ESTIMATING LNG SPREADING ON WATER[1]

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In order to meet the growing demands for energy, plans are currently being made to construct several new liquefied natural gas (LNG) off-load terminals in North America. While LNG provides a relatively clean source of fuel, increased shipment means increased potential for accidental releases. Governmental agencies have recognized the safety concerns about such a possible spill event and have recommended the proactive and preemptive addressing of such concerns.

Several recent studies have examined the likely thermal and other hazards from an LNG vessel accident. One possible threat from such an incident is a pool fire, which could be quite large since the volume of a single tank on an LNG vessel can contain as much as 25,000 m of liquefied gas. In general, there is agreement in the literature on the pool fire geometry, burn regression rate, and thermal emissive power of the fire but less concurrence on possible tank leak rate or surface spread rate on water.

The authors review the existing approaches to this latter phenomenon for unconfined spills. Comparison of model predictions with limited experimental data is also discussed.

For low wave conditions, two methods, one by Fay and the other by Weber , have been the most widely used in past models, sometimes with modifications that are discussed in the paper. Similarly, two alternative algorithms have recently been suggested for high wave conditions. The authors review the merits of these two approaches, the expected consequences from each approach, and finally compare them to widely used oil spill spreading formulas under energetic wave conditions.

INTRODUCTION

While there are currently only four operating liquefied natural gas (LNG) import terminals in the United States, as many as a dozen new ones are in various stages of planning. While LNG provides a relatively clean source of fuel, increased shipment means increased potential for accidental or deliberate releases. Governmental agencies have recognized the safety concerns about such a possible spill event and have recommended the proactive and preemptive addressing of such concerns.

Havens (2004) has determined that the greatest hazard from LNG releases is thermal radiation from pool fires on the surface of water or on land. However, he notes that much of the research on pool fires dates from the 1970's when the existing terminals were built (G. Opschoor, 1977; B. Otterman, 1975). While LNG has been transported by sea since 1959, by marine standards it is still a relatively new marine carriage with little past spill history. There have been no experiments of LNG pool fires larger than 10,000 gallons while a typical LNG vessel may have the a capacity of as much as 33 million gallons.

SPILL LEAKAGE

Recently the authors and others (Lehr and Simecek-Beatty, 2004; Fay,2003; Quest, 2001) have re-examined the likely mechanics of a LNG pool fire on water. It could be quite large since the volume of a single tank on an LNG vessel can contain as much as 25,000 m of liquefied gas. ABS consulting (2004) has determined that for a hole diameter of 5 m. just above the waterline, the initial spill rate for a LNG carrier could be as large as 130,000 kg/sec. Depending upon the nature of the leak scenario, the leak rate should drop quickly (Simecek-Beatty et al., 1997). For large holes, it is possible that a partial vacuum could be created in the tank due to the rapid removal of the LNG. Air ingestion through the hole to balance the pressure difference in the tank would slow the release rate. ABS Consulting, assuming straight gravity flow, estimates that as much as 12,500 cubic meters could leak out in less than ninety seconds. However, Pitblado (2004) has concluded that the maximum credible hole size, even for a deliberate attack on an LNG carrier, would be more likely around one and half meters with enough energy generated to cause immediate ignition. Whether the resulting pool fire would compromise the integrity of the whole vessel remains a question that is beyond the scope of this paper. Figure 1 shows the expected initial flow rate for round hole of different diameters 13 m. below the LNG level in the tank.

WHY POOL SIZE MATTERS

Most pool fire models assume a cylindrically shaped solid flame for the pool fire. The height of the cylinder is often calculated using some version of the Thomas equation (1961). This typically has the length of the flame proportional to the diameter of the pool fire raised to the seven tenths power. The total emitted thermal radiation is proportional the surface area of the flame. For the cylindrical part, the surface area is linearly proportional to the circumference of the pool fire. While the calculation of the received radiation to some object on the ground from the fire depends upon the distance and relative orientation with the cylinder

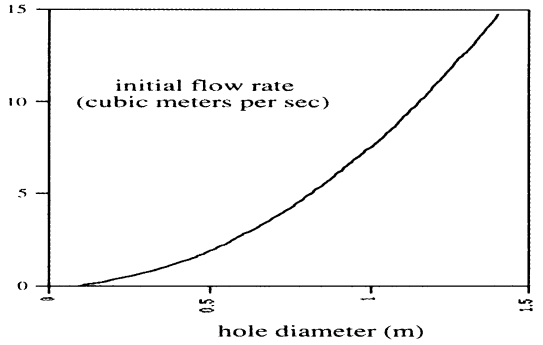

FIGURE 1 INITIAL RELEASE RATE FOR A ROUND HOLE 13 M. BELOW THE LEVEL OF LIQUID IN THE TANK BUT ABOVE THE WATER LINE.

