

Integrated Consequence Modelling for Fire Radiation and Combustion Product Toxicity in offshore Petroleum Platform using Risk Based Approach

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Abstract. The processing area of offshore platform has high probability of leakage of hydrocarbons. Liquefied Natural Gas (LNG) is one of the most common hydrocarbon produced in offshore platforms. Leakage of LNG can cause pool fire, jet fire, flash fire or fire ball. Thermal radiations due to fire is the major source of damage to workers on board. But due to fire, various combustion product toxic gases are also produced that have both acute and chronic health effects. These toxic gases can cause incapacitation, increased heart rate, vomiting and even death. Predicting the human injury due to thermal radiations and concentration of toxic gases are the key issues. A risk based approach takes in to consideration the duration a worker spent on different location of offshore platform and also it has the additive ability to evaluate overall risk due to fire radiation and toxic gases. Grid based approach helps in better visualization of risk posed by fire radiation and combustion product toxic gases at different locations of platform. The current study proposed an integrated consequence modelling approach for fire and combustion product toxic gases using risk based and grid based approaches. The integrated accident is modelled using Computational Fluid Dynamics (CFD) code Fire Dynamics Simulator (FDS). The results showed that risk posed by thermal radiation is confined on sub cellar deck (lower deck) but estimated risk due to combustion product gas (carbon monoxide) on cellar deck (upper deck) has significant value that needs to be considered. The current approach would be useful for emergency preparedness plans and safety measures designs for offshore platforms.

1 Introduction

There are diverse studies on consequence modelling involving the leakage of hydrocarbons. The studies ranges from use of simple empirical modeling to advance CFD modeling [1-7]. Hydrocarbon fire is the most frequent accident occurring on offshore platforms [8]. Vianna and Huser *et al.* [9] also described that total risk due to fire on an offshore facility is

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significantly high. Fire accident analysis exhibited that among different categories of hydrocarbon fire, pool fire has the highest probability of occurring [10].

Koo *et al.* [1] conducted a study to model pool fire at an LNG terminal using PHAST software. Based on LNG release hole sizes, six different scenarios were constructed. Early and late pool fire effects were evaluated through this study. It was concluded that late pool fire possessed higher hazard than the early one and the accidents will have an impact outside the plant domain. Rajendram *et al.* [2] modelled two scenarios jet fire and fire ball on offshore platform. Fire cases were modelled using CFD and solid flame model. Radiative heat flux determined from the fire was used to assess the risk and impact to human for different degree of burns was studied. Result showed that CFD method provided better results than solid flame model. Skarsbo *et al.* [3] studied extensively pool fire and compared CFD simulation results with experimental results. Results indicated that temperature and velocity in smoke layer was close to experimental results for both FLACS and FDS. Heat flux was well predicted by FDS. Khan *et al.* [4] calculated human injuries due to fire and explosion on offshore platform using grid based approach and enhanced onsite ignition model for better consequence modelling. Weng *et al.*, Kamikawa *et al.* and Liu *et al.* [5-7] studied the separation distance between the individual pool fires and concluded through experiments that it has a huge impact on the interaction among them. It also has significant effect on human injury as well. The consequences of LNG release were also studied by Mary O'Connor Process Safety Center. Parameters like dike wall height, high expansion foam, conductivity of floor etc. were investigated [11, 12]. In all these studies, focus and evaluation of hazard was done considering one accident only, ignoring the combustion product toxic gases due to these fires that have both chronic and acute health effects.

Toxic combustion products are also a major concern due to fire accidents in offshore platforms [13]. Prediction of risks due to combustion product toxic gases is important for emergency preparedness plans [14]. There are numerous accidents in past that resulted in deaths of workers due to combustion product toxic gases. In 2005, the massive fire at Buncefield Oil Storage Depots resulted in production of smoke that caused health problems for the workers [15]. The Piper Alpha disaster in 1998 resulted in loss of lives of 167 workers. Gas pipeline riser failure resulted into massive explosion that was the main reason for damaging the drilling derrick. Studies demonstrated that the major loss of lives were mainly due to inhalation of smoke [16]. In 1984, dispersion of methyl isocyanate (MIC) in a pesticide production plant in Bhopal, India caused the death of 2000 to 4000 people [17].

