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Predicted Impact of Spilled Liquefied Natural Gas from Nigeria Liquefied Natural Gas Plant on its Host Water Areas

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Abstract: Spilled Liquefied Natural Gas (LNG) on water could be dangerous if not properly handled because of its cryogenic nature and this always necessitates quantification of dangers associated with such in marine transportation. Potential spills from Nigerian Liquefied Natural Gas (NLNG) plant located on the western coast of Bonny Island in Niger Delta area of Nigeria and their impacts on the host water were considered in this study. Simulations were carried out for different spill masses and vaporization rates established. In addition, radiation flux zone for a thermal flux of 5 kW m^{-2} (set limit for human tolerance) on the host environment was investigated. The percentage fatality of the host communities was established based on this limit. Simulated period for the smallest spill mass (70,000 kg) to vaporize is 128 sec. This mass could attain a maximum radius of 75 m with vaporization rate of 547 kg s^{-1}. For the largest spill mass (14,500,000 kg, about a full tank load), simulated period of vaporization is 466 sec. with a maximum radius of 257 m and vaporization rate of 6,620 kg s^{-1}. Bonny and Finima, the major towns around the Plant fall within the 5 kW m^{-2} allowable thermal flux for humans but the percentage fatality for this (in case of accident) on the host communities was predicted to be zero.

Key words: Spills, liquefied natural gas, vaporization, radiation flux, environment

INTRODUCTION

For improvement of air quality in the Niger Delta Area of Nigeria, reduction of air pollution through elimination of routine flares is being vigorously pursued. One of the existing ways to accomplish this is the liquefaction of associated gas at Nigeria Liquefied Natural Gas plant for export.

This Liquefied Natural Gas Plant located in Bonny Island in the Southern part of the country (Western Coast of Bonny Island, Rivers state, Nigeria) is the largest natural gas utilization project in Nigeria[1]. It is jointly owned by Agip (10.4%), NNPC (49%), Shell (25.6%) and TotaFinaElf (15%). Trains 1 and 2 of the $3.8 billion plant began operating in September 1999, supplying liquefied natural gas to markets in Europe and the US. The company processes about 20 million m^3 of natural gas per day with associated gas accounting for just about 30%. Later, it is anticipated that associated gas inputs will increase to 50%. In November 2002, the third train began operations. This has increased overall processing capacity to about 30 million m^3/day. An additional 2 trains set to be in operation by the end of 2005, providing 28 million m^3/day extra production capacity. The Island is relatively flat with Mangrove, freshwater swamp forest and dry land rainforest as the vegetation. Two major towns located therein are Bonny and Finima with population of 46368 and 22980, respectively[2].

LNG is a clear, colourless and odourless cryogenic liquid at a temperature of 112 K at atmospheric pressure but could be hazardous in handling[3]. When it spills on water, it floats since it weighs 424.1 kg m^{-3} compared to 1000 kg m^{-3} for water. It is predominantly made up of methane with a flammability range lying between 5 and 15% concentration in air by volume[4]. LNG can cause freeze burns if it touches the skin and while landing on water, it can spread out to receive heat from the water surface which makes it to vaporize simultaneously[5]. Usually, the spread of LNG on water is initially affected by gravity-inertial forces later by gravity-viscous forces and finally by surface tension viscous forces[6].

Impacts of LNG spill on water and the environment are numerous. Being a cryogenic liquid with a temperature of about 112 K when spilled on water, there could be a sharp drop in temperature of the surrounding water body to some distance below the surface; this could result in an unbearable condition for the aquatic life and also the flora around the spill site. Bybee[7] reports the latest

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developments in rapid phase transition (RPT), a phenomenon associated with LNG on water. LNG contact with water results in a very high rate of vaporization such that explosions called RPT can occur. These RPT can generate air and underwater blast pressures that could damage ship and adjacent plants or structures, lead to serious accidents and disrupt the aquatic life habitat. The RPT phenomenon is part of the safety context of LNG facilities and is usually considered from the design stage of the LNG site and adjoining facilities of the host environment. Shock waves resulting from RPT can break windows, produce explosions equivalent to 4.15 kg of TNT. The occurrence and strength of RPT are functions of the mixed-zone but resulting boiling characteristics depend on LNG composition[8].

Also by virtue of the cryogenic nature of LNG, physical contact with it could cause freeze injuries while the same contact with equipment could result in hazards resulting in brittle fracture on carbon and alloy steel[9]. Though natural gas (LNG at room temperature) is not known to have any toxic property, it can asphyxiate when its concentration in air is up to 82%.

