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THERMAL AND OVERPRESSURE HAZARDS MODELLING AND SIMULATION: A CASE STUDY OF REFINERY FIRED HEATER

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ABSTRACT

Crude oil-fired heaters are associated with considerable fire and explosion hazards. The heaters present higher risks at later operational life due to ageing, wear and obsolescence. It is therefore important to re-evaluate such heaters to determine the adequacy or otherwise of the existing safeguards. This paper presents results of studies on hazard levels in aged fired heaters through quantitative consequence modeling method. A number of credible failure scenarios were considered. In particular, characteristics of potential jet fires due to Liquefied Petroleum Gas (LPG) leaks from hole sizes: 15, 30, 50 and 100 mm were investigated. For the 100 mm hole size, it was found that thermal radiation level of up to 37.5 kW/m² could be experienced within 25 m radius of the heater, which is enough to affect nearby operators severely and could also adversely affect critical pieces of equipment around. Fireball potential with peak thermal density of about 12.5 kW/m² was also observed within 2 m radius. For the 100 mm hole size, lower flammability limit of the fuel could be attained within 16 m downwind which poses flash fire risks. Overpressures of 1.02, 1.14 and 1.21 bar could be experienced at 30, 6 and 4 m respectively away from the fired heater which could result in partial demolition of structures that are within the radius.Overall, the results indicate that the risk profile is very sensitive to leak sizes, operating and atmospheric conditions as well as the fuel quantity being held, among others. For the chosen case study, higher integrity protection layers, in form of safety instrumented systems, relief, blow down and alarm systems, are recommended.

Keywords: *Downwind distance; Consequence modeling; Radiation intensity; Flame length; Overpressure; Toxicity; Liquefied Petroleum Gas.*

INTRODUCTION

Fire is the most frequently reported process-related incident in Nigerian petroleum industry (DPR annual report, 2017). Fire may result in no damage/loss, medium to catastrophic damage/loss, depending upon the fire characteristics (type of fire, mode of occurrence and potential of escalation). Leakage or spillage of flammable material can lead to a fire that is triggered by any number of potential ignition sources (sparks, open flames, etc.). Depending upon the types of leakage scenarios, fires are mainly categorized into four types, jet fire, pool fires, flash fires and fire balls, therefore there is need to study the risk associated with fire (Niazi *et al*. 2006). Figure 1 is a schematic flowchart showing a typical risk assessment process.

Consequence analysis predicts magnitude, direction vulnerability zones of negative effects of incidents. Once these zones are identified, the risk analysis suggests measures of mitigation or prevention that can be proposed to eliminate damage to plant and potential injury to personnel. Estimation of vulnerability zone of such an incident plays an important role in preparing a realistic emergency plan (Pula *et al*., 2005). Consequence modelling refers to the calculation or estimation of numerical values (or graphical representations of these) that describe the credible physical outcomes of loss of containment scenarios involving flammable, explosive and toxic materials with respect to their potential impact on people, assets, or safety functions (Assessment Directory, 2010).

Estimation of vulnerability zone due to credible scenarios via consequence analysis would play important role in preparing realistic preventive and mitigative measures- including emergency response and evacuation plan. Physical models can be used to estimate hazards zones in case of accidents (Osman *et al*., 2015). For these reasons, it is important to determine consequences due to accidental leak or rupture of a component at various locations around the heater. The following section highlights the methodology involved in this study.

This work sets out to model and simulate the consequences due to liquefied petroleum gas leakage from fuel pipe supplying one of the fired heaters of Kaduna Refining and Petrochemical Company (KRPC). Further details on this case study are given below.