Due to these accidents, risk estimation considering toxic gases has been done. In a study conducted by Markatos *et al.* [15], CFD was used to predict dispersion of different combustion products (CO, SO₂, volatile organic compounds, polycyclic aromatic hydrocarbons, smoke, etc.) from fires of fuel tanks. Markatos *et al.* deduced that the production of combustion products and smoke caused environmental problems and health issues over the whole plant and the concentration of toxic substance should be estimated. In another study conducted by Markatos *et al.* [18], the toxic combustion products after a pool fire was modeled using CFD simulation. The results of simulations were used to determine risk zones on the facility. Dadashzadeh *et al.* [14] calculated the combustion product toxicity using risk based approach. The factor of exposure time was incorporated in the calculation as personnel spend different time in processing, living and office areas. Similarly, like previous fire studies, all these studies discussed and evaluated hazards from toxic gases only, ignoring the hazards due to thermal radiations from fire. CFD codes were extensively used for assessing the concentration of toxic gases and thermal radiations from fire [2, 3, 19-21]. The application of CFD codes for predicting the thermal radiations and combustion products from fires on offshore platforms is also proposed by Health and Safety Executive (HSE) [22]. CFD codes have the advantage of high speed, low cost, accurate estimation and ability to model realistic and ideal conditions [23].

In this study, the interaction between pool fire and combustion product toxic gas and the resulting consequence are modelled. Pool fire and combustion product toxic gas (carbon monoxide) are modelled using CFD software Fire Dynamics Simulator (FDS). For risk profiles, risk based approach together with grid based approach was used.

2 Methodology

The methodology for current study is outlined in Fig. 1. The study consist of following steps.

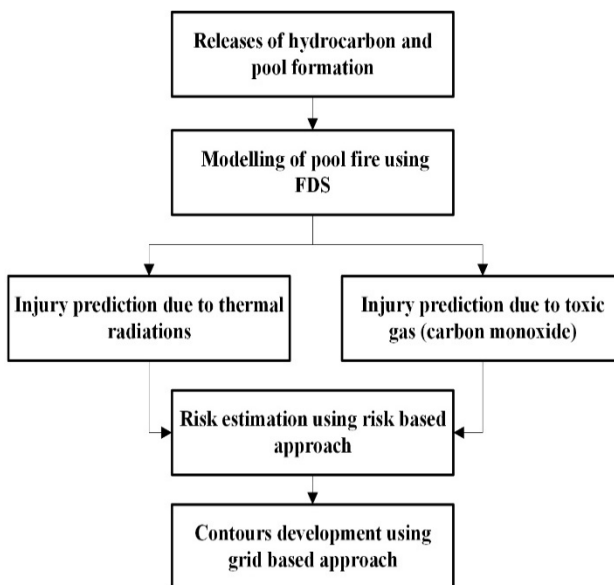


Fig. 1. Methodology

2.1 Geometry Consideration

The geometry considered here for offshore platform is shown in Fig. 2. The leakage of LNG took place at sub cellar deck (lower deck) of offshore platform. The thermal radiation intensity and corresponding risk were estimated at sub cellar deck (lower deck). The concentration of combustion product toxic gas (CO) and corresponding risk due to inhalation of CO was determined at cellar deck (upper deck) of offshore platform.

2.2 Liquefied Natural Gas (LNG)

It mainly consists of methane and traces of other gases like ethane, propane and butane. It is colorless, odorless, non-corrosive and non-toxic gas. After removing impurities from natural gas, it is cooled to condensation temperature of $-161.5\text{ }^{\circ}\text{C}$ at high pressure to turn into liquid called as Liquefied Natural Gas (LNG). The volume of gas is reduced to 600 times. The reduction in volume helps in storage and transportation of LNG to different locations.

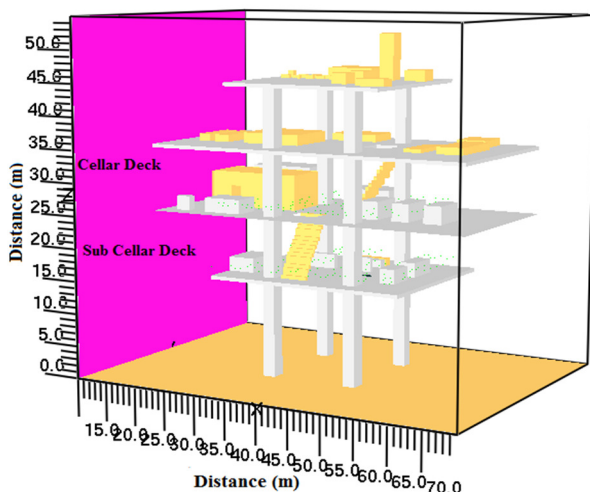


Fig. 2. Geometry of offshore platform.

