Petroleum and Coal

Article **Open Access**

Pipeline Leak Analysis, Risk Assessment and Consequence Evaluation and Remedial Actions

Henry Freedom Ifowodo; Christopher Okechukwu Izelu; Chinedum Ogonna Mgbemena

Department of Mechanical Engineering, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria

Received February 20, 2023; Accepted July 3, 2023

Abstract

Pipeline leak is a necessary evil that the petroleum industry has to deal with occasionally from time to time. Depending on the gravity of the leakage, each leak comes with diverse consequences ranging from mere land or water pollution to catastrophes like ecosystems, lives, and property destructions, tarnishing the image and reputation of the industry concern and leading to unending litigation. This paper described a mathematical procedure for finding, locating, and quantifying a fossil oil pipeline leak. The derived leak rate is integrated into a designed crude oil model for pipeline leak analysis, risk assessment and consequence evaluation of fossil oil pipeline leakages. The analysis helps classify and rank the severity and consequences of pipeline leaks and the necessary remedial actions to be taken bearing in mind the gravity of these severities and consequences to avoid legal suits.

Keywords: *Pipeline leak analysis; Fluid model; Risk analysis; Consequence evaluation; Remedial actions.*

1. Introduction

The importance of risk assessment and analysis cannot be overemphasized as it cut across all fields in the petroleum industry [1]. Risk management employs certain scientific principles and standards to create a systematized approach so as to achieve its aims and assist people in protecting themselves, their assets, and their activities against occurrences that always put them in danger. This enables individuals, entities, and establishments to come up with a vision to assess, control and finance damages and put a plan in place to check potential future recurrences [2].

Petroleum is one of the vast natural resources provided to man by nature. Extracting petroleum comes along with diverse challenges involving risks and potential hazards. One of the great challenges is the failure or leakage of petroleum transportation pipelines which is a dreaded occurrence in the petroleum industry. Top incidents that are catastrophic with several fatalities have taken place foretime as a result of pipeline leaks or failure particularly if spills were met with ignition sources resulting in explosions and infernos. As a result of the socio-economic and environmental costs of hydrocarbon leaks, the petroleum industry places much interest and focus on how to mitigate leak incidents [3].

Pipeline leaks must be prevented at all costs not only because of the loss of fluid content but also because of its aftermath and devastating effects on people, assets, environments and the reputation of the petroleum industry [4]. Hydrocarbon spills result in pollution and degradation of the environment, destruction of arboreal, terrestrial, and aquatic ecosystems, destruction of vegetation, land wastage, destruction of lives and property, direct product expenses and idle time lost, expenses of remedial works and environmental cleanup, imposed fines and litigations [5]. Pipeline leak incidents are caused by corrosion, rupture, mechanical integrity failure, operational error, third-party activity, intentional act of vandalism, natural hazard, obsolescence, design fault and/or poor process design, uncontrolled or unexpected reactions, human errors [6-7]. No matter how much attention or interest is paid to pipelines, there must always be leak incidents as it is impossible to absolutely eliminate or to have total control over all the causes of pipeline leak. Therefore, the antidote to the pipeline leak menace is an adequate and reliable emergency response and quick recovery procedure or policy put in place. For this to be achievable there must be prompt detection of pipeline leak whenever it occurs to prevent escalation of the incident. The length of time between when a leak occurs and when it is detected must be made infinitesimal as much as possible. This is possible with a good and reliable leak detection system. If pipeline operators are alerted of pipeline leak or failure in the early stages with immediate effect, the adverse effects of such failure and its impending consequences can be mitigated.

The emergency response and quick recovery procedures adopted in Niger Delta area is inefficient and ineffective. These have resulted to some catastrophic and devastating effects on the region. In 1998, there was a pipe leak that flooded a large area of Jesse community which resulted to an explosion in which over seven hundred (700) people perished; two years after, three hundred (300) persons died as a result of two pipeline explosions in the southern part of Nigeria [8]. Large quantity of fossil oil spillage has transformed a great portion of Ogoni community into wastelands. For instance, in 2001, an internet page of the United Nations depicts Yaata, a village in Ogoni as an uninhabitable environment as dying vegetation in divers form with soil polluted fossil oil spills turning soggy, dark, and greasy in nature [9].

