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 safety and reliability of offshore structures (SAROS) 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.

Keywords: offshore, fires, explosions, risk, reliability, Monte Carlo simulation

1 INTRODUCTION

The areas containing processing equipment on offshore platforms are known as modules. There are two fundamental types of module, namely open and enclosed, categorized 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 vary 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 pressurized 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 depressurize or blowdown, routeing 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 manual detection, gas detection, or fire detection systems dependent 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 infrared beams, tripping at some preset limit; the second is a sonic

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detector that 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 on to 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 the safety and reliability of structures (SAROS) software, 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 to 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. Earlier developmental work on SAROS has been reported in references [**6**] and [**7**].

2 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 that it no longer supports 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 dependent on the availability of leaking hydrocarbons rather than oxygen.

The magnitude of an explosion will be specified by the overpressures that 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.

3 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 that 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 with 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 $1/\lambda$ 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 from 0 to 1 and equating to $F(t)$ since both quantities have the same properties. The time t to failure 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 with the probability of the event failure; if the random number is less than this probability, the system is assumed to be unavailable.

SAROS was run a number of times, varying the number of simulations each time up to a maximum of 3×10^6 simulations. The results were found to converge prior to 10^6 simulations.

4 DEVELOPMENT OF THE MODEL

The SAROS model was initially developed as an analytical method for explosion modelling by Andrews *et al.* [**8**]. 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.

4.1 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.

4.2 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 [**9**, **10**]. Bernoulli's equation is used to model the discharge speed W_g of the gas, and hence the gas flowrate (when the flow is unchoked) is given by

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

where A is the cross-sectional area of the hole; γ is the ratio of specific heats c_p/c_v, p_a is the atmospheric pressure; p is the pressure within the leaking section. 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 the 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 flowrate is now modelled using

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

It is assumed that the condensate and gas leak in the same proportions in which they exist in the section and that the condensate vaporizes 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 W_o (kg/s) of oil will be modelled by

$$W_o = \left[2A^2 (p - p_a) \rho_o \right]^{1/2} \quad (5)$$

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 H_{head} of oil, is calculated by subtracting the height of the hole from the height of the oil and is then used in

$$W_o = \left[2A^2 \rho_o (p - p_a + g\rho_o H_{head}) \right]^{1/2} \quad (6)$$

to calculate the oil mass flowrate, where g is the acceleration due to gravity.

4.3 Gas release detection

The methodology accounts for three types of detection system on the platform, namely 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 flowrate is greater than 0.5 kg/s, the leak will be detected in 15 s.

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 infrared beam. The time t_{det}, to detection, for both of these instruments is calculated using

$$t_{\mathrm{det}} = \frac{\pi h^3 C}{6 q_{\mathrm{g}}} \tag{7}$$

where h is the assumed minimum gas cloud diameter that can be detected, q_{g} is the volumetric release rate of gas, and C represents the fraction of the gas in air at which the gas detector is activated. Dividing the volume of the gas cloud by the rate at which the gas is released into the module determines the time required to detect a cloud of a certain diameter.

For beam detectors the minimum gas cloud diameter that can be detected is 8 m, and 10 m 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.

4.4 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.

4.5 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.

4.6 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.

4.7 Ventilation rate

It is assumed that 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.

4.8 Gas cloud build-up and dispersion

Gas released into the module will form a cloud that 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 that would cause the highest overpressures should ignition occur. The estimation of the cloud volume $V_{\mathrm{g(at)}}$ (m^3) at atmospheric pressure, uses M, the mass of gas released into the module, and $\rho_{\mathrm{g(at)}}$, the density of the gas at atmospheric pressure, according to

$$V_{\mathrm{g(at)}} = \frac{M_{\mathrm{g}}}{\rho_{\mathrm{g(at)}}} \tag{8}$$

When the cloud has expanded to fill the module, then the concentration can increase up to the UFL. Because of 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.

4.9 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 A_p of the pool, is calculated using

$$A_p(t) = \frac{\int_0^{t_{oil}} W_o(t)\mathrm{d}t}{\rho_o d_p} \tag{9}$$

where W_o is the mass flowrate 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.