2.3 Pool formation and Pool Fire

Accidental release of liquid fuel due to rupture of storage tanks and pipes forms a pool on the confined areas of platforms and upon ignition results into pool fire. The probability of pool fire on offshore platforms is quite high due to presence of heavy hydrocarbons [4]. Thermal radiations from pool fire can severely damage the skin and results into first degree burns, second degree burns and death. For the current research, a pool of LNG is formed at the sub cellar deck of offshore platform and gets immediate ignited.

2.4 Modelling of Pool Fire

Pool fire is modelled using Computational Fluid Dynamics software Fire Dynamics Simulator (FDS). FDS is developed by National Institute of Standards and Technology (NIST). FDS utilizes partial differential equations (PDE) to explain the transportation of energy, momentum and mass for hydrocarbon fire [24]. By using Large Eddy Simulation method (LES), FDS resolves the conservation equations and upgrade the solution based on time on a 3 dimensional grid. The finite volume technique is utilized to determine the thermal radiations [1].

2.5 Modelling of Combustion Product Toxic Gas

Due to pool fire, various toxic combustion product gases are produced that have both acute and chronic health effects. Major toxic products from fire are nitrogen dioxide (NO_2), carbon monoxide (CO) and methane (CH_4). The effects varies from respiratory and coughing (primary ones) to cardiovascular diseases and lung cancer (secondary ones). For the current research, concentration of carbon monoxide (CO) is determined on cellar deck of offshore platform for risk estimation. Harmful effects due to CO are listed in Table 1 [25]. Acute effects (short term effects) will be considered here as most toxicological studies considered difficulties in assessing chronic effects (long term effects) [26]. Computational Fluid Dynamics software FDS is used for estimating the concentration of CO at different points on cellar deck of offshore platforms. Wind speed of 1 m/s is considered here.

Table 1. Adverse health effects.

Toxic Gas	Acute Health Effects	Chronic Health Effects
CO	Low blood pressure, fast heart rate, unconsciousness, dizziness and death	Memory loss, persistent headache, vomiting and nausea

2.6 Impact Modelling and Risk Estimation

The consequence of fire and combustion product toxic gases are expressed in terms of thermal radiation intensity and concentration of different toxic combustion products experienced by the worker. To estimate the risk, these effects (thermal radiation and toxic gases concentrations) are converted into impacts causing damage. To quantify the damage from thermal radiation and concentration of toxic product gases, dose response evaluation method is used.

2.6.1 Probit Model

Thermal radiation intensity at different points on sub-cellar deck is measured as incident heat flux by FDS. The thermal radiation effects on workers are 1st degree burns, 2nd degree burns and deaths. Probit model defines these impacts. For calculating the number of burns and deaths, incident heat dose “D” due to incident heat flux is employed [27] given by the Eq. (1),

$$D = t_{eff} \times q^{4/3} \tag{1}$$

where q (W/m^2) is the incident heat flux calculated, t_{eff} (s) is person’s exposure time to this heat.

The exposure time is calculated from Eq. (2),

$$t_{eff} = t_r + \frac{x_0 - r}{u} \tag{2}$$

where t_r (s) is person’s reaction time considered as five seconds [27], x_0 (m) represents the distance between the flame’s surface and the place where intensity of incident heat flux is lower than 1 KW/m², r (m) is the distance of the worker from the surface of flame and u (m/s) is the worker escape velocity considered as 4 m/s [27]. For determination of probability of injury for 1st degree burns, 2nd degree burns and death due to thermal radiation dose “D” is given by the Eq. (3),

$$P = f_k \frac{1}{s} \left[1 + erf \left(\frac{Pr-5}{\sqrt{2}} \right) \right] \tag{3}$$

where probit function is given by the empirical Eqn. (4),

$$P_r = c1 + c2 \ln D \tag{4}$$

For calculating the combined risk due to thermal radiations (1st degree burns, 2nd degree burns and death), risk based approach together with grid based approach were used to estimate risk at different location on the platform. Grid based approach helps in better analysis of radiation at different locations in process area [4]. The process area of sub cellar deck is divided into number of computational grids and risk estimation is made at each grid. For contour plotting, MATLAB software was used for plotting the risk of probability of injuries of 1st degree burns, second degree burns and death. Also, the risk of combustion

product toxic gas CO was plotted as contours. The effects from thermal radiations (1st degree burns, 2nd degree burns and death) were graded based on severity of damage. Table 2 shows the scores for different types of burns and death based on expert judgement from scale of 1-10 [28].