LNG spills on water spread out rapidly, exposing the liquid to the air above and vaporizes rapidly (faster than an equal sized spill on land) but if ignited before vaporizing (common if spill is initiated by chemical explosion or boat bomb) the floating oil pool could burn vigorously. The time to burn spills as much as 10,600,000 kg (on the average, each LNG vessel can carry as much as 14,500,000 kg of LNG) is less than 5 min. The thermal radiation from such huge fires can be damaging to people and can set afire combustible buildings[10]. It can cause skin burns on humans exposed to the radiation or ignite wood and cellulose materials and even buildings.

Though personnel and individuals in control rooms, residential homes and other types of compartments could be exposed to just low thermal radiation levels, associated high air temperature could result in physiological effects such as difficult breathing. Attendant rapid, unbearable pain with dry skin, depending on the temperature level could be additional burden. These elevated temperatures could have influence on the pulse rates and this may climb steadily with time. It could even jump from normal 84 to 120 beats a minute when the air temperature increases to 100°C. As the temperature rises above 150°C, thermal radiation becomes the dominant factor and pathological effects could result (the different degrees of burns). Severity of an injury from heat is determined by the depth of skin to which a temperature difference of 9 K has occurred[11].

The shore at this NLNG plant site consists of a relatively flat beach before a steep drop into the central channel, about 15 m deep. The NLNG Jetty is approximately 700 m in length and it is designed to accommodate LNG carriers with a cargo load of 122,000 to 145,000 m^3. Located close to the jetty area is a passenger terminal[2].

LNG can get to the water surface due to tank failure[12] which could be from a puncture in the vessel due to collision with jetty structures[13] or other ocean going vessels or even a bomb attack, which is not unlikely due to the increasing incidence of terrorist attacks being reported widely in the Niger delta area of the country. The spill on water can also be as a result of leaks in pipes feeding onshore and offshore vessels. The vessel route on Bonny river is such that the risks involved in the transport of LNG could impact on some third party installations located on the Bonny island coast. These installations deal in large quantities of flammable materials on site. In addition to these are residential areas (which include Bonny town and new Finima community), located very close to the potential spill point of LNG on water. Other areas of concern are located far off from the Bonny river.

Though environmental studies were carried out before the commencement of construction work on the NLNG site, no thought was given to the consequences of potential spill of LNG which could occur during loading and transport on Bonny river. In this study potential dangers inherent in the spill on water (Bonny river) of LNG were studied together with its effect on the aquatic life, personnel and equipment. If ignited, the thermal radiation that could ensue with the distance to which this could go on the island was also predicted.

MATERIALS AND METHODS

To predict the effects of potential LNG spill from NLNG plant on Bonny water, three stages of the spill scenario modeled were spreading of instantaneously discharged LNG on water, heat transfer from the water body into the spreading LNG and vaporization rates of the spreading LNG. In the first stage, it was assumed that the spilled LNG gets ignited before vaporizing. Also, as the pool spreads out, it was assumed that it vaporizes simultaneously-second and third stages.

Spreading of LNG on water surface: Water surface was assumed to be flat throughout the spreading process and that the spills were instantaneous. Also, it was assumed that gravitational-inertia regime prevailed all through the spreading and vaporization process[5]. Equation 1 describes the rate of change of radius with time and it was used to model the spread of the cryogen on the water

Table 1: NLNG thermo-physical properties

Parameter	NLNG
T_{av}	203.34 K
Liquid phase density	424.1 kg m^{-3}
Vapour phase density	0.962 kg m^{-3}
Thermal conductivity	2.15×10^{-2} $Wm^{-1} K^{-1}$
Kinematic viscosity	8.2178×10^{-6} $m^2 s^{-1}$
Surface tension	0.0141 N m^{-1}
Prandtl number	0.7740
Archimedes number	8.0873×10^7
Nusselt number	75.44
Critical wavelength	0.010817
Final heat transfer coefficient	150.00 W $m^{-2} K^{-1}$
Resultant heat transfer	27.507 kJ $s^{-1} m^{-2}$

surface to determine the maximum radius that could be attained by each simulated spill mass[14]

$$\frac{dR}{dt} = 1.64\left[\frac{Mg\,(\rho_w - \rho)}{\pi \rho \rho_w}\right]^{½} \frac{1}{R} \tag{1}$$

where, M is the mass of liquid remaining in the pool (kg)
ρ and ρ_w are the densities of LNG and water, respectively (kg m^{-3})
R is the pool radius (m)
g is acceleration due to gravity (m s^{-2})
t is time (s)

Heat transfer: Since the released cryogen could instantaneously reach boiling point, heat transfer from other sources apart from the water body was neglected. This is because they account for less than 5% of the total heat transferred from the surroundings into the pool. Water evaporation was neglected too while Nigeria's LNG was assumed to comprise principally methane. The heat transferred to pool was modeled using:

$$q = h(T_W - T) = h\Delta T \tag{2}$$

where, h is the heat transfer coefficient
T_W is the water temperature (K)
T is LNG temperature (K)
ΔT is the characteristic temperature difference.