Because of 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 all oil has been burned. The equation

$$\frac{R_B \int_0^{t_{burn}} A_p(t)\mathrm{d}t}{\rho_o d_p} \tag{10}$$

is used to calculate the decrease in pool area when R_B is the mass burn rate per unit area of the oil and t_{burn} is the burn time of the pool fire.

4.10 Ignition model

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

4.11 Modelling overpressures

It is assumed that a delayed ignition occurring following a gas leak will result in an explosion. The overpressure Opr (Pa) of the explosion is calculated using

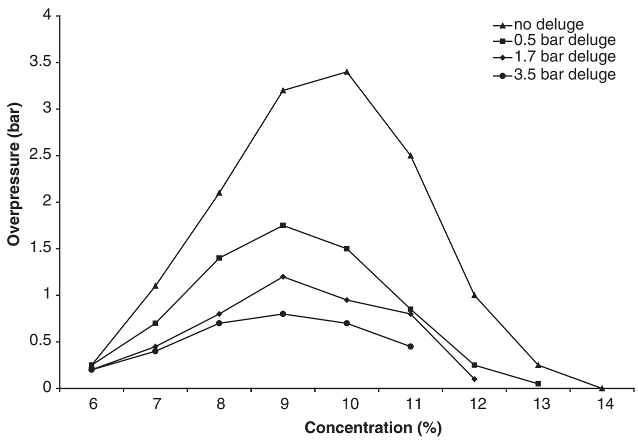

Fig. 1 Variation in overpressure with concentration

$$\mathrm{Opr} = \mathrm{Opr}_{max} \exp\left[A\left(\frac{C_g}{C_s} - 2B + 1\right)\left(\frac{C_g}{C_s} - 1\right)\right]F_c \tag{11}$$

where Opr_{max} is the maximum value that the overpressure can be, and A and B are constants which give the shape of the distribution. All these parameters are dependent 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.

The form of this equation is established with experimental results presented in reference [**11**]. A typical plot of the resulting overpressures with and without the deluge active is given in Fig. 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.

4.12 Modelling fires

It is assumed that the presence of an ignition at the time of a release of gas (or oil at a high pressure) will generate a jet fire. A jet fire will also result if gas continues to be released following an explosion. The flame length F_j (m) of the jet fire is calculated using

$$F_j = 15W_g^{0.41} \tag{12}$$

which was developed using the work by Thomas [**4**]. If the initial length is below 2 m, it is assumed that the fire has not become established and is disregarded.

The time period is established in the code for which the flame length exceeds 2 m. 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 characterized by the time duration for which the flame length exceeds 2 m.

The occurrence of 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 of the pool fire is calculated using

$$\frac{L_\mathrm{p}}{D} = 6.2u^{-0.044}\left[\frac{R_\mathrm{B}}{\rho_{\mathrm{o(at)}}(gD)^{1/2}}\right]^{0.254} \qquad (13)$$

derived by Moorhouse and Pritchard [**12**] to model the flame height of cylindrical pool fire flames. If the initial length is below 2 m, it is assumed that the fire has not become established and is disregarded, where D is the pool diameter, u is the wind speed, R is the mass burn rate of the oil, and $\rho_{\mathrm{o(at)}}$ is the density of the oil at atmospheric pressure.

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

4.13 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.

5 MODULE DATA

The data used for the analysis, not shown elsewhere in the paper, are given in Appendix 2. A brief explanation of the data is provided below.

For each isolatable section on the platform, a set of data describing the section inventory is required. An example of one section is provided in Appendix 2 (Table 8) as a full list of all sections used in the example platform would be too voluminous. The model requires the proportion and densities of oil, gas, condensate, and water occurring in the section and the section volume, temperature, and pressure.

The dimensions of the module under analysis are required in a number of calculations throughout the simulation and are provided in each module input file (Appendix 2, Table 8). Also the ventilation rate within an open module platform is supplied in terms of the maximum windspeed.

