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Risk Modelling of Fires and Explosions in Open-Sided Offshore Platform Modules

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Abstract

Incidents involving fires and explosions present a major hazard to the workforce on offshore oil and gas platforms. Following the Piper Alpha Disaster in 1988, platform operators for the UK sector are required to submit safety cases for approval by the Health and Safety Executive. A key requirement of these safety cases is that hazards associated with an accidental release of hydrocarbons have been demonstrated to be as low as reasonably practicable.

This paper aims to describe a process for estimating the expected number of fatalities on offshore platforms with open-sided modules using a Monte Carlo simulation method implemented within the SAROS (Safety and Reliability of Offshore Structures) software. The process involves estimation of the frequency and magnitude of jet fires, pool fires and explosions. This is combined with the distribution of the workforce over the platform at the time of the incident to predict the risk of fatality.

Notation

A	Cross-sectional area of the hole	m^2
A_{px}	Previous surface area of pool	m^2
C	Constant representing the fraction of LFL at which the detector is activated	%
C_g	Concentration of the gas within the module	%
C_s	Stoichiometric concentration	%
D	Pool fire diameter	m
d_p	Depth of oil pool	m
$F(t)$	Cumulative Failure Distribution	
F_c	Fraction of the module occupied by the gas cloud	-
F_j	Flame length of Jet Fire	m
F_p	Flame length of Pool Fire	m
g	Acceleration due to gravity	ms^{-2}
h	Assumed minimum gas cloud diameter	m
H_{HEAD}	Height of the head of oil above a leak on a vessel	m
M_g	Mass of gas released into the module	kg
Opr	Overpressure of the explosion	bar
Opr_{max}	Maximum possible overpressure of the explosion	bar
p	Pressure of gas within the leaking section	bar
p_a	Atmospheric Pressure	bar
q_g	Release rate of gas	m^3s^{-1}
R_B	Mass burn rate of oil	kgs^{-1}
t_{det}	Time to detection of a leak	s

t_{oil}	Time for release of oil	s
u	Wind Speed	ms^{-1}
$V_{g(at)}$	Volume of the cloud at atmospheric pressure	m^3
W_g	Mass flow rate of gas	kgs^{-1}
W_o	Mass flow rate of oil	kgs^{-1}
ρ_g	Density of gas	kgm^{-3}
ρ_o	Density of oil	kgm^{-3}
$\rho_{g(at)}$	Density of gas at atmospheric pressure	kgm^{-3}
$\rho_{o(at)}$	Density of oil at atmospheric pressure	kgm^{-3}
γ	Ratio of specific heats (cp/cv)	-

Introduction

The areas containing processing equipment on offshore platforms are known as modules. There are two fundamental types of module, open and enclosed, categorised according to the platform construction. Enclosed modules require forced ventilation, open modules are open-sided, allowing the module to be naturally ventilated by the wind. It is the latter that will be considered in this paper.

The number and configuration of modules making up an individual platform varies depending on the design and construction. Each process module contains pipework, process vessels, storage containers and the required control systems dependent on the function of the individual module.

The well fluids, oil, gas, condensate and water, are delivered to the platform from any well into the wellhead module. The fluid is then passed to the separation module where the water is drained, the oil is separated from the remaining fluid and transported to shore for refining. The condensate is removed from the gas mixture and the gas pressurised within the compression module before leaving the platform.

Each module will contain a number of isolatable process sections containing hydrocarbon fluids. These sections may have the potential to depressurise or blowdown, routing gas to the flare. On detection of a leak on a section, isolation valves would close to restrict the amount of inventory available to leak into the module and where present a blowdown valve would open to vent gas from the section to the flare. Both systems function to reduce the magnitude of the gas release.

The occurrence of a loss of containment is identified by either manual detection, gas detection or fire detection systems dependant on the nature of the event and how it develops. Gas detection systems installed on the platform can take two forms, the first detects the concentration of gas in the module by either sampling or using infra red beams, tripping at some preset limit, the second is a sonic detector which identifies the sound made by the gas release.

On detection of a leak or a fire, the deluge system on the platform will be activated. The deluge system releases water onto the affected area of the module, with the intention of suppressing the severity of the fire or reducing the overpressures should an explosion occur.

Combustion of a flammable-gas air mixture occurs if the composition of the mixture lies in the flammable range and if the conditions exist for ignition^[1]. The concentration is required to be above the Lower Flammable Limit (LFL) and below the Upper Flammable Limit (UFL). Experimental work conducted by British Gas^[2,3] has shown that substantial reductions in overpressure result when the concentration of gas in air deviates from the stoichiometric concentration.

Significant amounts of research have been conducted into the characteristics of fires occurring in process plants. One method used in modelling both jet and pool fires was to consider the flame dimensions and the surface emissive power^[1]. In SAROS the jet fire is modelled as a conical flame radiating away from the source of the leak and a pool fire is represented by an upright cylinder^[4].