The h in the above equation is film heat transfer coefficient (since methane boils in the film boiling regime) and a correlation for boiling of pure saturated liquids on horizontal flat plate surface given by Klimenko[15] as:

$$h_f = \frac{\lambda_v N_U}{l_C} \tag{3}$$

is used where, λ_V is the thermal conductivity, N_U is Nusselt number, h_f is film heat transfer coefficient and l_C is the critical wavelength of instability given by:

$$l_C = 2\pi\sqrt{\frac{\sigma}{g(\rho - \rho_v)}} \tag{4}$$

where, ρ is the cryogen density, (subscript v indicates vapour phase of the cryogen) and σ is the surface tension.

The Nusselt number N_U is given by the following empirical correlation:

$$N_U = 0.19[ArPr]^{0.33} f_1 \qquad Ar<10^8 \tag{5}$$

$$N_U = 0.0086\,\sqrt{ArPr}^{1/3} f_2 \qquad Ar>10^8 \tag{6}$$

where, the Prandtl number, Pr, refers to the vapour phase and the Archimedes number Ar is given as:

$$Ar = (2\pi)^3 \frac{\sigma^{3/2}}{\rho_v v_v^2 \sqrt{g(\rho - \rho_v}} \tag{7}$$

where, ν is the Kinematic viscosity. f_1 and f_2 for brevity are omitted.

Factors affecting the film heat transfer coefficient (Table 1) were computed at a water temperature (T_W) of 295 K. Thermo-physical properties of LNG (i.e. methane) were estimated at its boiling temperature (T_{sat}) i.e. 111.62 K but the vapour phase thermo-physical properties were computed at the mean film temperature T_{av}[16].

Vaporization model for the spreading LNG: The vaporization of the LNG as it spreads out over the water surface was modeled by a first order differential equation:

$$V \equiv \frac{dM_v}{dt} = \frac{\pi R^2 q}{L_m} \tag{8}$$

Where, V is the vaporization rate (kg s^{-1})
M_V is the mass of liquid vaporized (kg)
q is heat transferred to the pool from the water surface (kJ $s^{-1} m^{-2}$)
L_m is Latent heat per unit mass (KJ kg^{-1})
R is Pool radius (m)
t is time for the pool to vaporize (s)

As the pool spreads out, its radius R increases with time and the cryogen vaporizes simultaneously. Therefore the spread equation (1) and the vaporization equation (8) were solved simultaneously using the following initial conditions:

$$t = 0 \qquad M = M_0 \qquad R = 0 \tag{9}$$

with R_0 taking values ranging from 1 to 1.5 depending on the mass spilled. The model equation was solved by the fourth order Runge-Kutta method. A constant value was used for h in the simulation process since it was assumed that the LNG is predominantly made up of methane. Though Conrado and Vesovic[5] claimed that representing the vaporization rate of LNG with that of methane could underestimate the vaporization rate of LNG by as much as 10-15%, this underestimation is dependent on the composition of the LNG. Due to average composition of Nigeria's LNG, this work regards it to be predominantly made up of methane.

Substitution of the initial conditions in both Equations (1) and (8) for spread and vaporization, respectively, their simplified forms become:

$$\frac{d(R_f)}{d(t)} = 0.106 \times M_0^{1/2} \times \frac{1}{R_0} \tag{10a}$$

$$\frac{d(M_f)}{d(t)} = -0.16897 \times R_0^2 \tag{10b}$$

Simulations to determine vaporization rates were carried out for different cases representing different instantaneous mass spillages.