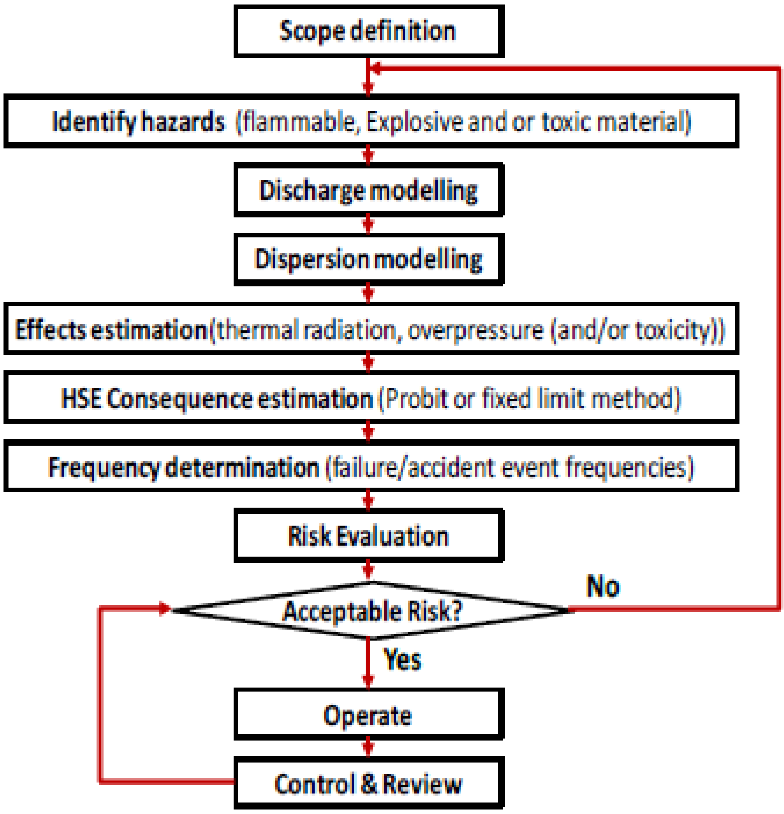

Figure 1. Typical risk assessment procedure (Abubakar *et al*., 2017)

Case Study of Kaduna Refining and Petrochemical Company (KRPC)

The crude heating section (Fired Heater 10H01) is one of the most hazardous sections of the Crude Distillation Unit 1 (CDU-1). This is where the crude is heated to distillation temperature before it is finally charged into the fractionator. This is because the fired heater contains naked flames and handles crude in the pipe which is highly flammable. In this work, the emphasis was on hazard resulting from fire that is associated with crude discharge fired heater (10H01) of KRPC (CDU-1 Manual, 1978).

The fired heater is an exchanger that transfers heat from the combustion of fuel to fluids contained in tubular coils within an internally insulated enclosure. The fired heaters are an essential component of CDU-1 of the KRPC. The functions served by fired heaters in chemical plants are many, these include: simple heating or provision of sensible heat and raising the temperature of the charge to heating and partial evaporation of the charge, where equilibrium is established between the unvapourised liquid and the vapour. The charge leaves the furnace in the form of a partially evaporated liquid in equilibrium. Fired heaters may also be used to provide the heat required for cracking or reforming reactions. Fired heaters process fluids flowing inside tubes mounted inside the furnace, the fluid is heated by gases produced by the combustion of a liquid or gaseous fuel. The major advantage of fired heaters is the achievement of continuous operation (Garg, 1997). These heaters are widely used for heating purposes in petroleum refining, petrochemical plants and other chemical process industries.

Fired heaters present high safety risks as the process streams contain highly flammable hydrocarbons with potential catastrophic fire incidents. Due to ageing (over 30 years after commissioning of the refinery), wear and obsolescence, the fire risk profile of the crude charge fired heater (10H01) of KRPC within the CDU-1 needs to be reevaluated. For instance, in the year 2017 there was explosion at fired heater 12H01 at KRPC due to tube rupture which led to the breakdown of the unit for about two years. Therefore, it is important to determine the vulnerability zone of other heaters in the company.

Table 1 presents the potential effects due to a number of radiation intensity levels. The table is usually used to estimate potential thermal damages/impacts.