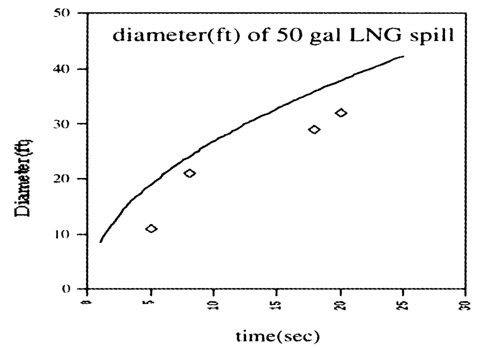

FIGURE 2 THEORETICAL DIAMETER COMPARED TO MEASURED VALUES FOR 50 GAL LNG SPILL.

of the receiving surface, in general we can approximate that the received radiation R_{therm} will increase roughly as $R_{therm} \alpha R^{1.7}$, where R is the radius of the pool fire. This implies a strong dependence between received radiation and pool size, noting, of course, that both the solid flame cylinder assumption and Thomas equation are approximations that may not hold for large incidents.

SPREADING ON CALM WATER

In comparison to the pool fire geometry, burn regression rate, and thermal emissive power of the fire, there is less concurrence on surface spread rate on water. Most modelers use a version of the famous Fay spreading formulas (Fay, 1971). In the Fay approach, the spill is idealized as a circular pool of relatively uniform thickness. The driving-retarding forces fall into three time-dependent categories. Initially, gravity-inertial forces dominate spreading, followed by gravity-viscous, and finally by surface tension-viscous forces. While most models for LNG spills consider only the first category, Lehr and Simecek-Beatty (2004) showed that, for large LNG spills (larger than 200 cubic meters for an instantaneous release) with delayed ignition, there is a theoretical possibility for a transition to gravity-viscous spreading. In the absence of any actual large spill events, it is impossible to know if this would actually happen.

For the gravity-inertial phase, the radial spread velocity is proportional to the square root of the average thickness of the slick,

$$\frac{dR}{dt} = \sqrt{2g\frac{\rho_w - \rho_{LNG}}{\rho_w} \cdot h} \tag{1}$$

Here, R is the radius of the LNG pool, ρ_w *is* the water density, ρ_{LNG} is the LNG density, h is the average thickness, and g is the gravitational constant. Figure 2 shows the theoretical diameter using equation 1 of an instantaneous 50 gallon LNG spill compared to actual measured values by Burgess et al. (1970)

Theory somewhat overestimates the pool size, probably due to the idealization of an instantaneous release, mass loss due to evaporation, and frictional affects. Webber (1990) suggests modifying equation 1 to include frictional effects

$$\frac{d^2R}{dt} = \frac{4gh}{R} - K\left(\frac{dR}{dt}\right)^2 - F(\frac{dR}{dt}, h, \nu_{LNG}, \nu_w) \tag{2}$$

where K is an empirically determined constant and F is a function of thickness, radial spread velocity and ν_{LNG}, ν_w, the corresponding viscosities of LNG and water. If the two last terms on the right hand side are set to zero, the remaining terms can be integrated to yield Equation 1. These two terms represent, respectively, the resistance force of the water on the circumference of the spreading LNG and the friction at the water-LNG surfaces. ABS consulting (2004) determined that for some cases, inclusion of the frictional affects had a significant difference in the maximum size of the pool radius, particularly in the instantaneous or near instantaneous circumstance. For example, a 12,500 cubic meter spill through a 5 m. diameter hole with initial liquid 13 m. above the hole, the non-frictional case gave a maximum pool diameter of 240 m. while with frictional case, the diameter was 130 m.

However, this equation is computationally troublesome. Moreover, Equation 2 leads to an early solution that is proportional to the solution of Equation 1. Therefore, the authors recommend a pragmatic approach similar to that of Conrado and Vesovic (2000) where the form of equation 1 is retained but a suitable scaling parameter is used to adjust the area size based on experimental data. This presumes sufficient future experiments on larger LNG releases.