To date there have been two major incidents resulting in the loss of production platforms in the North Sea. One of these incidents was the Piper Alpha disaster, which occurred in the British sector and resulted in the loss of 167 lives^[5]. Recommendations made during the enquiry following this disaster led to the requirement that operators submit a Safety Case for each offshore platform. The Safety Case is to assess all types of hazard, including fires and explosions, and requires acceptance by the Health and Safety Executive.

This paper presents a methodology to model fires and explosions on a platform and estimate the number of fatalities in an incident as is consistent with the requirements of the Health and Safety Executive. Modules are assumed to be of the open-sided, naturally ventilated type. The methodology presented has been implemented within the SAROS software package.

Hazards on Offshore Platforms

There are a number of hazards experienced when well fluids are processed on offshore platforms. The hazard considered in this paper is the uncontrolled release of hydrocarbons combined with the potential for ignition. This can result in a pool fire (oil release) or a jet fire (gas release) if ignition is immediate or an explosion if, following a gas release, there is a delayed ignition.

In order for an explosion or a fire to occur on a platform there must initially be a release of hydrocarbons which can take one of three forms; liquid only release, gas only release or combined liquid and gaseous release.

Immediate ignition of a high pressure gas release within a module will create a jet fire. The amount of oxygen available to support combustion within an open module is unlimited and therefore the fire will be extinguished only when the volume of inventory available has been reduced sufficiently to no longer support a flame.

A delay between commencement of a gaseous release and occurrence of the ignition source has the potential to cause an explosion. Prior to ignition the gaseous fuel will form a cloud within the module. An ignition source could ignite the gas cloud causing an accelerating flame-front to propagate through the cloud.

Ignition of an oil pool results in the formation of a pool fire. As for jet fires, the sustainability of the fire in an open module is dependant on the availability of leaking hydrocarbons rather than oxygen.

The magnitude of an explosion will be specified by the overpressures it produces. For a fire the heat generated and radiated to the platform structure and process vessels is of concern. Flame length and fire duration are used to indicate the magnitude of the fire.

Monte Carlo Simulation

The method used to model the risks on offshore platforms is the Monte Carlo Simulation method. Monte Carlo analysis is conducted as an experiment on a computer. The method uses random samples from distributions which govern the physical parameters and times to occurrence of events in the process. For this particular model each run starts with a hydrocarbon release and monitors the actions of the safety systems and the occurrence of an ignition through to the consequences. The results of a great number of simulations are then used to determine the probability distributions for the magnitude of the resulting fires and explosions and the consequential fatalities.

The method requires the use of a random number generator to create the random sample in variables during each simulation. Initially the leaking section will be selected according to the relative likelihood of a leak on each particular section in comparison to the others in the module. The size of the hole is selected as a random sample from the hole size distribution. This determines the leak characteristics.

The occurrence of many events in the simulation are specified by a constant rate of occurrence. The ignition rate and failure rates of various systems such as the deluge system are examples. In this case, the cumulative failure distribution, $F(t)$, for an exponential distribution with mean $\frac{1}{\lambda}$ is given by:

$$F(t) = 1 - e^{-\lambda t} \quad (1)$$

A random sample can be taken by generating a random number, X in the range 0 to 1, and equating to $F(t)$ since both quantities have the same properties. The time to failure, t , is given by:

$$t = -\frac{1}{\lambda} \ln X \quad (2)$$

Specific conditions, such as functionality of the isolation or blowdown valves, are determined by sampling a fixed probability event. A random number is compared to the probability of an event, if the random number is greater than this probability the system is assumed to be unavailable.

Development of the Model

The SAROS model was initially developed as an analytical method for explosion modelling by Andrews, Smith and Gregory^[6]. It has since been adapted to model fires

and explosions using Monte Carlo Simulation. The model determines the attributes of the initial release, calculates the fire or explosion characteristics and predicts the number of fatalities. The following sections describe how each of the events in a simulation are modelled.

Hydrocarbon Release

The section on which the leak occurs is selected according to the relative likelihood of a leak occurring on each section. The hole-size is then obtained by randomly sampling from the section hole size distribution. Whether the leak is oil, gas or condensate is determined by the specific inventory of the section and the location of the hole.

Initial Hydrocarbon Release Rate

Prior to detection, the initial release rate of hydrocarbons is calculated assuming that the inventory available for release is infinite and the driving pressure in the leaking section will remain constant.

The gas discharge rate is calculated using the laws of gas dynamics and the condensate discharge rate is calculated by assuming that there is a reservoir of ideal incompressible fluid^[7]. Bernoulli's equation is used to model the discharge speed of the gas, W_g , and hence the gas flow rate (when the flow is unchoked) is given by Equation (3) where A is the cross sectional area of the hole, γ is the ratio of specific heats c_p/c_v , p_a and p are the atmospheric pressure and pressure within the leaking section.

$$W_g = \left(2A^2 \left(\frac{\gamma}{\gamma-1.0} \right) K^{\frac{-1}{\gamma}} p_a^{\frac{1.0+\gamma}{\gamma}} \left[\left(\frac{p_a}{p} \right)^{\frac{1.0-\gamma}{\gamma}} - 1.0 \right] \right)^{\frac{1}{2}} \quad (3)$$

K is a constant derived from $p = K\rho_g^\gamma$, where ρ_g is the density of the gas, assuming that no heat is input into the system and gas is modelled as perfect.