Table 1. Effect of Various Radiation Intensities

Intensity of heat radiation kw/m^2	Potential effect
1.6	Insufficient to cause discomfort for long exposure
2.2	Threshold pain. No reddening or blister
4.2	First degree burn
8.3	Second degree burn
10.8	Third degree burn
15.0	Piloted ignition of wood
25.0	Spontaneous ignition of wood
4.0	Glass crack
12.0	Plastic melt
19.0	Cable insulation degrade
37.5	Damage to process equipment
100.0	Steel structure fail

Source: (AIChE/CCPS, 2000)

Table 2 presents certain pressure levels and the corresponding potential overpressure effects and could be used to predict the damages resulting from a range of explosion overpressures.

Table 2: Overpressure Effects of Explosion

Pressure (psig)	Damage
0.02	Annoying noise (137 dB if of low frequency 10-15 Hz).
0.03	Occasional breaking of large glass windows already under strain.
0.04	Loud noise (143 dB), sonic boom glass failure.
0.1	Breakage of small windows under strain.
0.15	Typical pressure for glass breakage.
0.3	“Safe distance” (probability 0.95 no serious damage beyond this value).
0.4	Limited minor structural damage.
0.5-1.0	Large and small windows usually shattered; occasional damage to window.
0.7	Minor damage to house structures.
1.0	Partial demolition of houses, made uninhabitable.
1-2	Corrugated asbestos shattered; corrugated steel or aluminium panels, fastenings.
1.3	Steel frame of clad building slightly distorted.
2	Partial collapse of walls and roofs of houses.

Pressure (psig)	Damage
2-3	Concrete walls, not reinforced, shattered.
2.3	Lower limit of serious structural damage.
2.5	50% destruction of brickwork of houses.
3	Heavy machines in industrial building suffered little damage; steel frame.
3-4	Frameless, self –framing steel panel building demolished; rupture of oil storage.
4	Cladding of light industrial buildings ruptured.
5	Wooden utility poles snapped; tall hydraulic press in building slightly damaged.
5-7	Nearly complete destruction of houses.
7	Loaded train wagons overturned.
7-8	Brick panels, 8-12 in. thick, not reinforced, fail by shearing or flexure.
10	Probable total destruction of buildings, heavy machines tools moved and badly damaged, very heavy machine tools (12,000lb) survived

Source: MS. K.G.O.C Terminals PVT LTD

The consequence modelling involves three major steps. Firstly, the discharge calculations are carried out to determine the release characteristics for the hazardous chemicals (including depressurization to ambient). Scenarios which may be modelled include: releases from vessels (leaks or catastrophic ruptures), short pipes or long pipes and releases of combustion products following a warehouse fire. Thermo-physical states considered include releases of sub-cooled liquid, superheated liquid and/or vapour phase releases. Other conditions often considered are: unpressurized/pressurized releases, continuous, time-varying and/or instantaneous releases (Witlox, 2010).

Secondly dispersion calculations are carried out to determine the concentrations of the hazardous chemical when the cloud travels in the downwind direction. This includes effects of jet, heavy-gas and passive dispersion. In the case of a two-phase release, material rainout may occur, hence pool formation/spreading and re-evaporation may also have to be modelled. Also, effects of indoor dispersion (for indoor releases) and building wakes can be accounted for (Witlox, 2010).

Thirdly, toxic or flammable calculations are carried out. For flammables, ignition may lead to fireballs (for instantaneous releases), jet fires (for pressurised flammable releases), pool fires (after rainout) and vapour cloud fires or explosions. Radiation calculations are carried out for fires, while overpressure calculations are carried out for explosions.

For each event, the probability of fatality is determined using toxic or flammable PROBIT function given in equation 1.

$$P_r = -36.38 + 2.56 * \ln(t * q^{4/3}) \quad \ldots\ldots.(1)$$

Where q is the radiation heat flux, t is the time of exposure and Pr is the PROBIT function for heat radiation lethality (Pula et al., 2005).

Probability of fatality (in percentage) can be calculated from equation 2, (CCPS 2000)

$$P = 50[1 + \frac{P_r - 5}{|P_r - 5|} \operatorname{erf}\left(\frac{|P_r - 5|}{\sqrt{2}}\right) \quad \ldots\ldots (2)$$

Expected fatality can be calculated from equation 3

$$Expected\ fatality = P * N(exposed\ people) \quad \ldots\ldots\ldots (3)$$

Determination of the parameters such as flame dimensions, release rates, heat flux and distances to radiation levels is an important aspect of the risk assessment process (Abubakar et al., 2017).