Raj and Kalekhar (1974) derived a different spreading relationship based on the fact that the inertia of the entire pool is a fraction of that given by using the acceleration of the leading edge, as done in the Fay approach. However, Otterman (1975) indicates that these methods give similar results.

The spilled LNG will keep spreading until it either all evaporates (or burns if ignited) or it reaches a minimum thickness. This thickness is quite large compared to the spreading of spilled oil. Opschoor (1977), based on earlier studies, recommends a minimum average thickness of 0.17 cm for an LNG slick.

For the more realistic case where an instantaneous release is replaced by a leak over time, the leak rate from the vessel is likely to control the eventual size of the LNG slick with mass losses due to evaporation or burning from the LNG slick just balancing the spill rate from the vessel. Mudan (1984) provides a critical leakage time versus spill size to classify a spill as instantaneous or continuous. Spills that take longer than a size-sensitive critical time (see Figure 3) should, according to Mudan, be modeled as continuous releases since in such cases the leak rate will control the maximum area of the pool. However, there will be a brief period of overshooting where the area exceeds the coverage that can be supported by the leak rate (Lehr and Simecek-Beatty, 2004)

Spreading of LNG under wind and wave conditions.

Quest Consultants (2003) and Fay (2004) have recently looked at the affects of surface waves on LNG spreading. Quest, by assuming that the water surface could be modeled by simple cycloid process, believes that the dimensions of the LNG slick would be greatly reduced by waves. For example, an instantaneous 10,000 cubic meter spill of non-burning LNG would, according to the Quest analysis, make a slick of 253 meter radius in calm waters but only 67 meters in two foot waves. According to this model, the LNG will stop spreading when the volume of the LNG in any

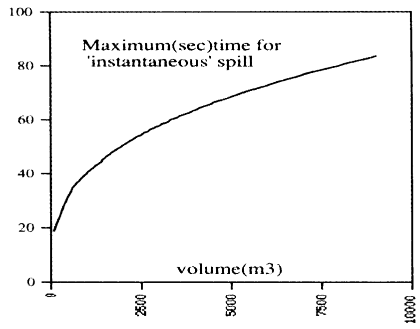

FIGURE 3 MAXIMUM TIME FOR A LNG POOL FIRE SPILLAGE TO BE CONSIDERED 'INSTANTANEOUS'.

wave trough drops below 50% of the trough's capacity. At this point, the model assumes that the LNG layer is not tall enough to overcome the wave and thus ceases to spread radially.

Fay disagrees with this conclusion. Estimating the reflecting energy of an incident wave on the edge of a LNG slick, he calculates a critical thickness where spreading will cease due to wave impact. According to Fay, this critical thickness will be about two orders of magnitude smaller than the average wave height. If we use Opschoor's minimum thickness value of 0.17 cm, then waves of 17 cm. or less would have no affect on maximum area of the slick, However, according to Fay, even much larger waves will have a negligible impact on the final size of the slick. For a 10,000 cubic meter spill in one meter high waves, Fay's approach predicts less than a one percent correction to slick size.

The authors suggest that experience with oil spills under wind and wave conditions indicates how a large LNG spill would likely behave. When a neutrally buoyant dye is dropped onto the water surface, the dye begins to disperse due to water turbulence. Presumably this same phenomenon would cause the dispersion of positively buoyant LNG. Elliot and Hurford (1989) suggest that this process can be modeled by using a non-Fickian diffusion process where the diffusion parameter is a weakly increasing function of time. As in the case of an oil slick, this might cause the LNG slick to break up into patches. The model of a single burning cylinder for a pool fire may have to be replaced by several smaller cylinders.

Lehr et al (1984) recorded that oil spills tend to elongate along the direction of the wind with the thicker oil in the downwind direction (Figure 4).

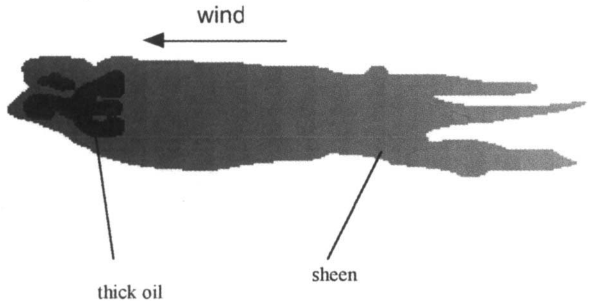

FIGURE 4 PROCESSED IMAGE OF 50 BBL ARABIAN CRUDE OIL SPILL

Elliot et al (1986) speculated that the 'comet' shape was due to submerging of the slick due to waves and differential surfacing of the resulting oil drops. The bigger droplets would be expected to resurface faster than the smaller ones. Such a scenario for LNG is more complex to analyze because LNG is a cryogenic fluid. LNG dispersed into droplets will have more surface area exposed to the relatively hot water than would a simple surface layer of LNG. This should lead to a more rapid phase transition and increased natural gas vapors above the slick.