If the gas reaches its maximum discharge speed, the speed of sound, it is assumed that the flow becomes choked and the flow rate is now modelled using Equation (4).

$$W_g = A \left(p\rho_g \gamma \left(\frac{2}{1.0+\gamma} \right)^{\frac{1.0+\gamma}{\gamma-1.0}} \right)^{\frac{1}{2}} \quad (4)$$

It is assumed that the condensate and gas leak in the same proportions that they exist in the section and that the condensate vapourises immediately on release to the atmosphere. Consequently the condensate is not considered further.

The modelling of the oil release rate depends on the location of the leak. If the leak occurs in the pipework before the separator, then it is assumed that water will be present in the leaking fluid, and the mass flowrate of oil, W_o (kgs^{-1}), will be modelled by Equation (5).

$$W_o = (2A^2(p - p_a)\rho_o)^{\frac{1}{2}} \quad (5)$$

where ρ_o is the density of the oil

The flowrate of water can be calculated by substituting the density of water into Equation (5). It is assumed that the water will affect the release rate on a section but once released will not be considered further.

If the leak occurs on a separation vessel then water is not present in the leaking fluid and the height of the hole on the vessel affects the release rate. The greater the head of oil the greater the pressure and release rate will be. The head of oil, H_{HEAD} , is calculated by subtracting the height of the hole from the height of the oil and is then used in Equation (6) to calculate the oil mass flow rate, where g is the acceleration due to gravity.

$$W_o = (2A^2\rho_o(p - p_a + g\rho_o H_{HEAD}))^{\frac{1}{2}} \quad (6)$$

Gas Release Detection

The methodology accounts for three types of detection system on the platform, sonic, beam and point detectors each of which are modelled independently. Sonic detectors identify the sound of gas escaping from the section. The parameter for this type of detector is the leak rate above which the leak will be detected. For the platform modelling presented later it is assumed that if the gas flow rate is greater than 0.5kg s^{-1} the leak will be detected in 15 seconds.

Beam and point detectors both rely on detection of a gas cloud. Point detectors sample the surrounding air and beam detectors detect the gas cloud if it passes through an infra-red beam. The time to detection, t_{det} , for both of these instruments is calculated using Equation (7) where h is the assumed minimum gas cloud diameter that can be detected, q is the volumetric release rate of gas and C is a constant representing the fraction of the LFL at which the gas detector is activated. The equation is based on Computational Fluid Dynamics modelling of jet releases.

$$t_{det} = \frac{\pi h^3}{6q_g C} \quad (7)$$

For beam detectors the minimum gas cloud diameter that can be detected is 8m and 10m is assumed for point detectors. The failure probability of each detector system is also taken into account.

If all three detection systems were to become unavailable the leak would be detected manually. In this case the model requires an input to specify a maximum time to detect a leak if none or only one of the workforce was in the module at the time. The detection time is reduced in proportion to the number of additional people.

Isolation and Blowdown System

Once a gas leak is detected the safety systems should activate. This includes the isolation and blowdown systems designed to limit the magnitude of the leak. Random numbers are compared against each valves failure probability to determine the functionality of each isolation and blowdown valve associated with the module. If the valves are working it is assumed that they are activated following a short delay after the leak is detected.

If an isolation valve on the leaking section is unavailable it is assumed that the inventory from the adjoining section will also contribute to the leak. If the sections are at higher pressures it is assumed that the inventory from the higher pressure section contributes to the leak until the pressure is equal to that of the lower pressure section. The inventory of the two sections then combine. This being a conservative approach to the modelling.

Deluge System

On fire or gas detection the deluge system is also activated. Two parameters need to be specified in the failure model for this system. It has a probability of failing to start and a failure rate once active. The availability of the deluge system is determined as for the isolation and blowdown systems. If the system is available it is assumed to activate following a specified short delay after detection, this is the time taken for water to fill the dry pipework sections. It is possible that after an active period the system could fail. This time to failure is generated using Equation 2. The characteristics of an explosion are affected by whether ignition occurs when the deluge is active or not.

Hydrocarbon Release Rate Following Isolation

Following isolation it is assumed that the inventory is no longer infinite. Equations (3) to (6) remain valid in calculating the release rates however the amount of inventory in the section will now decrease over time. The subsequent decrease in the pressure, density of gas and head of oil will lead to a reduction in the release rates.

Ventilation Rate

It is assumed the module is ventilated naturally by the wind. The ventilation rate for each simulation is determined by taking a random sample from between zero and a maximum value for the wind speed. The wind speed distribution is measured for the platform.