Table 2. Score for major fire effects (expert judgement).

Hazard (Fire)	Score
1 st degree burns	2
2 nd degree burns	5
Death	10

Severity index for different effects (1st degree burns, 2nd degree burns, and death) at any location on the offshore platform is calculated [28] using the Eqn. (5),

$$Risk_i = S_i \times P_i \tag{5}$$

where i indicate the effects (1st degree burns, 2nd degree burns, and death) and P_i denotes the probability of injury due to these effects. The combined risk at any point on offshore platform was calculated [28] using the Eqn. (6),

$$Risk_{fire} = \sum(Risk_{1st\ degree\ burns} + Risk_{2nd\ degree\ burns} + Risk_{death}) \tag{6}$$

This enabled to determine risk of fire at any location of platform and creating contour based risk profiles.

2.6.2 Dose Response Assessment for Combustion Product Toxic Gas

Exposure time is the time spent by the worker on different areas of offshore platform. Normally, every worker spends around 8 hours in the processing area, therefore it is assumed that same time was spent by each worker. The severity and probability of damage to worker’s health is associated to risk agent through dose response assessment. On dose response curve, the threshold dose exhibits the maximum concentration of toxic gases at which the person can inhale the contaminants with no harmful effects. Threshold limit values (TLV) are determined by American Conference of Governmental Industrial Hygienists (ACGIH) [29]. Short term exposure limit (TLV-STEL) represents the limited exposure during which there is no harmful effect. For current study, TLV-STEL for CO is 440 mg/m³ [29]. Risk due to inhaling of CO for every individual at different location (using grid based approach) of cellar deck is calculated [14] by using following Eqn. (7)

$$Risk_{Toxic\ Gas\ (CO)} = \frac{Concentration \times Exposure}{TLV-STEL} \tag{7}$$

3 Results and Discussion

3.1 Scenario Definition

Liquefied Natural Gas (LNG) is released due to rupture from a pipe at 25 Kg/s at sub cellar deck of offshore platform. The total release duration is 110 seconds. The wind speed is 1 m/s with ambient temperature of 24 °C. LNG pool is formed with equivalent diameter of 7.5 m and ignited immediately. FDS is used for modelling of pool fire by specifying mass loss rate

per unit area which for LNG is 0.078 kg/m.s^2 . The total simulation volume is $60 \text{ m} \times 55 \text{ m} \times 55 \text{ m}$ with grid dimension of 0.30 m in X-axis, 0.30 m in Y-axis and 0.36 m in Z-axis. Due to computer power and speed limitations, total number of cell for mesh are selected to be 4.5 million that are reasonable for getting accurate results. As grid based approach is used for developing contours for risk profiles, incident heat flux devices are put at every 2 m on sub cellar deck (lower deck) for estimating risk of fire. Similarly, for determining risk of inhalation of CO at cellar deck (upper deck), devices are put at every 2 m. Average heat release rate (HRR) for pool fire is found to be 170 MW.

3.2 Risk estimation due to pool fire

Fig. 3 show the pool fire at the sub cellar deck of offshore petroleum platform. Radiative heat flux devices were placed at every 2 m in X and Y direction. The incident heat flux measured at different locations helped in getting contours for probability of first degree burns, second degree burns, deaths and subsequently total risk due to fire (including risk of first degree burns, second degree burns and death). The maximum incident heat flux was recorded to be 130 KW/m^2 at the center of pool that gradually decreases with the increase in distance from the fire.

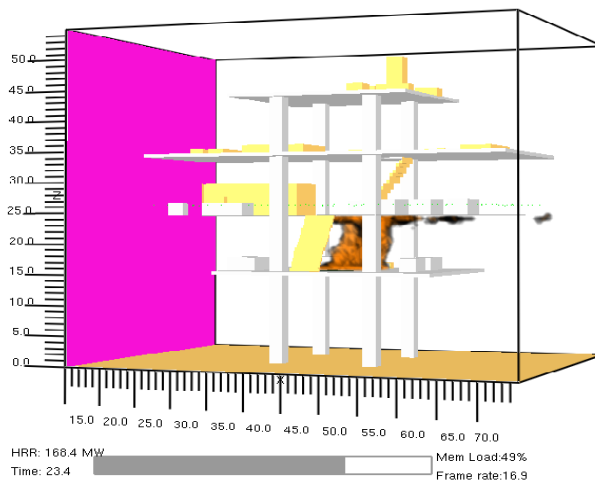


Fig. 3. Pool fire on sub cellar deck.