METHODOLOGY

This work applies Process Hazard Analysis Software Tool (PHAST). Key data/information and some fundamental assumptions used are presented in Table 3.

Table 3: Required input parameters and specification

Parameter	Specification	Reference
Location under consideration	KRPC	
Case study location coordinate & date	10.41159 N,7.49065 E 28/02/2019, 2pm	Measured

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Wind speed	5 m/s maximum	Measured
Wind direction	SSW/208.150 upper angular limit	Measured
Solar radiation flux	1 kW/m^2	Measured
Ambient temperature	28 ^{0}C maximum	Measured
Pasquill stability	Class D	Measured
Humidity	78 %	Measured
Cloud cover	67 % cloud level	Measured
Altitude	620 m	
Pipe diameter	0.16m	Measured
Height/elevation	2.65 m	Measured
Temperature at burner	45 ^{0}C	CDU-1 Crude Charge heater (10H01) Design Specification
Pressure at burner	1.5 bar + 1 bar atm	"
Phase/state of release	Liquid	"
Inventory/consumption rate	0.35 kg steam/kg oil	"
Leak sizes identified	15 mm, 30 mm, 50 mm and 100 mm	"
Assumption	Unbreaking end of a pipe is connected to an infinite tank source	
Softwares	PHAST 7.2 and ALOHA 5.4.7	Internet

These input data were used in the identified scenario i.e. LPG leak as shown in Figure 2 and was simulated. After the simulation, the result of the different fire models was selected and analyzed considering wind speed and atmospheric stability.

The scenario was selected after careful study of the design and operating principles of the fired heater. Leak sizes were selected based on literature and KRPC maintenance record (further details given in Table 3). The simulation exercise was based on a range of fire models, available in PHAST - considering wind speed and atmospheric stability. The consequence study results were analyzed for the different leak sizes, injuries potentials and catastrophic equipment damage within the study perimeter.

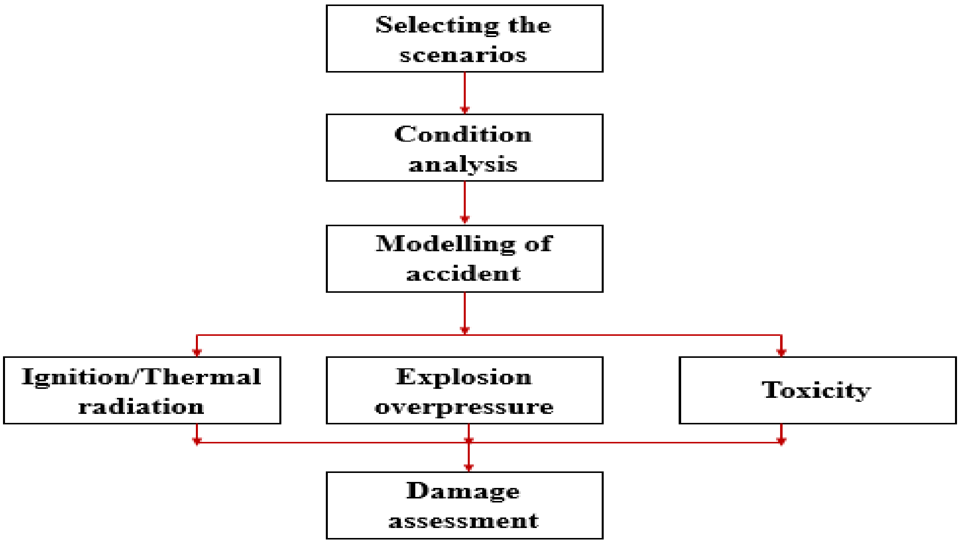

Figure 2: Research Methodology (adopted from Mohammad *et al.*, 2018)

A number of other input details including: wind direction, solar radiation flux, ambient temperature, Pasqual stability, humidity and Cloud cover were specified to reflect the situation under study (Table 3).