Gas Cloud Build-up and Dispersion

Gas released into the module will form a cloud which will change in size and gas concentration. A conservative approach is taken to the cloud growth model. As a worst case the gas cloud is assumed to grow at a uniform stoichiometric concentration. This being the concentration of gas in air which would cause the highest overpressures should ignition occur. The estimation of the cloud volume at

atmospheric pressure, $V_{g(at)}$ (m^3), uses M the mass of gas released into the module and $\rho_{g(at)}$ the density of the gas at atmospheric pressure.

$$V_{g(at)} = \frac{M_g}{\rho_{g(at)}} \quad (8)$$

When the cloud has expanded to fill the module, then the concentration can increase up to the UFL. Due to the open sides of the module, it is assumed that the cloud volume cannot exceed the module volume.

Once the leaking inventory is exhausted then the ventilation rate is greater than the release rate of the gas and the cloud disperses. The volume of the cloud remains constant while the concentration of the cloud decreases until the stoichiometric concentration is reached. Once the cloud is at stoichiometric concentration, the volume of the cloud decreases.

Oil Pool Build-up and Reduction

It is assumed that oil released and not ignited will form a pool assumed to grow with uniform depth. Prior to ignition the growth of the pool is proportional to the release rate of the oil. The area of the pool, A_p , is calculated using Equation (9) where W_o is the mass flow rate of oil, t_{oil} is the time for the release of oil, ρ_o is the density of oil and d_p is the depth of the pool.

$$A_p = \frac{W_o t_{oil}}{10 \rho_o d_p} \quad (9)$$

Due to the open sides of the module it is assumed that the pool area cannot exceed the module area and the depth of the pool cannot increase.

Following ignition, the area of the pool is assumed to increase only if the rate of release exceeds the mass burn rate, otherwise the pool area will decrease until it reaches zero. Equation (10) is used to calculate the pool area when R_B is the mass burn rate of the oil and A_{px} is the surface area of the pool.

$$A_p = \frac{W_o t_{oil}}{10 \rho_o d_p} - \frac{A_{px} R_B t_{oil}}{600 d_p} \quad (10)$$

Ignition Model

Three parameters are used to specify the ignition model, the probability of immediate ignition, and rate of occurrence of ignition sources both pre and post isolation. Post isolation, the rate of occurrence of an ignition source is reduced due to shutdown of the electrically powered equipment in the module.

Modelling Overpressures

It is assumed that a delayed ignition occurring following a gas leak will result in an explosion. The overpressure of the explosion, Opr (Pa), is calculated using Equation (11) where Opr_{max} is the maximum value the overpressure can be, A and B are constants which give the shape of the distribution. All of these parameters are dependant on the ignition location and the availability of deluge. C_g is the

concentration of the gas, C_s is the stoichiometric concentration and F_c is a factor dependent upon the fraction of the module occupied by the gas cloud.

$$Opr = Opr_{\max} \exp\left(A\left(\frac{C_g}{C_s} - 2B + 1\right)\left(\frac{C_g}{C_s} - 1\right)\right) F_c \quad (11)$$

The form of this equation is established with experimental results presented in Reference 9. A typical plot of the resulting overpressures with and without the deluge active is given in Figure 1. It can be seen that the overpressures peak at approximately stoichiometric concentration. Activating the deluge system prior to ignition can also substantially reduce the overpressures.

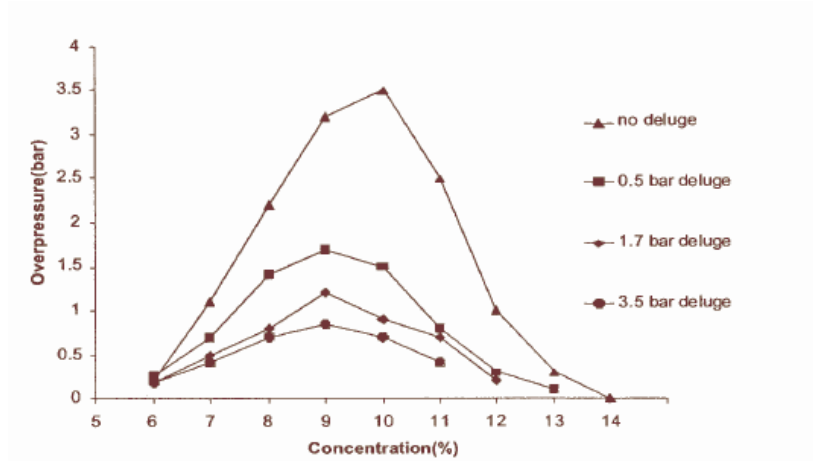


Figure 1 – Variation of overpressure with concentration

Modelling Fires

It is assumed that an ignition being present at the time of a release of gas (or oil at high pressure) will generate a jet fire. A jet fire will also result if gas continues to be released following an explosion. The length of the flame, F_j (m), is calculated using Equation (12), developed using the work by Thomas^[4]. If the initial length is below 2m it is assumed that the fire has not become established and is disregarded.

$$F_j = 15(W_g)^{0.41} \quad (12)$$

The time period is established in the code for which the flame length exceeds 2m. A decrease in length would be expected after isolation, when the release rate of the gas has decreased. The severity of the jet fire is characterised by the time duration for which the flame length exceeds 2m.

