[21] F.P. Lees, Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control, second ed., vol. 2, Butterworth-Heinemann, Oxford, Great Britain, 2001.
[22] J. Fraser, I. Buist, J. Mullin, A review of the literature on soot production during in situ burning of oil, in: Proceedings of the 20th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, Environment Canada, Ottawa, Canada, 1997, pp. 1365–1405.
[23] W.D. Walton, W.H. Twilley, J. McElroy, D.D. Evans, E.J. Tennyson, Smoke measurements using a tethered miniblimp at the Newfoundland Offshore Oil Burn Experiment, in: Proceedings of the 17th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, Environment Canada, Ottawa, Canada, 1994, pp. 1083–1098.
[24] M.T. Mills, Modeling the release and dispersion of toxic combustion products from chemical fires, in: J. Woodward (Ed.), Proceedings of the International Conference on Vapor Cloud Modeling, American Institute of Chemical Engineering, New York, 1987, pp. 801–816.
[25] W. Lehr, R. Overstreet, Smoke plume screening tool for in situ burning, in: R. Garcia-Martinez, C.A. Brebbia (Eds.), Oil and Hydrocarbon Spills, Modelling, Analysis, and Control, WIT Press, Southampton, UK, 2001, pp. 121–132.
[26] K.B. McGrattan, W.D. Walton, D.D. Evans, Smoke plumes from in situ burning of crude oil, in: Proceedings of the International Oil Spill Conference, American Petroleum Institute, Washington, DC, 1999, pp. 137–147.
[27] N. Barnea, C.B. Henry, P. Roberts, R.R. Laferriere, Monitoring of in situ burning operations, in: W. Walton, N. Jason (Eds.), Proceedings of the In Situ Burning of Oil Spills Workshop, National Institute of Standards and Technology, Gaithersburg, MD, 1998, pp. 67–73.
[28] M. Fingas, In situ burning of oil spills: a historical perspective, in: W. Walton, N. Jason (Eds.), Proceedings of the In Situ Burning of Oil Spills Workshop, National Institute of Standards and Technology, Gaithersburg, MD, 1998, pp. 55–61.
[29] American Institute of Chemical Engineers (AICHE), Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVE's, AICHE, Center for Chemical Process Safety, New York, 1998, 387 pp.
[30] L.E. Brown, H.R Wesson, J.R. Welker, Predict LNG fire radiation, Hydrocarbon Process. (1974) 141–143.
[31] S. Glastone, P.J. Dolan, The Effects of Nuclear Weapons, third ed., Tonbridge Wells, Castle House, 1977.
[32] D.A. Lihou, J.K. Maund, Thermal radiation hazards from fireballs, The Assessment of Major Hazards, Rugby: Inst. Chem. Eng. (1982) 191.
[33] I. Hymes, in: J.I. Petts (Ed.), The Effects on People and Structures of Explosion, Blast, Thermal Radiation and Toxicity, 1984.