Fig. 4 (a), (b) and (c) shows the contours for probability of injury for first degree burns, second degree burns and death. The contours shows that the area covered by first degree burns is large as compared to second degree burns and death. 100 % chances of the probability of first degree burns exist with an area of 64 m^2 . Injury probability increases slightly towards the right as wind speed effects pool fire and results into tilt of flame. Probability of death is mainly confined to area of pool fire i.e. 48 m^2 .

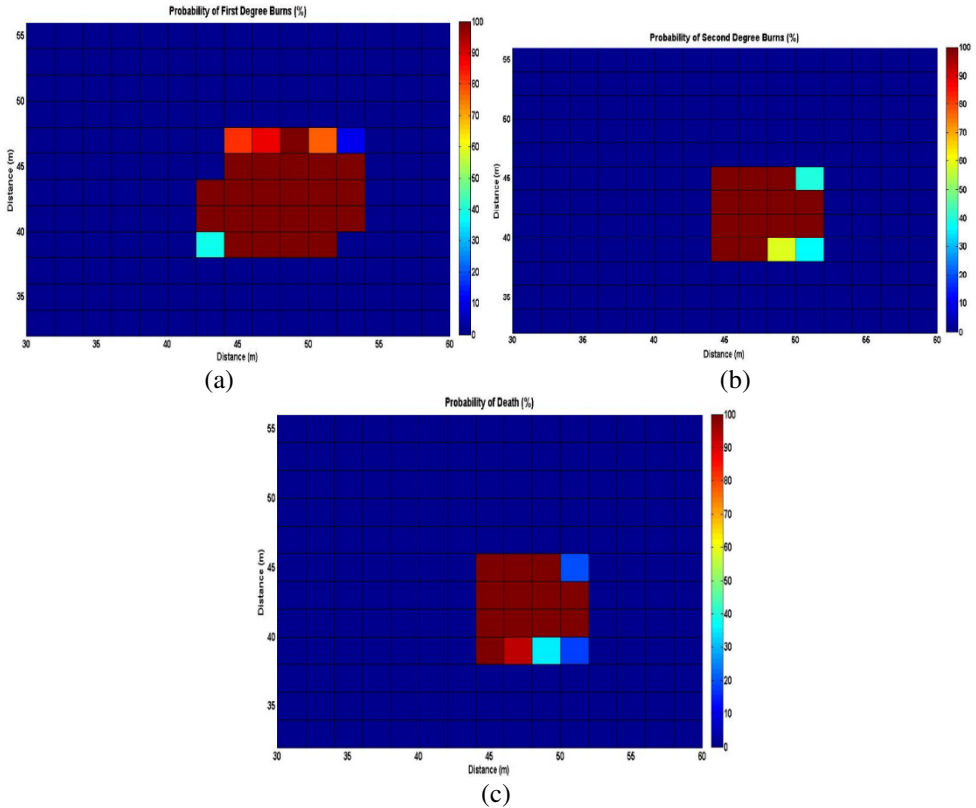


Fig. 4. (a) Probability of 1st degree burns (b) Probability of 2nd degree burns (c) Probability of death.

Finally, risk based approach was used to plot the risk of fire (1st degree burns, 2nd degree burns and death) as shown in Fig. 5. The contour for risk of fire shows the level of risk at different locations of offshore plant. Risk was found to be higher near the pool and gradually decreases away from it.

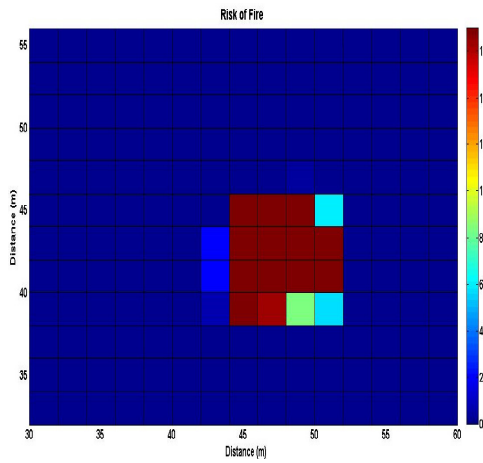


Fig. 5. Risk of fire on sub cellar deck.