An ignition occurring during or following a release of oil will result in a pool fire, with the diameter of the oil pool forming the base of a cylindrical flame. The flame length, L_p , is calculated using Equation (13), derived by Moorhouse(1982) to model the flame height of cylindrical pool fire flames. If the initial length is below 2m it is assumed that the fire has not become established and is disregarded.

$$\frac{L_p}{D} = 6.2[u]^{-0.044} \left[\frac{R_B}{\rho_{o(at)} (gD)^{\frac{1}{2}}} \right]^{0.254} \quad (13)$$

where D is the pool diameter, u is the wind speed, R is the mass burn rate of the oil, $\rho_{o(at)}$ is the density of the oil at atmospheric pressure.

As for jet fires the duration for which the flame length is over 2m is calculated.

Modelling a Gaseous Release Following a Liquid Release

Following exhaustion of an oil only release it is assumed that a section containing gas could have the potential for an explosion or jet fire. If the pool fire is burning when the leak begins the gas will ignite causing a jet fire. If the pool fire has been extinguished before the gas begins to leak, a gas cloud will form and the potential for an explosion exists.

Fatality Modelling

The distribution of personnel over the platform is used together with the magnitude of each ignition event to estimate the frequency of fatalities on the platform. The fatalities have been considered to occur due to four types of event; jet fire, pool fire, explosion or fire following explosion. Fatalities due to smoke inhalation have not been considered.

Dependent on the location of the workforce at the time of any event, the fatalities have been categorised as: local, pre-muster and post muster. Local fatalities are those of the workforce in the same module as the event. The input file provides the module layout model with the resistance of each internal wall to explosion overpressure and fire exposure. An internal wall will fail if either the overpressure or fire duration exceeds the resistance of the wall. In the event of failure of an internal wall, it is assumed that all the workforce within the module become local fatalities. Pre-muster fatalities comprise the workforce distributed within the adjacent process modules. Failure of the internal wall of an adjoining module results in all workforce within the module becoming pre-muster fatalities. Post-muster fatalities are the workforce within the other process modules and the Temporary Safe Refuge, TR. It is assumed that fifty percent of the workforce will be in the TR at any one time. Prior to evacuation, all workforce will gather in the TR. In the event of evacuation, the workforce population will reduce at a specified rate.

The number of fatalities due to an explosion or fire is a function of the initial mass of fuel in the release, the module floor area and the number of people in the module. The event is modelled as a fireball and the distance away from the centre, at which the incident radiation is a safe level, is calculated. All personnel estimated to be within that distance are considered fatalities.

Ignition of a gas cloud occurring over 30 seconds after detection of the leak will result in no local fatalities as the population of the module have evacuated. If the explosion does not then cause the wall to fail it is assumed that no pre or post muster fatalities

are generated by this explosion. Failure of a wall by an explosion occurring within 6 minutes of detection will establish the population of the original module and the adjacent module as pre-muster fatalities. After this time it is assumed that all the workforce has become mustered in the TR and has started to evacuate.

It is assumed that all the workforce not evacuated become fatalities if there is no barrier between the TR and original module and the overpressure is sufficient to exceed the blast resistance of the TR. When one or more barriers exist between the TR and the original module, an explosion can only breach the TR if it causes platform collapse.

Further fatalities could result from a jet fire following an explosion where collapse of the internal walls between the event and the TR has occurred. If the flame length covers the distance from the module to the TR and fails the wall, all remaining personnel in the TR are considered fatalities.

Results

The method outlined in this paper is used to estimate the frequency of fatalities due to explosions, jet and pool fires on an open sided offshore platform. It is demonstrated by application to a typical example platform structure where three process modules; Wellhead, Separation and Compression have been analysed. Data was input to the model for each module in terms of module dimensions, hydrocarbon inventory, failure rates and locations of valves and times to blowdown.

The model was run through one million simulations and requires data on the average number of people in each module at any one time and the strength of blast and fire walls to predict the fatalities. It also requires the distance from each module to the TR to determine fatalities after mustering has completed.

Detailed results are output for each section within a module and a platform summary provided.

Module Results

Results for the Separation module are presented due to the diversity of events that can occur in the module since its inventory contains oil, gas and condensate. The module contains seven isolatable process sections, linked to each other and to sections outside the module. Figure 2 illustrates the layout of the sections, the location of the isolation valves which bound the sections and blowdown valves for depressurisation.

Two of the sections, labelled 13 and 21, contain only gas while sections labelled 32 and 33 are very small sections which contain only oil. The remaining three sections in the module, 1, 2 and 3, contain both gas and oil.

Explosion Results – The explosion frequencies predicted resulting from a leak on each of the sections are given in Table 1. These results are categorised with respect to the overpressure range of the explosion and leaking section.