Nigeria Focus (2001) disclosed that on 29th April 2001 at Yorla oil field belonging to SDPC, there was a quiver that brought about violent disturbance in an Ogoni village called Yaata and nearby communities. In no time and before people could realize that something is not right, jet spray of fossil oil were already up as high as 100 meters, showering on the environment. The oil jets associated with intense vapor of fossil gas, hasten the villagers to run for safety as the community became uninhabitable. Persons engulfed by the vapors started experiencing shortness of breath together with coughing as well as mucus discharge from their nostrils. The resulted streams of fossil oil flooded nearby farmlands, forests, streams and rivers which contaminated drinking water and destroyed crops, plants, fishes and livestock. The spilled fossil oil penetrated further beneath surface, contaminating underground water miles below and around. Similar cases of different magnitude have been noted in all regions where fossil oil pipelines crisscrossed in Nigeria.

The NPDC Olomoro oil field is not an exception as leakages are major reasons for process and operation’s shutdown. Fossil oil leakages have changed a great part of the Olomoros' homeland into wastelands causing vegetation destruction, drenched soil having dark and greasy color as fossil oil penetrates in and deep down the soil. Oil spill from leakages has played a significant adverse role because it wasted lands, destroy vegetation/environment, and create an ecological dead region in water courses that supplied consumable water for the local residents. It has met with fire sources that have potentially led to fire accident/explosion with negative and unfavorable consequences. On July 3, 2006, for instance, leakages from the outlets of a triple wellhead have generated an ecological dead zone near Ukoli community in Olomoro. Furthermore, on October 1, 2012 leakages from a pipeline conveying fossil oil from reservoir seeped into ponds and farmlands that caused a wild protest by the indigenes of Olomoro which led to litigation and fines and damages were paid by the company. In yet another development, on April 30, 2014 there was an inferno caused by pipeline leak at the wellhead of well 20 in Olomoro field that met with fire from bush burning that resulted to injuries, destruction of natural resources, lives and property etc. All of these are but few examples of problems caused by pipeline leaks in the petroleum industry in Nigeria generally. To avoid tragedy, 24hr surveillance should be mandatory. Pipeline leak detection using online software plays a vital part in the overall management of pipeline system integrity because workers' perambulation efficiency is quite low [10].

Preventing content spillage is a principal aim of the industrial Process Safety Management programs [11]. A total comprehension of the risks, the identification of a wide range of failure-causing events, and a thorough analysis of the effects of events that are likely to result in failure., and an assessment all the risks in a process that accounts for all the protections can help majorly in averting and reducing loss fossil oil occurrences [9]. A crucial first step is to have a fundamental understanding of and thorough assessment of the risks which, should go beyond mere surveying or sharing material safety data sheets. Second step, is a comprehensive examination of the entire range of failure modes using qualitative and quantitative techniques to gather information about possible outcomes. A hazard evaluation team can evaluate the sufficiency of a system with a thorough understanding of hazards and their effects as well as exact process data and the protection strata necessary for averting spillage events.

2. Methodology

In this work, the pipeline leak analysis, risk assessment and the evaluation consequences and remedial actions in place consists of two stages: which include a procedure for pipeline leak finding and locating analysis and a crude oil fluid model algorithm for risk assessment, consequence evaluation and remedial actions. These will be achieved by:

1. An analysis of a procedure for finding and locating fossil oil pipeline leak
2. A description of a fluid model algorithm for crude oil for risk assessment, consequence evaluation and remedial actions.

2.1. Analysis of a procedure for finding and locating fossil oil pipeline leak

In this section, a suitable procedure for finding and locating fossil oil pipeline leak is formulated based on SCADA as follows:

- **Determine the change in pressure or pressure drop**

The disparities between the intake pressure and the output pressure are what cause the pressure drop or change in pressure. It is acquired through:

$$\Delta P = P_I - P_O \qquad (1)$$

where ΔP= pressure drop; P_I= inlet pressure and P_O= outlet pressure

- **Determine the velocity profile**

Since the flow rate along the pipeline is not uniform, the velocity profile represents the fluid's average speed. It is acquired through:

$$v = \frac{D^2}{32\mu} . \frac{\Delta P}{L} \qquad (2)$$

where v = average velocity; D = diameter of pipe; μ = viscosity; ΔP = pressure drop and L = length of pipe.