RESULTS AND DISCUSSIONS

Table 4 gives the jet fire flame length and downwind distance at which 4.0, 12.5 and 37.5 kW/m^2 radiation intensities are likely to be experienced.

Table 4: Jet fire downwind distance to experience defined radiation levels, for Weather Category 5/D

Scenario	Down Distance [m]to Radiation Levels			
	Flame length	4 kW/m^2	12.5 kW/m^2	37.5 kW/m^2
15mm Leak	5.29	n/a	n/a	n/a
30mm Leak	9.956	10.95	n/a	n/a
50mm Leak	15.7	20.65	15.53	n/a
100mm leak	27.26	40.77	32.55	25.41

Figure 3 gives the radiation levels and respective downwind distance for jet fire

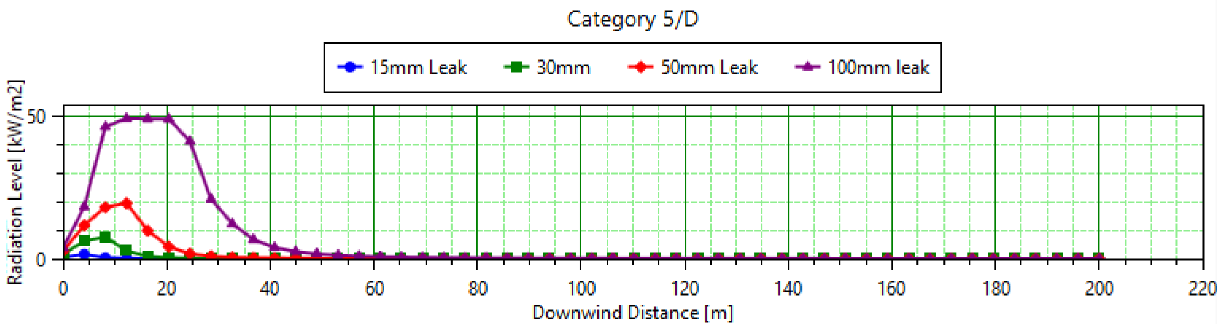

Figure 3: Radiation vs Distance for Jet fire

For Jet Fire, using PHAST the radiation level was plotted for the leakage sizes of 15, 30, 50, and 100 mm in 5/D climate weather as shown in Figure 3, the result of the flame length, radiation levels and calculated distance in downwind direction are presented in Table 4. As depicted in Table 4, the 100 mm leak size has the highest flame length followed by 50 mm, 30 mm and least 15 mm leak size. 4, 12.5 and 37.5 kW/m^2 intensity could not be experienced at 15 mm leak size, 12.5 and 37.5 kW/m^2 intensity could not be experienced at 30mm leak size, 37.5 kW/m^2 could not be experienced at 30 mm leak size and all the defined radiation levels could be experience at 100 mm leak size.

The following equipments; 51-31A, LAB flare knockout drum 90T01, VDU heater 15H01, NHU heater11H01, CRU heater 12H01 column10C01, column 10C07, desalter 10DO3, and heat exchangers 20E0C were identified to be surrounding the heater at approximate and respective distances of 80, 55, 30, 150, 181, 16, 43, 92, 166 and 200 m away from the heater (10H01) as shown in Plate 3. Hence 10C01 fractionator that is in the wind direction could experience 37.5 kW/m^2 radiation at 100 mm leak size which could result in catastrophic damage of the column while 10C07 may experience 4 kW/m^2 radiation intensity which could result in first degree burn on the personnel around as highlighted in Table 1 and could also trigger another accident. It can be observed that radiation consequences are concentrated more toward the downwind direction due to flame tilt caused by the wind as equally reported by (Pula *et al.*, 2005). Table 5 gives the fireball downwind distance to experience 4, 12.5 and 37.5 kw/m^2 radiation intensities and fireball diameter.