Overpressure Range (bar)	Section							Module Total
	1	2	3	13	21	32	33	
0 – 1	2.60×10^{-03}	7.59×10^{-04}	1.40×10^{-03}	4.65×10^{-04}	3.14×10^{-04}	2.34×10^{-07}	9.37×10^{-07}	5.54×10^{-03}
1 – 2	1.17×10^{-06}	4.69×10^{-07}	7.03×10^{-07}	9.37×10^{-07}	4.69×10^{-07}	0	0	3.75×10^{-06}
2 – 3	1.41×10^{-06}	2.34×10^{-07}	0	1.17×10^{-06}	0	0	0	2.81×10^{-06}
3 – 4	4.69×10^{-07}	0	2.34×10^{-06}	2.34×10^{-07}	0	0	0	3.05×10^{-06}
4 – 5	7.03×10^{-07}	2.34×10^{-07}	9.37×10^{-07}	9.37×10^{-07}	4.69×10^{-07}	0	0	3.28×10^{-06}
5 – 6	7.03×10^{-07}	0	9.37×10^{-07}	4.69×10^{-07}	0	0	0	2.11×10^{-06}
6 – 7	2.34×10^{-07}	2.34×10^{-07}	0	2.34×10^{-07}	0	0	0	7.03×10^{-07}
7 – 8	0	0	0	2.34×10^{-07}	0	0	0	2.34×10^{-07}

Table 1 – Explosion frequencies for the Separation Module (per year)

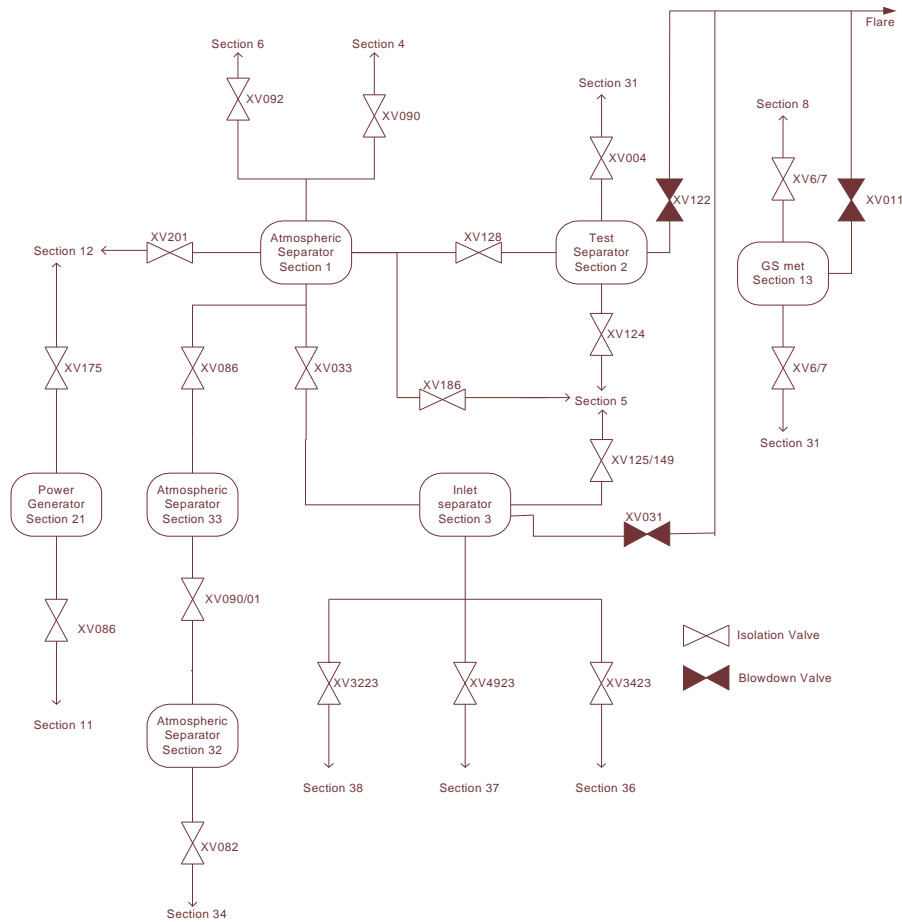


Figure 2 – Flow diagram for Separation Module

Five sections within the module contain gas, two of which contain only gas. The model predicted a frequency of 5.55×10^{-3} per year of an explosion occurring following a leak on any of the sections within the module. Section 1 accounted for approximately 47% of the total explosions within the module. Section 3 had the second highest frequency, accounting for 25% of the explosions.

Analysis of these results show that the sections containing gas at the highest pressures did not generate the largest number of explosions. It can be reasoned that a higher pressure within a section will generate a higher gas release rate into the module, and therefore the concentration of the accumulated gas cloud quickly exceeds the UFL.

The largest proportion of explosions was those with an overpressure between 0 and 1 bar; 5.54×10^{-3} per year, accounting for over 99% of all explosions.

Jet Fire Results - Two aspects of fires are considered by the model; the initial flame length and the length of time that the fire burns with a flame length of over two metres. The results for initial flame length for jet fires is presented within Table 2 and for fire duration in Table 3. The frequency of each event is again presented for each section that the leak indicates.

The model predicts a frequency of 2.94×10^{-2} per year of a jet fire occurring in all sections in the Separation Module.