Other parameters specifying the system functionality are provided. These include, the percentage of the LFL required for gas detection by the automatic gas detection system (Appendix 2, Table 8).

The probabilities of failure of each of the three detector types, sonic, beam, and point, are also required to determine the availability of each individual detector type during each simulation. A probability of failure is also provided for the fire detection system. All these probabilities are given in Appendix 2, Table 8.

There will be a time delay between activating the deluge system and the water spray functioning while the water is pumped through the dry pipework. The deluge system has an initial unavailability and also a frequency that the system should fail once active (Appendix 2, Table 8).

The magnitude of the leak is established from a hole-size distribution. This is specified in Appendix 2, Table 9, which is derived from existing data on offshore oil and gas incidents [**13**, **14**]. The Monte Carlo method takes random samples from this distribution of hole sizes for each simulation.

Each isolatable section in a module has an independent frequency that a leak will occur. The total number of sections and the frequency of a leak on each of the sections used in the example simulation are also provided in Appendix 2, Table 10.

An ignition model for each module on the example platform is provided in the input file (Appendix 2, Table 11). The first parameter specified is the probability that a leak will be ignited immediately. If an immediate ignition does not occur, there are then two further frequencies to model delayed ignition, the frequency that a delayed ignition occurs prior to isolation and post-isolation. Post-isolation it is assumed that many of the potential ignition sources will be removed.

Three ignition locations are modelled within SAROS: next to a module wall, in the centre of the module and at the open end of the module. The severity of an explosion is dependent on the location of the ignition source. For each of these situations (only one is listed in Appendix 2, Table 12) the constants A, B, and the maximum overpressure in equation (11) are provided for both deluge active and deluge inactive. For other locations the parameter which changes significantly is the maximum overpressure.

In order for a fire or explosion to escalate into other modules, the ignition must produce an incident of a certain severity. The minimum flame length for a fire to be established is provided, together with the length of time that the fire would be required to burn for before it would cause structural damage. For explosions, there is a critical overpressure that will fail a boundary between two modules and an overpressure that is required to cause structural damage.

An average population is specified for each module; the proportion of this population that is in a module at the time of ignition is estimated using random sampling from the population distribution an example of which is specified in Appendix 2, Table 13.

6 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 owing 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 categorized as follows: 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 the 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 consist of the workforce distributed within the adjacent process modules. Failure of the internal wall of an adjoining module results in the fact that all workforce within the module become pre-muster fatalities. Post-muster fatalities are the workforce within the other process modules and the temporary safe refuge (TR). It is assumed that 50 per cent 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 s after detection of the leak will result in no local fatalities as the population of the module has 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 min 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 if 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.

7 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 were 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 10^6 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.

7.1 Module results

Results for the separation module are presented owing 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 depressurization.

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, namely section 1, 2, and 3, contain both gas and oil.