Pool fire thermal radiation: The width of Bonny river at the thinnest point is about 2.83 km while at the entry channel to the Atlantic ocean, it measures as much as 12.7 km. Two typical spill points were considered to illustrate the pool fire impact on the host environment. The first is exactly at the NLNG jetty while the other is about 3.2 km from it and are both about 2.4 km from Bonny and Finima towns. These choices were guided by the closeness of the points to both facilities and humans on the Island. The mass spills that could produce a thermal flux of 5 kW m^{-2} (limit for human tolerance) were used in simulation. Computing the mass burning and heat release rates of different masses after which the distance at which this heat flux could be 5 kW m^{-2} was predicted did this. The percentage of the populations of the towns that could be at risk (usually death) at 5 kW m^{-2} heat flux was established using the Probit (probability) function given as[17]:

$$Pr = k_1 + k_2 \ln I^n t \tag{11}$$

Where, Pr is probit;
k_1, k_2 are constants, -14.9 and 2.56, respectively;
I is radiation intensity (kW m^{-2});
n is 4/3
t is time (s).

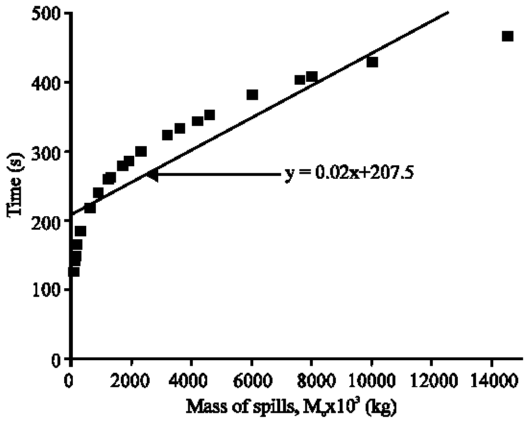

Fig. 1: Final time for spills vaporization

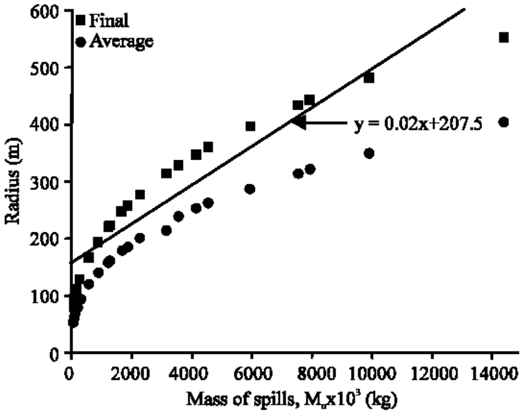

Fig. 2: Radius of LNG spills

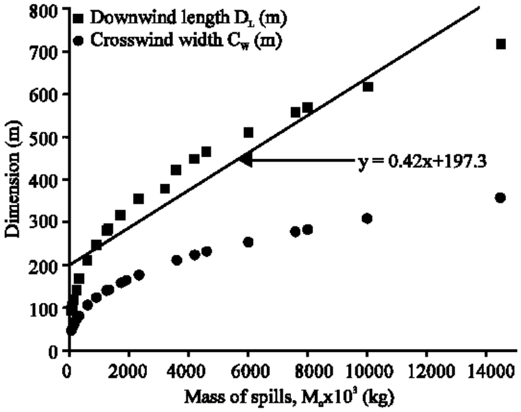

Fig. 3: Crosswind and downwind of LNG spills

RESULTS AND DISCUSSION

Various masses of possible LNG spills from NLNG considered in this study range between 70000 and 14500000 kg (Fig. 1-4). While 70000 kg was considered the least significant that could be spilled, 14500000 kg was chosen based on the maximum capacity of a tank in the train. These masses are those that if spilled, the resulting vapour cloud could have a downwind concentration of LNG within the flammability range of methane (5-15%).

LNG installations carry actual and perceived hazards[18] and in hazardous materials management plan, the importance of time cannot be overemphasized.

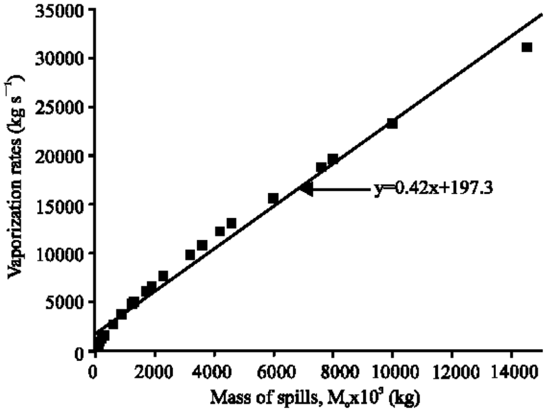

Fig. 4: Vaporization rates of spilled LNG

Availability of sufficient time signifies the possibility of total containment and it gives room not only for proper management plan but execution of such. Using a linear regression analysis, predicted final time of vapourization of spills as a function of mass could be described as y = 0.02x+207.5; where x and y are, respectively mass of spill and final time for total vapourization (Fig. 1). The larger the mass of potential spills, the longer the time required for vapourization, all other conditions being equal. This is significant in two ways.