Initial Flame Length (m)	Section							Module Total
	1	2	3	13	21	32	33	
0 – 10	6.24×10^{-03}	1.92×10^{-03}	3.18×10^{-03}	7.87×10^{-04}	6.21×10^{-04}	2.84×10^{-03}	2.27×10^{-03}	1.78×10^{-02}
10 – 20	4.10×10^{-04}	2.42×10^{-04}	4.22×10^{-04}	4.08×10^{-04}	1.64×10^{-04}	1.77×10^{-04}	1.43×10^{-04}	1.97×10^{-03}
20 – 30	2.09×10^{-04}	6.09×10^{-05}	1.12×10^{-04}	1.83×10^{-04}	9.00×10^{-05}	6.54×10^{-05}	5.04×10^{-05}	7.71×10^{-04}
30 – 40	7.03×10^{-05}	6.84×10^{-05}	1.26×10^{-04}	1.05×10^{-04}	1.97×10^{-05}	4.26×10^{-05}	3.61×10^{-05}	4.68×10^{-04}
40 – 50	5.15×10^{-05}	2.88×10^{-05}	6.02×10^{-05}	4.48×10^{-05}	8.90×10^{-06}	3.12×10^{-05}	2.86×10^{-05}	2.53×10^{-04}
50 – 60	3.19×10^{-05}	1.85×10^{-05}	3.66×10^{-05}	1.90×10^{-05}	1.57×10^{-05}	2.34×10^{-05}	1.80×10^{-05}	1.63×10^{-04}
60 – 70	2.65×10^{-05}	1.52×10^{-05}	2.37×10^{-05}	1.80×10^{-05}	1.83×10^{-05}	1.27×10^{-05}	9.14×10^{-06}	1.23×10^{-04}
70 – 80	2.18×10^{-05}	1.15×10^{-05}	1.48×10^{-05}	6.09×10^{-06}	9.61×10^{-06}	7.73×10^{-06}	8.44×10^{-06}	8.13×10^{-05}
80 – 90	2.48×10^{-05}	4.92×10^{-06}	1.20×10^{-05}	1.55×10^{-05}	7.97×10^{-06}	1.29×10^{-05}	8.91×10^{-06}	8.69×10^{-05}
90+	1.67×10^{-03}	1.94×10^{-04}	2.97×10^{-04}	1.28×10^{-04}	1.13×10^{-04}	2.95×10^{-05}	2.33×10^{-03}	7.68×10^{-03}

Table 2 – Frequencies of jet fire initial flame lengths for Separation Module (per year)

Fire Duration (s)	Section							Module Total
	1	2	3	13	21	32	33	
0.0 – 7.2	8.33×10^{-03}	2.35×10^{-03}	3.68×10^{-03}	1.39×10^{-03}	9.24×10^{-04}	6.17×10^{-03}	4.90×10^{-03}	2.77×10^{-02}
7.2 – 14.4	2.15×10^{-04}	1.21×10^{-04}	3.10×10^{-04}	1.05×10^{-04}	6.44×10^{-05}	0	0	8.15×10^{-04}
14.4 – 21.6	1.92×10^{-04}	7.97×10^{-05}	2.50×10^{-04}	1.40×10^{-04}	6.75×10^{-05}	0	0	7.28×10^{-04}
21.6 – 28.8	1.52×10^{-05}	5.62×10^{-06}	5.08×10^{-05}	2.23×10^{-05}	1.17×10^{-05}	0	0	1.06×10^{-04}
28.8 – 36.0	2.34×10^{-07}	0	2.34×10^{-07}	1.64×10^{-06}	4.69×10^{-07}	0	0	2.58×10^{-06}
36.0 – 72.0	0	0	0	0	0	0	0	0
72.0 – 144.0	0	0	0	0	0	0	0	0
144.0 – 216.0	0	0	0	2.34×10^{-07}	0	0	0	2.34×10^{-07}
216.0 – 288.0	0	0	0	2.34×10^{-07}	0	0	0	2.34×10^{-07}
288.0+	0	0	0	0	0	0	0	0

Table 3 – Frequencies of jet fire durations for Separation Module (per year)

Section 1 generated the greatest frequency of fires accounting for approximately 30% of jet fires. Section 21, containing the lowest volume of gas, generated the fewest jet fires. Sections 32 and 33, although containing only oil, generated the second and third highest numbers of fires. This can be explained due to the assumption in the model that ignition of a oil release at a high pressure can be treated in the same way as a jet fire.

Each section generated fires with initial flame lengths between 0 and 100m in length. Overall, the greatest proportion of jet fires (over 60%) occurred with an initial flame length between 0 and 10m. 26% of the fires occurred with an initial flame length of over 90m.

Approximately 94% of the fires had a duration of between 0 and 7.2 seconds. The relatively short durations of the fires is due to the effectiveness of the detection systems in activating the isolation and blowdown valves.

Pool Fire Results – As for jet fires, the initial flame length (Table 4) and the duration at which the flame of the fire is over 2 metres in length (Table 5) are estimated for pool fires.

The model predicts a frequency of 8.35×10^{-03} of a pool fire occurring within the Module per year.