- **Determine the Renold's number, Re**

The following relation is used to compute the flow's Renold's number.:

$$Re = \frac{\rho D v}{\mu} \qquad (3)$$

where ρ = density of fluid; D = diameter of pipe; v = average velocity; μ = viscosity

- **Determine the Darcy-Weisbach Frictional Factor**

Friction is one of the factors that contribute to pipeline pressure drops. The pressure loss is handled by the Darcy friction. This model adapts the Goudar-Sonnad equation to obtain the Darcy-Weisbach frictional factor because it provides a better and more precise approximation of the Colebrook-White equation. It is acquired by applying the relations:

$$a = \frac{2}{\ln(10)}; \quad b = \frac{\varepsilon/D}{3.7}; \quad d = \frac{\ln(10)\, Re}{5.02}; \quad S = bd + \ln(d);$$

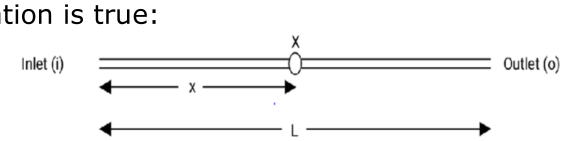
$$q = s^{s/(s+1)}; \quad g = bd + \ln\frac{d}{q}; \quad z = \ln\frac{q}{g}; \quad D_{LA} = z\frac{g}{g+1};$$

$$D_{CFA} = D_{LA}\left(1 + \frac{z/2}{(g+1)^2 + (z/3)(2g-1)}\right); \ \frac{1}{\sqrt{f}} = a\left[\ln\left(\frac{d}{q}\right) + D_{CFA}\right] \qquad (4)$$

where ε = roughness of pipe wall; D = diameter of pipe; ε/D = relative roughness; Re = Renold's number; f = Darcy frictional factor

- **Determine the inlet state pressure and its pressure drop**

Consider a pipeline section with inlet I and outlet O. A leak occurred at an unknown point x; then the following relation is true:



$\frac{P_I^2-P_x^2}{x} = KQ^2$ and $\frac{P_x^2-P_O^2}{L-x} = KQ^2$

Therefore; $\frac{P_I^2-P_x^2}{x} = \frac{P_x^2-P_O^2}{L-x}$

$x(P_x^2 - P_O^2) = (L-x)(P_I^2 - P_x^2)$

$xP_x^2 - xP_O^2 = (L-x)P_I^2 - (L-x)P_x^2$

$\cancel{xP_x^2} - xP_O^2 = LP_I^2 - xP_I^2 - LP_x^2 + \cancel{xP_x^2}$

$LP_x^2 = xP_O^2 + LP_I^2 - xP_I^2$

$P_x^2 = P_I^2 - \frac{x}{L}P_I^2 + \frac{x}{L}P_O^2$

Using the formula (5), the state pressure at a position x from the pipeline's inlet is calculated.:

$$P_x = \sqrt{P_I^2 - (P_I^2 - P_O^2)\frac{x}{L}} \tag{5}$$

where P_x = state pressure at point x; P_0 = outlet pressure; P_I = inlet pressure; x = a point away from the inlet; L = length of pipe.

Then, using the relationship in equation (1), the pressure drop at a position away from the inlet is computed. $\Delta P_x = P_I - P_x$

- **Determine the inlet and outlet mass flow rates**

The Darcy-Weisbach equation is used in the model to calculate the mass flow rate at a position 1 m from the input and at the outflow, as shown below:

$$M_I = \sqrt{\frac{\pi^2 D^5 \rho \Delta P_x}{8fx}} \tag{6a}$$

where M_I = inlet mass flow rate; D = diameter of pipe; ρ = density of fluid; ΔP_x = pressure drop at a point x (1m) from inlet; f = Darcy-Weisbach frictional factor; x = a point (1m) at the inlet.

$$M_o = \sqrt{\frac{\pi^2 D^5 \rho \Delta P}{8fL}} \tag{6b}$$

where M_o = outlet mass flow rate; D = diameter of pipe; ρ = density of fluid; ΔP = pressure drop along the pipeline; f = Darcy-Weisbach frictional factor; L = length of pipeline.