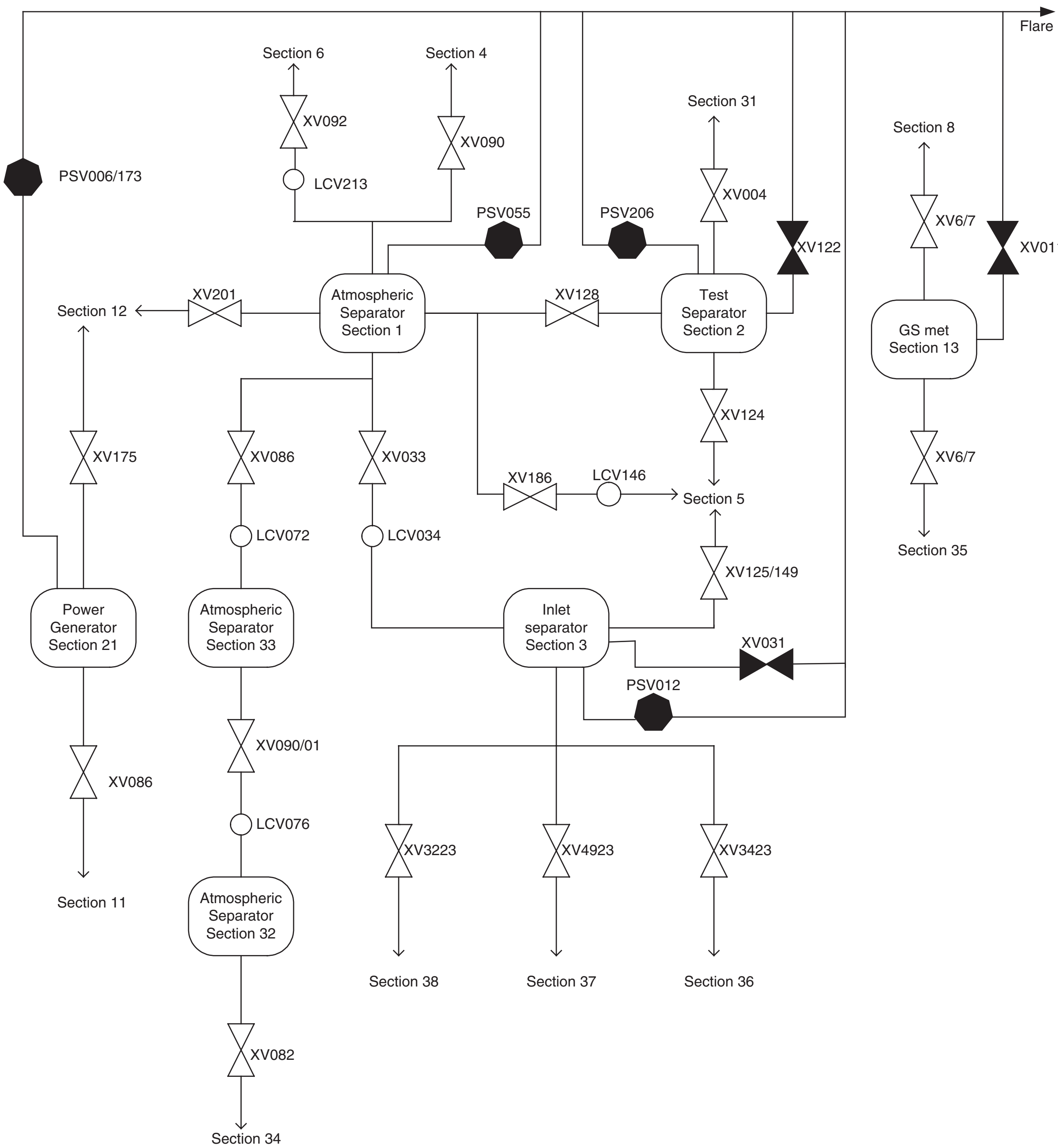

Fig. 2 Flow diagram for the separation module

7.1.1 Explosion results

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

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 per cent of the total explosions within the module. Section 3 had the second highest frequency, accounting for 25 per cent 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 per cent of all explosions.

Table 1 Explosion frequencies for the separation module

	Explosion frequency (per year) for the following sections							
Overpressure range (bar)	1	2	3	13	21	32	33	Module total
0–1	2.60×10^{-3}	7.59×10^{-4}	1.40×10^{-3}	4.65×10^{-4}	3.14×10^{-4}	2.34×10^{-7}	9.37×10^{-7}	5.54×10^{-3}
1–2	1.17×10^{-6}	4.69×10^{-7}	7.03×10^{-7}	9.37×10^{-7}	4.69×10^{-7}	0	0	3.75×10^{-6}
2–3	1.41×10^{-6}	2.34×10^{-7}	0	1.17×10^{-6}	0	0	0	2.81×10^{-6}
3–4	4.69×10^{-7}	0	2.34×10^{-6}	2.34×10^{-7}	0	0	0	3.05×10^{-6}
4–5	7.03×10^{-7}	2.34×10^{-7}	9.37×10^{-7}	9.37×10^{-7}	4.69×10^{-7}	0	0	3.28×10^{-6}
5–6	7.03×10^{-7}	0	9.37×10^{-7}	4.69×10^{-7}	0	0	0	2.11×10^{-6}
6–7	2.34×10^{-7}	2.34×10^{-7}	0	2.34×10^{-7}	0	0	0	7.03×10^{-7}
7–8	0	0	0	2.34×10^{-7}	0	0	0	2.34×10^{-7}