3.3 Risk estimation due to combustion product toxic gas (CO)

The combustion product toxic gases are also produced with pool fire that severely affects the workers working on offshore platform. The average height for a person to inhale air is 1.5 m, so concentration of CO is measured at this specific level on cellar deck [30]. Fig. 6 shows the movement of smoke on cellar deck of platform. The area affected by the smoke is quite large that not only causes acute and chronic health effects but also causes visibility problem that restricts and slow down movement of workers during emergency evacuation. The concentration of CO is measured at different locations of cellar deck and contour for risk is plotted. Congestions and confinements due to presence of equipment result into higher concentration. The maximum concentration is found to be 350 mg/m³ that is above the TLV-STEL. Risk for CO is plotted as shown in Fig. 7. The elevated values of risk is due higher concentration of CO at those specific locations.

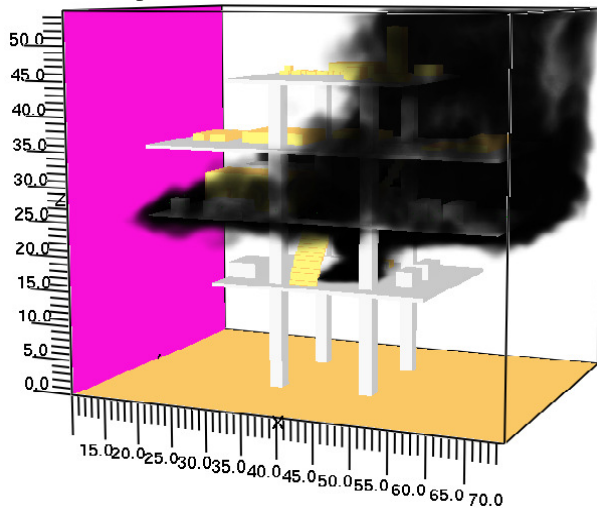


Fig. 6. Smoke movement on cellar deck.

The locations with zero risk on contour are positions of equipment. So, at those specific locations, zero concentration is assumed.

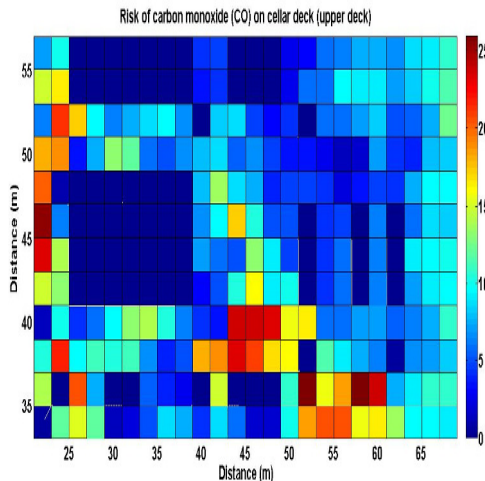


Fig. 7. Risk of CO on cellar deck.

4 Conclusion

An integrated approach was selected to predict the risk due to pool fire and combustion product toxic gas (CO) at sub cellar and cellar deck of offshore platform respectively. Probability of injury due to fire radiation (1st degree burns, 2nd degree burns and death) was also determined at sub cellar deck. Risk based approach together with grid based approach was used for better analysis and modelling of radiations and combustion product toxicity. The results show that probability of injury due to first degree burns covers an area of 64 m² while for probability of death is confined to 48 m². Risk based approach helped in identifying overall risk due to fire. The technique adopted would be useful for visualizing directly the area affected by fire incorporating probability of 1st degree burns, 2nd degree burns and death. The smoke production due to fire results into reduce visibility that can drastically affects the speed of workers during emergency evacuation on upper floors. Significant concentration of toxic gases are also produced that causes severe health effects. Risk estimation was done taking into consideration combustion product toxic gas i.e. CO. The results showed that cellar deck (upper deck) has significant value of risk due to high concentration of CO. It also showed that congestions and confinements have increased concentration of CO and consequently higher risk. It also revealed that the risk due to combustion product toxic gas (CO) affects almost all the area of cellar deck while risk of fire affects mainly the fire pool area. The study could be helpful in improving safety measures. It could also be helpful in improving emergency preparedness plans and evacuation.

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