- **Determine the discrepancies**

The measured (inlet and outlet) flow rates and the observed/estimated (inlet and outlet) flow rates are often equal before the occurrence of a leak, with their remainders being zeros or almost zero.

$$x = M_I - \dot{M}_I \tag{7a}$$

where x = discrepancies of mass flow rates at the inlet; M_I = observed/estimated inlet mass flow rate and $\dot{M}_I$ = measured inlet mass flow rate. $y = M_O - \dot{M}_O$ (7b)

Where y = discrepancies of mass flow rates at the outlet, M_O = observed/estimated outlet mass flow rate and $\dot{M}_o$ = Measured outlet mass flow rate.

- **Determine the leak flow rate**

The mass flow rate of the leakage is the difference between the mass flow rates at the pipeline's intake and outflow. It is provided as: $\dot{M}_{Leak} = x - y$ (8)

- **Determine the leak position**

The relationship between the leak flow rate and pipeline length (L) determines the leak position. It is provided as: $X_{Leak} = \frac{-y}{x-y}L$ (9)

The Leak flow rate $\dot{M}_{Leak}$, is the point of integration between the leak detection model and the crude oil fluid model. The leak flow rate in the Leak detection model is the liquid emission rate in the crude oil fluid model as seen in the following section.

2.2. Description of the crude oil fluid model for evaluation of leakage consequences

The evaluation of the consequences of a hazardous fluid can be done with the computational analysis of the fluid model. Crude oil is not health friendly and it is catastrophic when come in contact with fire which could result to multiple fatalities. The leak rate and/or leak quantity determines the extent of damage that could result from a hazardous fluid. The emission rate and volatility also play vital roles in determining the danger or catastrophic consequences pose by such fluid. Hence the pipeline conveyance model will be fused with the crude oil fluid model developed from computational analysis for crude oil.

A thorough explanation of the quantitative model, which was modified from the Dow Chemical Exposure Index (2006) for a poisonous and flammable fluid, that was used to estimate the effects of hazards for the evaluation of leakage consequences. In outline, the model comprises the following stages:

- **Determine the liquid emission rate:**

The liquid emission rate here is the fossil oil pipeline leak flow rate as obtained in equation 8 under pipeline leak analysis.

- **Determine the total mass released:**

To determine the size of the pool, the total amount of material contributing to the pool's development must be estimated. The pool is estimated to reach its final size after 15 minutes (900 seconds) for a continuous discharge with a longer period (one lasting more than 15 minutes). The mass determining the pool size in this instance is equal to the release rate multiplied by 15 minutes, or 900 seconds. The total amount of liquid that has leaked (W_T) is provided by:

$$W_T = t\dot{M}_{Leak} \quad t = 900sec \tag{10}$$

Compare the system's inventory to the W_T that has been calculated. The lesser of these two figures is used to represent the overall amount of liquid believed to have been released.

- **Determine the flash fraction:**

The liquid's operational temperature should be compared to its typical boiling point. The flash percent is 0 if the temperature is below the typical boiling point. Determine the fraction flashed (F_v) by if the temperature is higher than the typical boiling point:

$$F_v = \frac{C_p}{H_v}(T_s - T_b) \tag{11}$$

where; T_b = typical boiling point of the liquid °C; T_s = operational temperature of the liquid °C; C_P = average heat capacity of the liquid J/kg/°C; H_v = heat of vaporization of the liquid J/kg.

- **Determine the airborne quantity due to flash:**

The amount of airborne material the flash created (AQ_f) is given by:

$$(AQ_f) = 5F_v\dot{M}_{Leak} \tag{12}$$

where; $\dot{M}_{Leak}$ = leak flow rate (kg/sec). If $F_v \geq 0.2$ then $AQ_f = \dot{M}_{Leak}$ and no pool develops

- **Determine the pool size:**

Mass crude oil (W_p) entering the pool as a whole is given by:

$$W_p = W_T(1 - 5F_v) \tag{13}$$

where; W_T = total liquid released (kg); F_v = fraction flashed

As long as none of the material flashes, it should be noted that;

$$W_p = W_T \text{ (kg)} \tag{14}$$

The pool area (A_p) is given by:

$$A_p = 100\frac{W_p}{\rho} \tag{15}$$

where; W_p = mass entering the pool as a whole (kg); ρ = density (kg/m^3).