Table 2 Frequencies of the initial flame lengths of the jet fires for the separation module

	Frequency (per year) of the initial flame length of the jet fire in the following sections							
Initial flame length (m)	1	2	3	13	21	32	33	Module total
0–10	6.24×10^{-3}	1.92×10^{-3}	3.18×10^{-3}	7.87×10^{-4}	6.21×10^{-4}	2.84×10^{-3}	2.27×10^{-3}	1.78×10^{-2}
10–20	4.10×10^{-4}	2.42×10^{-4}	4.22×10^{-4}	4.08×10^{-4}	1.64×10^{-4}	1.77×10^{-4}	1.43×10^{-4}	1.97×10^{-3}
20–30	2.09×10^{-4}	6.09×10^{-5}	1.12×10^{-4}	1.83×10^{-4}	9.00×10^{-5}	6.54×10^{-5}	5.04×10^{-5}	7.71×10^{-4}
30–40	7.03×10^{-5}	6.84×10^{-5}	1.26×10^{-4}	1.05×10^{-4}	1.97×10^{-5}	4.26×10^{-5}	3.61×10^{-5}	4.68×10^{-4}
40–50	5.15×10^{-5}	2.88×10^{-5}	6.02×10^{-5}	4.48×10^{-5}	8.90×10^{-6}	3.12×10^{-5}	2.86×10^{-5}	2.53×10^{-4}
50–60	3.19×10^{-5}	1.85×10^{-5}	3.66×10^{-5}	1.90×10^{-5}	1.57×10^{-5}	2.34×10^{-5}	1.80×10^{-5}	1.63×10^{-4}
60–70	2.65×10^{-5}	1.52×10^{-5}	2.37×10^{-5}	1.80×10^{-5}	1.83×10^{-5}	1.27×10^{-5}	9.14×10^{-6}	1.23×10^{-4}
70–80	2.18×10^{-5}	1.15×10^{-5}	1.48×10^{-5}	6.09×10^{-6}	9.61×10^{-6}	7.73×10^{-6}	8.44×10^{-6}	8.13×10^{-5}
80–90	2.48×10^{-5}	4.92×10^{-6}	1.20×10^{-5}	1.55×10^{-5}	7.97×10^{-6}	1.29×10^{-5}	8.91×10^{-6}	8.69×10^{-5}
90 +	1.67×10^{-3}	1.94×10^{-4}	2.97×10^{-4}	1.28×10^{-4}	1.13×10^{-4}	2.95×10^{-5}	2.33×10^{-3}	7.68×10^{-3}

Table 3 Frequencies of the durations of the jet fires for the separation module

	Frequency (per year) of the duration of the jet fire in the following sections							
Fire duration (s)	1	2	3	13	21	32	33	Module total
0.0–7.2	8.33×10^{-3}	2.35×10^{-3}	3.68×10^{-3}	1.39×10^{-3}	9.24×10^{-4}	6.17×10^{-3}	4.90×10^{-3}	2.77×10^{-2}
7.2–14.4	2.15×10^{-4}	1.21×10^{-4}	3.10×10^{-4}	1.05×10^{-4}	6.44×10^{-5}	0	0	8.15×10^{-4}
14.4–21.6	1.92×10^{-4}	7.97×10^{-5}	2.50×10^{-4}	1.40×10^{-4}	6.75×10^{-5}	0	0	7.28×10^{-4}
21.6–28.8	1.52×10^{-5}	5.62×10^{-6}	5.08×10^{-5}	2.23×10^{-5}	1.17×10^{-5}	0	0	1.06×10^{-4}
28.8–36.0	2.34×10^{-7}	0	2.34×10^{-7}	1.64×10^{-6}	4.69×10^{-7}	0	0	2.58×10^{-6}
36.0–72.0	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^{-7}	0	0	0	2.34×10^{-7}
216.0–288.0	0	0	0	2.34×10^{-7}	0	0	0	2.34×10^{-7}
288.0 +	0	0	0	0	0	0	0	0

7.1.2 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 2 m. The results for initial flame length for jet fires are 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.