One factor that is important in oil spreading that would not probably be important for LNG spills on water is the formation of wind rows due to Langmuir circulation. LNG slicks on water are too short lived, on the order of minutes or less, for this phenomena to alter their shape significantly.

BIOGRAPHY

Merv Fingas is Chief of the Emergencies Science Division in Environment Canada. Dr. Fingas' specialty is research in the analysis and behavior of oil spills in the environment. He manages 35 other scientist and staff studying various aspects of oil and chemical spills. He has over 350 publications in the field.

REFERENCES

ABS Consulting, 2004. Consequence Assessment Methods for Incidents Involving Releases from Liquefied Natural Gas Carriers, Report to Federal Energy Regulatory Commission, 59 pp.

Burgess, D. S., J.N. Murphy, and M. G. Zabetakis, 1970. Hazards associated with the spillage of liquefied natural gas on water. Report No. 7448, U. S. Bureau of Mines.

Conrado, C. and V. Vesovic, 2000. The influence of chemical composition on vaporization of LNG and LPG on unconfined water surfaces, *Chemical Engineering Science* **55**:4549-4562.

Elliot, A.J., N. Hurford, and C.J. Penn, 1986. Shear Diffusion and the Spreading of Oil Slicks, *Marine Pollution Bull.*, **17**:308-313,

Elliot A.J. and N.Hurford, 1989. The influence of wind and wave shear on the spreading of a plume at sea, *Oil & Chemical Pollution* **5**: 347-363.

Fay, J. A. 2003, Model of spills and fires from LNG and oil tankers. *Journal of Hazardous Materials*, B96:171-188.

Fay, J. A., 2004. Response of oil pools to ocean waves, *Journal of Hazardous Materials*, to appear.

Fay, J.A., 1971. Physical processes in the spread of oil on a water surface. *Proc. of the Jount Conf. on Prevention and Control of Oil Spill*, American Petroleum Institute: Washington, DC, pp. 463-467.

J. Havens, 2004. Terrorism: Ready to blow?, *Bulletin of Atomic Scientists*, 59:16-18.

Lehr, W.J., R.J Fraga, M.S. Belen, and H.M. Cekirge, 1984. A New Technique to Estimate Initial Spill Size Using a Modified Fay-Type Spreading Formula, *Marine Pollution Bull.*, **15**:326-329.

Lehr, W. J. and D. Simecek-Beatty, 2004, Comparison of hypothetical LNG and fuel oil fires on water, *Journal of Hazardous Materials*, **107**:3-9.

Mudan, K.S., 1984. Thermal radiation hazards from hydrocarbon pool fires, *Progress in Energy and Combustion Science*, **10**: 59-80.

G. Opschoor, 1977. Investigations into spreading and evaporation of LNG spilled on water, *Cryogenics* 629-633.

B. Otterman, 1975. Analysis of Large LNG spills on water, *Cryogenics* 455-460.

Pitblado, R.M., J. Baik, G. J. Hughes, C. Ferro, S. J. Ferro, and S. J. Shaw, 2004. Consequences of LNG Marine Incidents, CCPS Conference, Orlando, June 29- July 1, 2004.

Quest Consultants, 2001. Spill and Thermal Radiation Calculations for Tanker Cargo Releases, Letter to Distrigas of Massachusetts.

Quest Consultants, 2004 Modeling LNG Spills in Boston Harbor, Report to Department of Energy,24 pp.

Raj, P. K., and A.S. Kalelkar, 1974. Assessment Models in Support of the Hazard Assessment Handbook, Technical Report No. CG-D-65-74, U. S. Coast Guard, NTIS AD776617.

Simecek-Beatty, D. A., W.J., Lehr, and J.F. Lankford, 1997. Leaking tankers: how much oil was spilled? *Proc. of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada: Ottawa, Canada, pp. 841-852.

Thomas, P.H., 1961.The size of flames from natural fires, *Combustion*, **9**, p.844.

Webber, D.M. , 1990. Source Terms, *Journal of Loss Prevention Process Ind.* **5**:5-15.

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