- **Determine the airborne quantity due to evaporation:**

$$(AQ_p) = 9.0(10)^{-4}(A_p^{0.95})\frac{(MW)P_v}{T_p+273} \tag{16}$$

where; A_p = pool region (m^2); MW = molecular weight; P_v= liquid's vapour pressure at the typical pool temperature (kPa); T = typical pool temperature (°C)

With; $T_p = T \qquad T_a < T < T_b \qquad = T_b \qquad T \geq T_b$

- **Determine the total airborne quantity**

The total number of particles in the atmosphere (AQ) is determined by:

$$(AQ) = (AQ_f) + (AQ_p) \qquad [(AQ_f) + (AQ_p)] < \dot{M}_{Leak} \tag{17}$$
$$= \dot{M}_{Leak} \qquad [(AQ_f) + (AQ_p)] \geq \dot{M}_{Leak}$$

where; AQ_f = the amount of flying particles caused by the flash (kg/sec); AQ_p = airborne amount evaporated from the surface of the pool. (kg/sec). Set $AQ = \dot{M}_{Leak}$ if the total airborne quantity (AQ) exceeds the leak flow rate $\dot{M}_{Leak}$..

- **Determine the hazard distances and injury/fatality areas (toxic release):**

The value of EPRG-3 is employed. The EPRG-3 number represents the concentration at which almost everyone could spend an hour without experiencing any serious health consequences.

$$HD = 6551\left(\frac{(AQ)}{ERPG-3}\right)^{1/2} \qquad (18)$$

where HD = hazard distance; EPRG-3 = emergency response procedure guideline.

The standard Dow hazard distance is as follows. What is needed, though, is a concentration that, for example, has a 50% chance of death after 5–10 minutes of exposure. As a result, the concentration must be raised in order to adapt the toxic effect from harm to death and to accommodate the shorter exposure time. For time adjustment for concentration, a factor of 10 is used so that:

$$HD_i = \frac{HD}{10^{1/2}} \qquad (19)$$

Additionally, a further factor of 10 is used to adjust from injury to fatality in order to account for the fact that a concentration that is fatal is higher than one that is only injurious:

$$HD_f = \frac{HD_i}{10^{1/2}} \qquad (20)$$

The location of toxic injury is then;

$$A_{ti} = \frac{\pi}{4}(HD_i)^2 \qquad (21)$$

And toxic fatality is

$$A_{tf} = \frac{\pi}{4}\left(HD_f\right)^2 \qquad (22)$$

- **Determine the hazard distances and injury/fatality area (flammable release):**

The same calculation is used for hazard distance for a flammable release, but the lower flammability limit is substituted for the ERPG value. Burgoyne gives the hydrocarbon LFLs from which an average value is derived. Thus, $C_{lfl} = 0.05\ ozft^{-3} = 0.05gl^{-1} = 50{,}000mgm^{-3}$

Hence; $$HD_{fl} = 6551\left(\frac{(AQ)}{C_{lfl}}\right)^{1/2} \qquad (23)$$

Half of this amount is assumed to be the cloud's effective diameter.

$$D_{fl} = 0.5HD_{fl} \qquad (24)$$

Only fatalities are calculated for clouds that are flammable. For this reason, it is presumed that no one outside the ignited cloud perishes.

Hence $$A_{flf} = \frac{\pi}{4}\left(D_{fl}\right)^2 \qquad (25)$$

- **Determine the appropriate population density (toxic release):**

Fundamental tasks population density

For the fundamental tasks of population density, $D_p = 0.003$ persons m^{-2} is used.