Table 5: Fireball downwind distance to experience defined radiation levels, for Weather Category 5/D

Scenario	Down Distance [m]to Radiation Levels			
	4 kw/m^2	**12.5 kw/m^2**	**37.5kw/m^2**	**Fireball Diameter**
15mm Leak	7.128	1.756	n/a	4.607
30mm Leak	7.128	1.756	n/a	4.607
50mm Leak	7.128	1.756	n/a	4.607
100mm leak	7.128	1.756	n/a	4.607

Figure 4 gives radiation levels and respective downwind distance for fireball

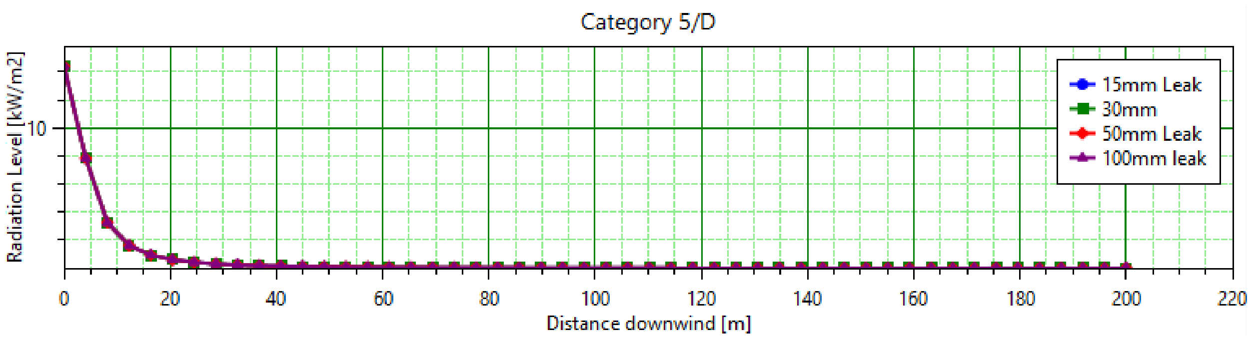

Figure 4. Radiation vs. Distance for Fireball

For the fireball, 15, 30, 50 and100 mm leak size show the same fire ball diameter of 4.607 m also the same downwind distance of 7.128 m to 4kw/m^2 intensity level, and 1.756 m to 12.5 kw/m^2 intensity. 37.5 kw/m^2 intensity could not be experienced for the different leak sizes as shown in Figure 4 and Table 5. The 12 kW/m^2 radiation intensity which could be experienced up to a distance of 1.756m from the epicenter may result in damaging of plastic materials and second degree burn to operators that are within the radius.

Table 6 gives scenarios downwind distance to lower and upper flammability limit of flash fire

Table 6: Flash fire downwind distance to defined concentrations, for Weather Category 5/D

Scenario	Down Distance [m]to LFL, LFL Fraction and UFL		
	LFL[m]	LFL[Fractions]	UFL
15mm Leak	3.211	5.644	0.6181
30mm Leak	5.17	10.45	1.224
50mm Leak	9.92	16.15	2.026
100mm leak	16.25	22.46	4.01

Figure 5 shows the flash fire envelope downwind distance for different scenarios at concentration of 8000 ppm