Longer time requirement for vapourization indicates that spills would stay longer on water surface[19]. Though this may allow effective management plan execution for adequate protection of potential receptors at some distances away from spill points, it could portend great danger for aquatic life. The longer the spills stay on water, the longer the possibility of aquatic life to experience the danger associated with its presence.

Secondly, longer time requirement for spills vapourization could increase the possible distance to be covered by the spill on water surface due to flow thus extending the coverage area of environmental impact on water surface. It should be noted that changes in environmental parameters like meteorological conditions could alter these predicted anticipated periods of total vapourization. For instance, high ambient temperature and wind speed could reduce required time for total vapourization while the reverse may be the case with low temperature and wind speed, other conditions being constant.

In addition to the vapourization time requirements predicted is the radius of spill. Both final and average spill radii (Fig. 2) depend strongly on mass of spills. The larger the mass, the bigger the radius attained. Generally, predicted radius of spill could be described as y =0.03x+156.3 with x and y being mass of spill and radius respectively. As longer time requirement for spill vapourization could extend period of havoc on aquatic life, so the larger radius of spills could extend the coverage area of such. Surface water temperature and flow rate could also change these predicted radii. Higher temperature which could increase vapourization rate thus reducing vapourization time requirement, could reduce highest radius attainable by spills on water surface. To reduce attainable radius by spills, the mass allowed to escape must be reduced. The same is applicable to other spill dimensions (Fig. 3) which can be described as y = 0.04x+197.3 where, x and y are, respectively, mass and dimension of spills.

Mass of spills is an indication of available quantity of LNG on water surface to vapourize thus it is not surprising that vapourization rates increase with mass of spills (Fig. 4). With vapourization rates obtained as a function of mass of spills with the expression y = 2.2x+186.71, prevention of LNG spill is the only antidote to vapourization.

Since LNG masses could ignite before vaporizing if spilled[20] resulting fire could lead to aquatic life destruction in the immediate environment of the NLNG host water. Should the LNG pool fail to ignite, it could vaporize and disperse downwind thus exposing neighbouring towns and facilities to further risk.

Spilled LNG on Bonny water could have a negative impact on the aquatic life because it could result in a sharp temperature drop in the immediate water surroundings. This could result in an unbearable habitat for the aquatic life leaving those unable to adapt dead. It could even be difficult for most of them to adapt due to ice formation that could result from the spill on the water surface. The water in consideration here is not the sea that is always characterized with ocean current but a river with very low freshwater flow into the Atlantic ocean[2]. In addition, the overpressures from Rapid phase transitions of LNG could also impact negatively on the vegetation, jetty facilities, coastal structures (like the passenger terminal constructed around the LNG jetty), coastal settlements, the LNG vessel itself, personnel on site and even individuals. The larger the mass spilled, the more the damage.

For a mass spill of about 8000000 kg of LNG on the Bonny river, there is a possibility of attaining a maximum radius of 440 m (Fig. 2) with a mass burning rate of 0.078 kg sm^{-2}. The radiation contour of this heat could cover a radius of about 2.4 km around the spill site (Fig. 5). The host communities of the gigantic LNG project, Bonny and Finima towns are about 2.4 km away from the typical spill point 1 (Fig. 6). For spill point 2, Finima town which is the only residential town around, is also about 2.4 km away (Fig. 6). The predicted thermal radiation damage zone is as shown in Fig. 5. With this, the maximum fire extent could impinge on shore side and jetty facilities, with the personnel on site receiving heat flux far