Effect of escape/shelter

It is unrealistic to suppose that if a hazardous discharge takes place, those impacted will stay in the cloud's path. They'll try to get away. This is especially true for the relatively minor releases. In other circumstances, they will find shelter on their own or will already be there. For toxic gas clouds, it is assumed that there is a 1 in 30 chance that there won't be any escape or shelter. By dividing the population density by 30, or applying an escape/shelter mitigation factor E = 0.033, this effect will be taken into consideration. After accounting for emigration and shelter, the effective population density is

$$D_{pe} = ED_p \qquad (26)$$

- **Determine the suitable population density (flammable release):**

Fundamental tasks population density

The population density is the same as that utilized in the toxic discharge scenario, i.e. $D_p = 0.003$ persons m^{-2} .

Effect of escape/shelter: Again, space must be left for safety/shelter. E = 0.1 because it is estimated that there is a 1 in 10 chance that there won't be any escape or shelter in poisonous gas clouds. This number is higher than the hazardous release value that was suggested. One explanation is that toxics frequently emit stronger warning aromas. Another is that unlike combustible clouds, which only become harmful when ignited—which happens in a small percentage of cases—whereas toxic clouds are always harmful. As a result, people strive to stop it more frequently, exposing themselves in the process. When a fire starts, the flame usually spreads quickly through the cloud. After accounting for emigration and shelter, the effective population density is given by equation (26) as: $D_{pe} = ED_p$

Effect of ignition: The likelihood of igniting is a further consideration while dealing with flammable clouds. This chance rises with the size of the leak for a gas leak. The equation that follows can be used to fit the line.

$$P_i = \exp[-4.16 + 0.642\ln(AQ)] \qquad P_i \le 0.3 \tag{27}$$

This formula accounts for emission rates up to $100kgs^{-1}$ per year.

Within this range, the majority of the emissions of interest will fall. Extrapolating the equation to greater flows is generally appropriate for the time being. When accounting for cloud ignition, the actual population density is $D_{pei} = P_i D_{pe}$ (28)

- **Determine the quantity of fatalities and injuries (toxic release)**

The count of injuries is then $I = A_{ti}D_{pe}$ (29)

And fatalities $F = A_{tf}D_{pe}$ (30)

- **Determine the quantity of fatalities and injuries (flammable release)**

We just take fatalities into account.

The number of deaths is: $F = A_{flf}D_{pei}$ (31)

2.3. Method of data collection

The data collected for this work are combinations of both static and dynamic parameters such as the fluid density, molecular weight, dynamic viscosity, EPRG-3, lower flammability limit, vapour pressure, pipeline operating temperature, average boiling point of crude, pipeline length, diameter and roughness of the pipeline. These specifications were taken from the manufacturer's manual for a commercial steel pipeline, the qualities of the oil being transported (Nigerian Bonny Light Crude Oil), the SCADA system in the control room, and the Heritage Energy Operational Services Limited (HEOSL) archive shown it Table 1.

Table 1. Static and dynamic parameters of fossil oil transmission pipeline

Parameters	Values	Units
Pipe's diameter, D	0.3556	Meter
Pipe's length, L	5000	Meter
Pipe's roughness, ε	0.0000457	Meter
Mass flow rate (input), $\dot{M}_I$	72.08	kg/s
Mass flow rate(output), $\dot{M}_O$	65.05	kg/s
Pressure (input) P_I	149.985	kPa
Pressure (output), P_O	105.005	kPa
Density of fluid, ρ	834.2	kg/m³
Molecular weight, MW	417	-
Dynamic viscosity, μ	0.00172	Pa.s
ERPG-3	58	mg/m^3
Lower flammability limit, C_{lfl}	50,000	mgm^{-3}
Vapor pressure (atmospheric) P_v	101.3	kPa
Pipeline operating temperature, T	22.5	°C
Average boiling point, T_b	500	°C

3. Results and discussions

Table 2 show the results obtained from the procedure for a leak found and located on a pipeline and the leak consequences evaluation necessary for the remedial action required to be taken:

Table 2. Procedure for fossil oil pipeline leak detection

Procedure for finding and locating fossil oil pipeline leak	
Quantity	Value
Change in Pressure or pressure drop, ΔP (ref: eqn. 1)	$44.98 kPa$
Velocity profile, v (ref: eqn. 2)	$20.67 m/s$
Renold's number, Re (ref: eqn. 3)	3564872.22
Darcy-Weisbach frictional factor, f (ref: eqn. 4)	0.013
Inlet mass flow rate (ref: eqn. 6a)	$82.17 kg/s$
Outlet mass flow rate (ref: eqn. 6b)	$51.93 kg/s$
Inlet flow rate discrepancy, x (ref: eqn. 7a)	$10.09 kg/s$
Outlet flow rate discrepancy, y (ref: eqn. 7b)	$-13.12 kg/s$
Leak flow rate (ref: eqn. 8)	$23.21 kg/s$
Leak position (ref: eqn. 9)	$2826.37\ m$
Crude oil fluid model for evaluation of leakage consequences	
Liquid emission rate (=leak flow rate), L (ref: eqn. 8)	$23.21 kg/s$
Total mass of liquid released, W_T (ref: eqn. 10)	20889kg
Flash fraction, F_v (Since OT < NBP) (ref: eqn. 11)	0
Airborne quantity due to flash, AQ_f (ref: eqn. 12)	0
Pool size, W_p ($W_p = W_T$) (ref: eqn. 14)	20889kg
Pool area, A_p (ref: eqn. 15)	$2504 m^2$
Airborne quantity due to evaporation, AQ_p (ref: eqn. 16)	$217 kg/sec$
Total airborne quantity, AQ (AQ = L) (ref: eqn. 17)	$23.21 kg/s$
Hazard distance for toxic release, HD (ref: eqn. 18)	4144m
Hazard distance for toxic injury, HD_i (ref: eqn. 19)	1310m
Hazard distance for toxic fatality, HD_f (ref: eqn. 20)	414m
Area for toxic injury, A_{ti} (ref: eqn. 21)	$1347822 m^2$
Area For toxic fatality, A_{tf} (ref: eqn. 22)	$134614 m^2$
Hazard distance for flammable release, HD_{fl} (ref: eqn. 23)	141m
Effective diameter of cloud, D_{fl} (ref: eqn. 24)	71m
Area for flammable release fatality, A_{flf} (ref: eqn. 25)	$3959 m^2$
Fundamental tasks population density, D_p	0.003 persons m^{-2}
Escape/shelter factor for toxic release, E	0.033
Effective population density for toxic release, D_{pe} (ref: eqn. 26)	0.0001
Escape/shelter factor for flammable release, E	0.1
Effective population density for flammable release, D_{pe}	0.0003
Effect of Ignition, P_i (ref: eqn. 27)	0.118
Effective population density adjusted for cloud ignition, D_{pei} (ref: eqn. 28)	$3.54(10^{-5})$
Quantity of injuries for toxic release, I (ref: eqn. 29)	404
Quantity of fatalities for toxic release, F (ref: eqn. 30)	40
Quantity of fatalities for flammable release, F (ref: eqn. 31)	0.14

3.1. Injuries and fatalities classification and consequences ranking

The risk ranking system determined specifically by the relationship between rank and the quantity of injuries and fatalities is summed up in Table 3. The following Table 4 has been created based on Table 3.

Table 3. Hazards ranking scheme [12]

Rank	Severity	Rank bases
5	Catastrophic	Three or more fatalities
4	Severe	Injuries to more than 5
3	Major	Injuries to less than 5, one in 10 chances fatality
2	Appreciable	Injury
1	Minor	Possible injury

Table 4. Injuries/fatalities ranking table [12]

Rank	Injuries	Fatalities
1	$I < 0.1$	$F < 0.01$
2	$0.1 \leq I < 0.5$	$0.01 \leq F < 0.05$
3	$0.5 \leq I \leq 5$	$0.05 \leq F \leq 0.5$
4		$0.5 < F < 3$
5		$F \geq 3$

Considering the quantity of injuries and fatalities which are on the high side, the toxic release severity is classified and ranked as 5, with catastrophic consequences. Furthermore, considering the number for flammable release, the severity is classified and ranked as 3, with major consequences. However, for an entire scenario, the highest severity rank is used. Therefore for this incident, the severity is at the apex rank number 5 with catastrophic consequences. Management decisions and remedial actions are to be taken bearing severity 5 with catastrophic consequences in mind.