Section 1 generated the greatest frequency of fires accounting for approximately 30 per cent 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 on 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 of between 0 and 100 m in length. Overall, the greatest proportion of jet fires (over 60 per cent) occurred with an initial flame length between 0 and 10 m. 26 per cent of the fires occurred with an initial flame length of over 90 m.

Table 4 Frequencies of the initial flame lengths of the pool fires for the separation module

	Frequency (per year) of the initial flame length of the pool fire in the following sections							
Initial flame length (m)	1	2	3	13	21	32	33	Module total
0–10	1.77×10^{-3}	0	0	0	0	3.66×10^{-3}	2.92×10^{-3}	8.35×10^{-3}
10 +	0	0	0	0	0	0	0	0

Table 5 Frequencies of the durations of the pool fires for the separation module

	Frequency (per year) of the duration of the pool fire in the following sections							
Fire duration (s)	1	2	3	13	21	32	33	Module total
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}

Approximately 94 per cent of the fires had a duration of between 0 and 7.2 s. The relatively short durations of the fires are due to the effectiveness of the detection systems in activating the isolation and blowdown valves.

7.1.3 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 m in length (Table 5) are estimated for pool fires.

The model predicts a frequency of 8.35×10^{-3} of a pool fire occurring within the module per year.

The SAROS results show that pool fires were only generated from a leak occurring on three sections, although five sections within the module contained oil. For the remaining two sections, the oil leaks occurring produced an initial flame length which was less than 2 m 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 10 m and the majority of the fires had a duration of less than 7.2 s.

7.2 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.

Table 6 Proportions of events occurring within each module

	Proportion (per cent) of the following events			
Module	Explosion	Jet fire	Pool fire	Module total
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

Ten of the sections within the compression module contain only gas and three contain both oil and gas. The wellhead module consists of three modules containing only gas and three containing oil and gas.

Explosions accounted for approximately 19 per cent 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 per cent of incidents were jet fires. The majority of fires occurred with an initial flame length of up to 10 m and a duration of up to 7.2 s.

Table 7 Proportions of fatalities occurring within each module

Module	Proportion (per cent) of fatalities for the following events: Explosion	Immediate ignition jet fire	Jet fire after explosion	Pool fire	Section total
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

Pool fires accounted for 6.5 per cent of all incidents on the platform. The majority of pool fires were generated in the separation module.

7.3 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 because of each incident type.

A total frequency of 4.768×10^{-2} fatalities per year was estimated for the platform. The compression module generated the highest number of fatalities, and the 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 per cent of the total number, followed by immediate ignition jet fires (about 25 per cent), pool fires (about 3 per cent), and jet fires following explosions (about 2 per cent). 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 to generate post-muster fatalities. Pool fires generated fewer fatalities than jet fires or explosions.

The 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.

8 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.

The simulation can account for a detailed description of the safety features incorporated on the platform. As such it has the maximum impact if utilized during the design phase where the influence of parameters of alternate safety system designs can be evaluated and cost-effective trade-offs made.

It is difficult to draw general design rules for open-sided modules as the optimal safety features depend on the equipment contained in each module. For example the results presented indicate the relative contributions to hazards for the separation module, which contains a relatively low-pressure process involving gas, oil, and condensate. Results for the compression module with its high-pressure, predominantly gas inventory would indicate different trends. However, with a simulation approach such as that presented, general trends need not be determined and each potential design can be assessed individually.