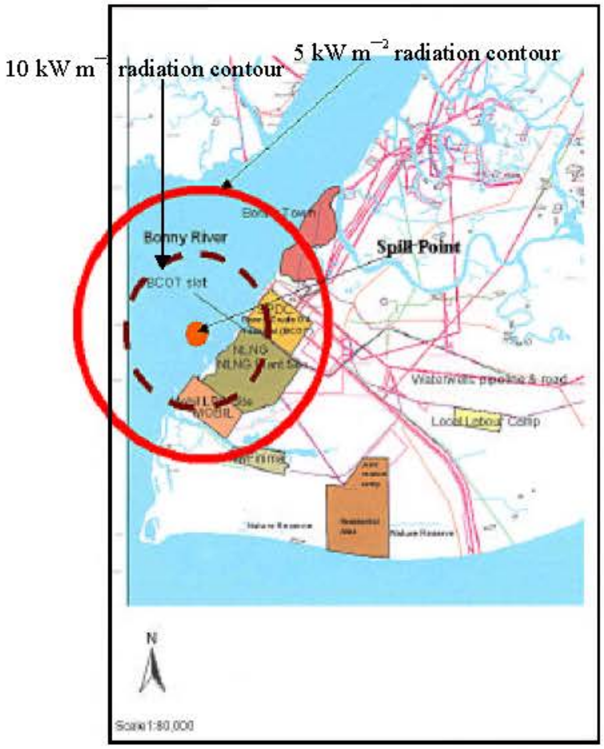

Fig. 5: Heat radiation contour around NLNG facilities

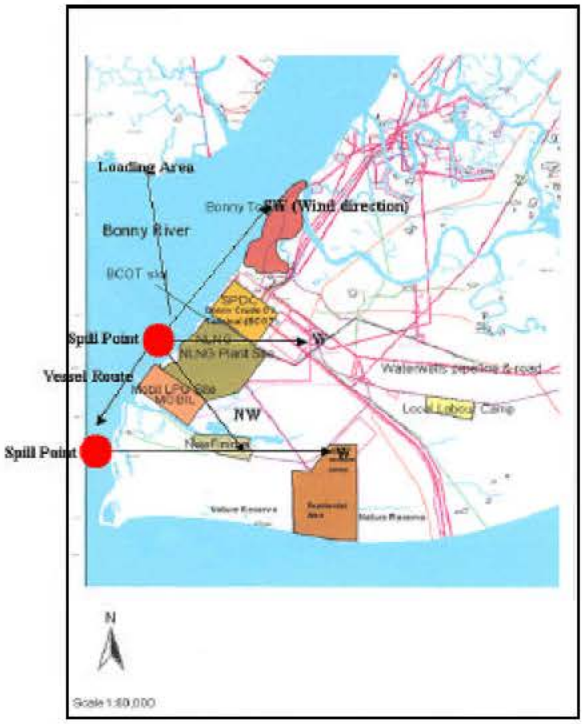

Fig. 6: Map of Bonny island showing the potential spill points

above the 5 kW m^{-2} limit for humans' tolerance in the event of spills as low as 100000 kg as they are closer to the spill sites. "Domino effect" in the event that any of the shoreline facility catches fire is an additional problem because the next door neighbors of the LNG plant are flammable fluid handling installations. When storage vessels bearing flammable fluids are subjected to high heat stress, they can rupture with the fluid catching fire.

To prevent this, there should be constant assessments of fatality rates with special attention given to installation of fire alarms, personnel reaction time, emergency procedures, escape time, shielding effects, radiation levels as a function of time, total exposure time, other critical aspects like visibility, toxic gases, explosion loads etc. For the 5 kW m^{-2} radiation contour at exactly 2.4 km, the percentage fatality of these host towns was predicted to be zero. But closer to the pool fire, there could be a higher fatality due to possibility of higher thermal flux.

Based on the aforementioned hazards associated with handling of LNG, the host water areas of the LNG plant on Bonny island could be at risk in case of spill. This is based on the layout of the installations and residential areas on the island which indicates that they are located too close to the LNG Plant. Though the new Finima town was relocated for LNG plant, this predicted areas of hazards show that the new town is still too close to the LNG plant. Also, location of a passenger terminal around the LNG Jetty could expose more lives to danger in case of accident. Asphyxiation, freeze burns, thermal flux from LNG pool fire and overpressures from Rapid Phase Transition which are associated with LNG spill on water are enough reasons for proper emergency plan to be put in place by the concerned authorities.

CONCLUSIONS

In conclusion, vapourization rates, time required and spill dimensions considered necessary for LNG spill management were predicted in this study for Nigeria Liquefied Natural Gas (NLNG) plant, Nigeria. Vaporization rates of various spill masses and some other pool-spread information is presented for LNG spills on Bonny river. The damage that can be done by a spill of LNG on the Bonny river on its host environment has been identified. Thermal radiation damage zone for a heat flux of 5 kW m^{-2} is also identified to include the host towns of Bonny and Finima but the percentage fatality that could result was predicted to be zero. All these could assist in accurate assessment of hazards associated with LNG project and subsequent prevention and control which are of utmost importance in LNG project safety as highlighted by Atallah and Schneider[21].

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