4. Conclusion and recommendation

It is highly recommended that petroleum industry emergency response department, process safety and risk management team should adopt the method discussed in this work to carry out their jobs effectively and efficiently to mitigate leakage consequences and proffer solutions to remedy an incident. An appropriate remedial actions and compensation in accordance with the weight of damages caused due to pipeline leak incidents could be come to terms with as x-rayed by the consequences ranking and classification.

References

[1] Mhanna A, Halafawi M, Charif M, Dilbani AE, Habib S, Albulescu A, Florinel D, Avram L. Environmental Impacts and Risk Assessment for Offshore Field in Lebanon: The First Exploratory Well Case Study. Petroleum and Coal, 2022; 65(2): 271-294.

[2] Mozaffari S, Jamshidi R. Environmental, Health, and Safety Risk Assessment in Marun's oil Field using the FMEA Method. Petroleum and Coal, 2022; 65(1): 164-171.

[3] Cordes EE, Jones DOB, Schlacher TA, Amon DJ, Bernardino AF, Brooke S, Carney R, DeLeo DM, Dunlop KM, Escobar-Briones EG, Gates AR, Génio L, Gobin J, Henry L-A, Herrera S, Hoyt S, Joye M, Kark S, Mestre NC, Metaxas A, Pfeifer S, Sink K, Sweetman AK and Witte U (2016) Environmental Impacts of the Deep-Water Oil and Gas Industry: A Review to Guide Management Strategies. Front. Environ. Sci. 4:58. https://doi.org/10.3389/fenvs.2016.00058 .

[4] Guire WMC, Holtmaat E A, Prakash A. Penalties for industrial accidents: The impact of the Deepwater Horizon accident on BP's reputation and stock market returns. PLOS ONE, 2022; 17(6): 1-20. https://doi.org/10.1371/JOURNAL.PONE.0268743

[5] Akpan EE, Akpan EE. Environmental Consequences of Oil Spills on Marine Habitats and the Mitigating Measures - The Niger Delta Perspective. Journal of Geoscience and Environment Protection, 2022; 10(6): 191-203. https://doi.org/10.4236/GEP.2022.106012

[6] Landrigan PJ, Raps H, Symeonides C, Chiles T, Cropper M, Enck J, Hahn ME, Hixson R, Kumar P, Mustapha A, Park Y, Spring M, Stegeman J, Thompson R, Wang Z, Wolff M, Yousuf A, Dunlop S. Announcing the Minderoo – Monaco Commission on Plastics and Human Health. Annals of Global Health, 2022; 88(1): 1-215. https://doi.org/10.5334/AOGH.3916

[7] Rusin A, Stolecka-Antczak K., Kapusta K., Rogoziński K., Rusin, K. Analysis of the Effects of Failure of a Gas Pipeline Caused by a Mechanical Damage. Energies, 2021; 14(22): 1-21. https://doi.org/10.3390/EN14227686

[8] Emmanuel A, & Emmanuel OD. United Nations and Conflict Resolution In Nigeria: A Study Of The Ogoni Crisis. Public Policy And International Affair Academic Journal, 2021; 3(3): 1–11. https://cirdjournal.com/index.php/ppiaaj/article/view/38

[9] Chinwuko EC, Ifowodo HF, Umeozokwere AO. Risk Assessment and Consequence Evaluation of Loss of Containment in Petroleum Industry. International Journal of Modern Studies in Mechanical Engineering, 2016; 2(1): 14-28 https://doi.org/10.20431/2454-9711.0201002

[10] Adegboye MA, Fung WK., Karnik A. Recent advances in pipeline monitoring and oil leakage detection technologies: Principles and approaches. Sensors), 2019; 19(11). 1-36 https://doi.org/10.3390/S19112548

[11] Halim SZ, & Mannan MSM. A journey to excellence in process safety management. Journal of Loss Prevention in the Process Industries, 2018; 55: 71–79. https://doi.org/10.1016/J.JLP.2018.06.002

[12] Purohit DP, Siddiqui DA, Nandan A, Yadav DP. Hazard Identification and Risk Assessment in Construction Industry. International Journal of Applied Engineering Research, 2018; 13(10): 7639–7667.

To whom correspondence should be addressed: Dr. Chinedum Ogonna Mgbemena, Department of Mechanical Engineering, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria,
E-mail: mgbemena.ogonna@fupre.edu.ng