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APPENDIX 1

Notation

A	cross-sectional area of the hole (m^2)
C	constant representing the fraction of gas in air at which the detector is activated (per cent)
C_g	concentration of the gas within the module (per cent)
C_s	stoichiometric concentration (per cent)
d_p	depth of oil pool (m)
D	pool fire diameter (m)
$F(t)$	cumulative failure distribution
F_c	fraction of the module occupied by the gas cloud (–)
F_j	flame length of the jet fire (m)
g	acceleration due to gravity (m/s^2)
h	assumed minimum gas cloud diameter (m)
H_{Head}	height of the head of oil above a leak on a vessel (m)
L_p	flame length of the pool fire (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^3/s)
R_B	mass burn rate per unit area of oil (kg/m^2s)
t_{det}	time to detection of a leak (s)
t_{oil}	time for release of oil (s)
u	wind speed (m/s)
$V_{g(at)}$	volume of the cloud at atmospheric pressure (m^3)
W_g	mass flowrate of gas (kg/s)
W_o	mass flowrate of oil (kg/s)
γ	ratio of specific heats (c_p/c_v) (–)
ρ_g	density of gas (kg/m^3)
$\rho_{g(at)}$	density of gas at atmospheric pressure (kg/m^3)
ρ_o	density of oil (kg/m^3)
$\rho_{o(at)}$	density of oil at atmospheric pressure (kg/m^3)

APPENDIX 2

Data for the example

The data used for analysis are given in Tables 8 to 13.

Table 8 Data on the isolatable section, module, and system parameters Data provided for each isolatable section (example)

Section volume	108.52 m^3
Section temperature	334.16 K
Section pressure	260 000.00 Pa
Section gas density	2.35 kg/m^3
Section condensate density	0.00 kg/m^3
Section oil density	987.00 kg/m^3
Section gas proportion	0.60
Section condensate proportion	0.00
Section oil proportion	0.30
Section water proportion	0.10
Module dimensions	
Module height	10.0 m
Module width	20.0 m
Module length	40.0 m
Maximum wind speed	2.4 m/s
System parameters	
Percentage of LFL for detection	0.2
Probability of sonic detector failure	0.07
Probability of beam detector failure	0.07
Probability of point detector failure	0.07
Fire detection system availability	0.98
Time delay to activate deluge	45 s
Deluge system unavailability	0.09
Deluge system failure frequency	9.446×10^{-6} per year

Table 9 Hole-size distribution

Cumulative probability	Hole size (mm)
0.00	0
57.56	5
70.64	10
82.93	20
87.43	30
88.93	40
89.31	50
93.71	80
95.22	100
97.00	150
97.75	200
99.62	500
100.00	600

Table 10 Leak rate data (number of sections, seven)

Section number	Leak frequency on section (per year)
1	6.53×10^{-2}
2	2.59×10^{-2}
3	4.18×10^{-2}
13	1.69×10^{-2}
21	1.06×10^{-2}
32	4.13×10^{-2}
33	3.25×10^{-2}

Table 11 Ignition model

Immediate ignition probability	0.07
Delayed ignition frequency prior to isolation	0.28
Delayed ignition frequency post-isolation	0.0028

Table 12 Overpressure data (one location)

Location label	loc1
Stochiometric concentration	8.88 per cent
Constant *A* (deluge inactive)	−19.693
Constant *B* (deluge inactive)	1.0563
Maximum overpressure (deluge inactive)	8.7 bar
Constant *A* (deluge active)	−18.215
Constant *B* (deluge active)	1.007
Maximum overpressure (deluge active)	0.32 bar
Critical fire flame length	2.0 m
Critical fire length (module)	15.0 m
Critical fire duration (structure)	120.0 min
Critical explosion overpressure (module)	0.6 bar
Critical explosion overpressure (structure)	1.6 bar

Table 13 Workforce distribution

Cumulative probability	Fraction of population
2.5	0.10
5	0.30
10	0.45
15	0.55
20	0.65
25	0.75
35	0.85
50	0.95
65	1.05
75	1.15
80	1.25
85	1.35
90	1.45
95	1.55
97.5	1.70
100	1.90