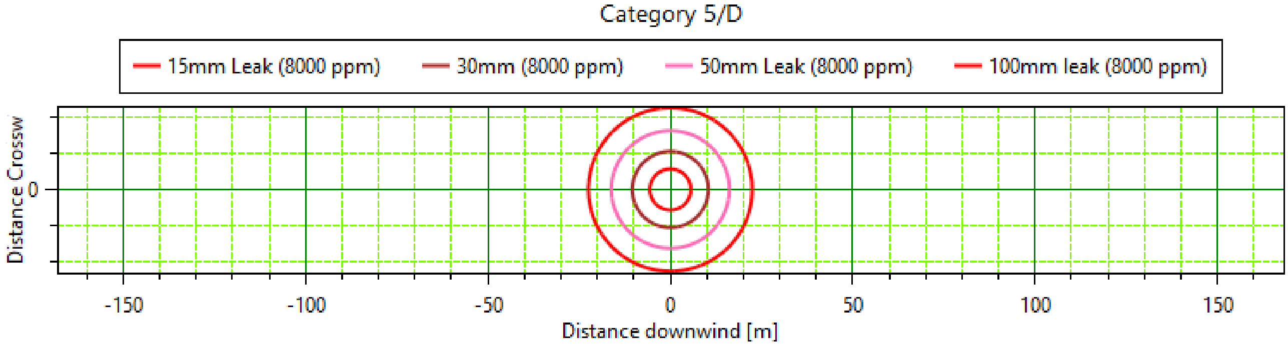

Figure 5: Flash Fire Envelope

Figure 5 shows that 15, 30, 50 and 100 mm leak sizes have the maximum downwind distances to Lower Flammability Limit (LFL) of 5. 64, 10.45, 16.15 and 22.46 m respectively with 100 mm leak scenario having the highest distance, the increase of LFL is due to increase in leak size. The LFL gives an idea on where the ignition could start below which no ignition is expected stoichiometrically. The flash fire envelope at concentration of 8000 and 16000 ppm for different scenarios is shown in Plate I.

Plate I: 10H01 LPG Fuel Pipe Flash Fire Envelope (on KRPC Arial Map)

Table 7 gives downwind distance to defined explosion overpressure for the different scenarios.

Table 7: Late explosion overpressure downwind distance to experience defined overpressures, for Weather Category 5/D

Scenario	Max. Distance [m]to Overpressure		
	1.02068 bar	**1.1379 bar**	**1.2068 bar**
15mm Leak	0	0	0
30mm Leak	25.15	12.94	12.21
50mm Leak	29.01	13.7	12.77
100mm leak	0.0	0.0	0.0

From Table 7, it can be seen that none of the three pressure levels was observable in the case of the 15 mm leak size which suggests that the concentration falls below the Lower explosive Limit. The Upper explosive limit was also exceeded in the case of the 100 mm leak size hence there was no explosion. However, both 30 and 50 mm leak cases fell within the explosive limits.

The 1.2068 bar overpressure could result in minor damage to structures, partial demolition of houses and shattering of corrugated asbestos as highlighted in Table 2.

Table 8 gives downwind distance to defined explosion overpressure for the different scenarios

Table 8: Maximum overpressure distance to experience defined overpressures, for Weather Category 5/D

Scenario	Max. Distance [m]to Overpressure		
	1.02068 bar	**1.1379 bar**	**1.2068 bar**
15mm Leak	0	0	0
30mm Leak	30.3	5.9	4.4
50mm Leak	38.0	7.4	5.5
100mm leak	0.0	0.0	0.0

For leak size 30 mm, overpressures of 1.02, 1.14 and 1.21 bar could be experienced at about 30, 6 and 4 m respectively away from the fired heater which could result in partial demolition of structures that are within the radius as highlighted in Table 2. For the 15 and 100mm leak size, all the overpressure scenarios (1.02 - 1.21 bars) may be experienced right at the epicenter.

CONCLUSION

From the results presented above, it can be seen that the 30m radius (with the crude oil fired heater at the epicenter) is particularly vulnerable to both fire and overpressure impacts. In particular, radiation level of up to 37.5 kW/m^2 could be experienced 25m away from the fired heater in the downwind direction. This radiation level is fatal and could damage process equipment catastrophically. Also, there is potential for ignition up to 16m away from the fired heater. Flame length and downwind distance to radiation intensity of a jet fire increase with increase in leak size. Overpressures of 1.02, 1.14 and 1.21 bar could be experienced at 30, 6 and 4 m respectively away from the fired heater which could result in partial demolition of structures that are within the radius. Leak size plays a significant role in fire accident. Therefore, leak should be prevented by minimizing number of joints, elbows, bend, using corrosion resistant pipes and proper maintenance practice. Ignition sources, such as sparks, hot surfaces and open flames should be eliminated within the 30 m radius (at least). Robust protective layers such as bund/dike, efficient emergency response plan and high integrity safety instrumented systems should be put in place to prevent/mitigate the thermal and overpressure incidents.

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