Initial Flame Length (m)	Section							Module Total
	1	2	3	13	21	32	33	
0 – 10	1.77×10^{-03}	0	0	0	0	3.66×10^{-03}	2.92×10^{-03}	8.35×10^{-03}
10+	0	0	0	0	0	0	0	0

Table 4 – Frequencies of pool fire initial flame lengths for Separation Module (per year)

Fire Duration (s)	Section							Module Total
	1	2	3	13	21	32	33	
0.0 – 7.2	1.33×10^{-3}	0	0	0	0	2.67×10^{-3}	2.25×10^{-3}	6.25×10^{-3}
7.2 – 14.4	0	0	0	0	0	0	0	0
14.4 – 21.6	0	0	0	0	0	0	0	0
21.6 – 28.8	0	0	0	0	0	0	0	0
28.8 – 36.0	0	0	0	0	0	0	0	0
36.0 – 72.0	0	0	0	0	0	0	0	0
72.0 – 144.0	2.34×10^{-7}	0	0	0	0	0	0	2.34×10^{-7}
144.0 – 216.0	0	0	0	0	0	0	0	0
216.0 – 288.0	0	0	0	0	0	0	0	0
288.0+	4.40×10^{-4}	0	0	0	0	9.91×10^{-4}	6.72×10^{-4}	2.10×10^{-3}

Table 5 –Frequencies of pool fire durations for Separation Module (per year)

The SAROS results show that pool fires were only generated from a leak occurring on 3 sections, although five sections within the module contained oil. For the remaining two sections oil leaks occurring produced an initial flame length which was below 2m and therefore a fire was not considered to have been established. Sections 32 and 33 contained only oil, and as expected resulted in the two highest frequencies of pool fires. Section 33 generated the highest pool fire frequency overall, and also the longest initial flame length.

All pool fires occurring within the module had a flame length of less than 10m and the majority of the fires had a duration of less than 7.2 seconds.

Platform Results

The results from the Separation, Compression and Wellhead modules were combined to provide overall predictions for the platform. Table 6 shows the percentage of each incident type occurring within each of the modules. The Separation, Compression and Wellhead modules consist of 7, 13 and 6 sections respectively, each containing gas and/or oil.

Ten of the sections within the Compression module contain only gas and 3 contain both oil and gas. The Wellhead module consists of 3 modules containing only gas and 3 containing oil and gas.

Module	Event			Module Total
	Explosion	Jet Fire	Pool Fire	
Separation	23.089	30.606	99.982	33.707
Compression	53.336	49.917	0.018	47.314
Wellhead	23.575	19.477	0.000	18.979

Table 6 – Proportions of events occurring within each module

Explosions accounted for approximately 19% of the total incidents on the module. The majority of explosions on the platform occurred with an overpressure of between 0 and 1 bar and the most severe explosions originated within the Separation module. This is due to the effectiveness of the detection and deluge systems installed on the platform.

Approximately 75% of incidents were jet fires. The majority of fires occurred with an initial flame length of up to 10 metres and a duration of up to 7.2 seconds.

Pool fires accounted for 6.5% of all incidents on the platform. The majority of pool fires were generated in the Separation module.

Fatality Results

The frequency of fatalities is estimated for each module of the platform, dependent on whether an explosion, immediate ignition jet fire, jet fire following an explosion or pool fire has occurred. Table 7 presents the percentages of fatalities occurring due to each incident type.

Module	Event				Section Total
	Explosion	ImmIgn Jet Fire	Jet fire after explosion	Pool Fire	
Separation	21.149	24.364	32.769	99.998	24.870
Compression	57.133	55.939	50.020	0.002	54.747
Wellhead	21.717	19.697	17.211	0.000	20.384

Table 7 – Proportions of fatalities occurring within each module

A total frequency of 4.768×10^{-02} fatalities per year was estimated for the platform. The Compression module generated the highest number of fatalities and Wellhead module the lowest. This reflects the results for the total number of events occurring within each of these modules.

Explosions generated the highest frequency of fatalities, approximately 70% of the total number, followed by immediate ignition jet fires (~25%), pool fires (~3%) and jet fires following explosions (~2%). Comparison of these results with Table 6 demonstrates that on average, more fatalities are generated by an explosion than by a jet fire. In fact further investigation of the results showed that explosions were the only events severe enough generate post-muster fatalities. Pool fires generated fewer fatalities than jet fires or explosions.

Occurrence of a jet fire following an explosion generated the lowest number of fatalities. The majority of the workforce in the area would have become fatalities during the explosion and the escalation of the event threatens those working in areas away from the source of the incident.

Conclusions

A methodology has been developed to examine all possible outcomes following a hydrocarbon release on an offshore platform. The incidents of concern are explosions, jet fires, pool fires and the escalation of an explosion to a jet fire. A Monte Carlo simulation methodology used has been incorporated into a software package called SAROS which can be used to provide a risk analysis for input to safety cases.

As the platform can be broken down into isolatable process sections, the methodology can be used to determine where the significant contribution to the explosion or fire hazard is located. This could be used to demonstrate methods of reducing hazards and assess optimum platform design with respect to minimising fatalities.

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